MODELLING THE AIR/FLUE-GAS CIRCUIT OF A THERMOELECTRIC POWER PLANT UNIT

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Abstract: The objective of this paper is the characterization of the air/flue-gas circuit of a large-scale thermoelectric power plant unit. The air/flue-gas circuit has a complex structure and is typically non-linear and time-variant. The structure that best describes its behavior, assuming a tradeoff between simplicity and reliability, is a model essentially based on physical principles, concentrated parameters type, non-linear and time-invariant. The model is validated using plant data.

Keywords: Modelling, Simulation, Thermoelectric Power Plant Unit, Steam Generator, Air/Flue-Gas Circuit.

1. INTRODUCTION

This paper is concerned with the development and validation of a model for the air/flue-gas circuit of a large-scale, coal fired, thermoelectric power plant unit. The aim of this model is twofold: First, to allow the development of simpler models used for observer based fault detection and isolation (FDI); Second, to be used as a simulation platform of the plant subsystem considered for testing of FDI algorithms.

In order to cope with these objectives, the model is based on physical principles (conservation of mass, energy and momentum) combined with the characteristics of the local components, obtained from plant or manufactures data. A number of examples of this type can be found in the literature (Åström, 2000; Coito, 1988; Soares, 1997; Thumm, 1983; Thysso, 1981; Usoro, 1977). However, most studies refer to whole thermoelectric groups. The contribution of this paper consists in the development of a detailed model of the air/flue-gas circuit and its validation based on actual plant data.

This paper is divided in three main sections as follows: First of all, a formal description of the air/flue-gas circuit components is presented (Coito, 1990; Gonçalves, 1993; Ordys, 1994); Following, mathematical models that describe static and dynamic behaviors for all system components are presented (Shirley, 1991); Finally, the developed model is compared with data from a thermoelectric power plant to demonstrate its capabilities under real situations. 1

The model presented provides an upgrade of the results of (Shirley, 1991; Gonçalves, 1993). In particular, (Gonçalves, 1993) provides an original methodology for modelling the furnace, which was closely followed.

2. THERMOELECTRIC POWER PLANTS

A thermoelectric power plant unit consists of two main blocks: the steam generator and the turbo-generator. A simplified block diagram of a thermoelectric power plant unit is shown in figure 1.

The steam generator provides the steam used in the turbo-generator for electricity production. Two main circuits exist: The fuel-air/flue-gas circuit and the water-steam circuit.

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2.1 Steam Generation

The steam generation cycle begins with the coal being transported from the bunkers to the mills where it is powdered. Then, it is sent to the burners through a so-called primary air flow. In the furnace, the coal is burned to supply energy to the water-steam circuit. The cycle ends with the vaporization of the water due to the heat. A simplified block diagram of a coal supplier is shown in figure 2.

Fig. 2. Block diagram of a coal supplier.

The primary air flow doesn’t allow the complete burn of the coal. The secondary air flow provides the necessary additional air flow through an air injector. The flue-gas produced in the burning process is used to heat up several parts of the boiler before being removed from the main circuit to the chimney through a flue-gas extractor. A simplified block diagram of an air circuit is shown in figure 3.

Fig. 3. Block diagram of an air circuit.

The drum, located inside the boiler, is the main component in the water-steam circuit. The water is sent to the vaporizer returning to the drum in gaseous state. The available steam is then sent to the turbine for torque production returning to the drum in liquid state. A simplified block diagram of a water circuit is shown in figure 4.

Fig. 4. Block diagram of a water circuit.

2.2 Air/Flue-Gas Circuit

The air/flue-gas circuit comprises air injectors, flue-gas extractors and furnaces. Typically, an air/flue-gas circuit consists of several air injectors and flue-gas extractors, and a single furnace. A simplified block diagram of an air/flue-gas circuit with two independent lines is shown in figure 5.

Fig. 5. Block diagram of an air/flue-gas circuit with two independent lines.

An air injector consists of one injection fan (forced-draught fan), one air pipe and one control valve. A flue-gas extractor consists of one extraction fan (induced-draught fan) and one control valve.

To guarantee the safety of coal boilers, the internal furnace pressure should be maintained within a narrow range, to avoid possible mechanical deformations resulting from high differentials between inside and outside furnace pressures. The control of the internal furnace pressure is an interesting problem from the point of view of control strategies.

3. MODELLING

The air/flue-gas circuit can be seen as the orderly linkage of the following components: injection fans, air pipes, control valves, furnace and extraction fans. Hereafter, each component will be modeled.

3.1 Injection and Extraction Fans

The main function of an injection or extraction fan is to provide enough air flow from a lower pressure to a higher pressure section. An injection or extraction fan consists of an air valve and a ventilation system.

An injection or extraction fan can be modeled in three steps. First of all, the dynamic characteristic of the air valve is determined. Then, the air flow as a function of the air valve aperture and of the differential pressure between input and output sections is determined. Finally, the useful air flow is computed, taking into account all circuit losses.

The air valve, due to its internal structure, can be modeled as a first-order system, with static gain $k$ and a dominant pole located at $s = -p$. Therefore, its dynamic, $D(s)$, is given by the following expression:

$$D(s) = k \cdot \frac{p}{s + p}$$  \hspace{1cm} (1)

The static behavior of the ventilation system can be obtained through their characteristic curves (supplied by manufacturers), which relate the manometric...
height, \( H \), with the volumetric air flow, \( C^v \), and the air valve rotation, \( R \). Characteristic curves of a ventilation system for several air valve rotations are shown in figure 6.

![Characteristic Curves of a Ventilation System](image)

Fig. 6. Characteristic curves of a ventilation system for several air valve rotations.

Due to the quadratic form of the characteristic curves, these can be approximated by a second-order function given by the following expression:

\[
H = c_2(R) \cdot (C^v)^2 + c_1(R) \cdot C^v + c_0(R) \tag{2}
\]

On the other hand, the manometric height is related with the total differential pressure, \( \Delta P_r \), through the following expression (where \( \rho \) is the air density and \( g \) is a constant):

\[
H = \frac{\Delta P_r}{g \cdot \rho} \tag{3}
\]

The total differential pressure depends on the static differential pressure, \( \Delta P_s \), on the dynamic differential pressure, \( \Delta P_d \), and on the load loss, \( P_l \), through the following expression:

\[
\Delta P_t = \Delta P_s + \Delta P_d + P_l \tag{4}
\]

The dynamic differential pressure and the load loss can be computed through the following expressions (where \( v_i \) is the input air velocity, \( v_o \) is the output air velocity, \( S_i \) is the input section area, \( S_o \) is the output section area and \( k_l \) is the load loss coefficient):

\[
\Delta P_d = \frac{1}{2} \cdot \rho \cdot (v_o^2 - v_i^2) \tag{5}
\]

\[
P_l = k_l \cdot \rho \cdot C^v \tag{6}
\]

with:

\[
v_{i/o} = \frac{C^v}{S_{i/o}} \tag{7}
\]

Using the previous results, the manometric height can be computed through the following expression:

\[
H = h_1 \cdot \Delta P_s + h_2 \cdot (C^v)^2 \tag{8}
\]

with:

\[
h_1 = \frac{1}{g \cdot \rho} \tag{9}
\]

\[
h_2 = \frac{1}{2} \cdot g \cdot \left( \frac{1}{S_o^2} - \frac{1}{S_i^2} + 2 \cdot k_l \right) \tag{10}
\]

Eliminating the manometric height in both models and after some algebraic manipulations, the volumetric airflow take the form given by the following expression (where \( k_1', k_2' \) and \( k_3' \) are functions to be detailed below):

\[
C^v = k_1'(R) + \sqrt{k_2'(R) + k_3'(R) \cdot \Delta P_s} \tag{11}
\]

In order to obtain the previous result in International System units, some conversions are needed. It is also needed to express the previous result in terms of the air valve aperture instead of its rotation, which can be done through the following expression:

\[
A = r_2 \cdot R^2 + r_1 \cdot R + r_0 \tag{12}
\]

Using the previous results, the massic air flow, \( C \), of the ventilation system can be obtained through the following expression:

\[
C = k_1(A) + \sqrt{k_2(A) + k_3(A) \cdot \Delta P_s} \tag{13}
\]

with:

\[
k_1(A) = \frac{\rho}{2} \cdot h_2 \tag{14}
\]

\[
k_2(A) = \frac{h_2^2 \cdot (c_1(A))^2 + 4 \cdot (h_2 - c_2(A)) \cdot c_0(A)}{4 \cdot (h_2 - c_2(A))^2} \tag{15}
\]

\[
k_3(A) = -\frac{10^5 \cdot \rho^2 \cdot h_1 \cdot \Delta P_s}{h_2 - c_2(A)} \tag{16}
\]

Not all the air flow supplied by the ventilation system of an injection fan is used in the burning process due to circuit losses. The most significant losses are the escape air flow (air that escapes to the reheater circuit given its own configuration), \( C_e \), and the boundary air flow (air that is used to maintain the furnace stability), \( C_b \). Thus, the useful air flow, \( C_u \), is calculated from the total air flow through the following expression (where \( k_e \) is the coefficient associated to the escape air flow and \( k_b \) is the coefficient associated to the boundary air flow):

\[
C_u = (1 - k_e - k_b) \cdot C \tag{17}
\]

The useful air flow of a ventilation system for several air valve apertures is shown in figure 7.

![Useful Air Flow of a Ventilation System](image)

Fig. 7. Useful air flow of a ventilation system for several air valve apertures.

Remark that this type of losses does not exist in an extraction fan.
3.2 Air Pipes

The main function of an air pipe is to provide enough air pressure to the next section of an air circuit.

An air pipe can be modeled in three steps. First of all, the relation between the air pressure and the differential flow is determined. Then, that relation is converted to the time-domain. Finally, the resulting model is obtained incorporating initial conditions.

Due to the internal structure of an air pipe, the air pressure depends on the amount of air in it. More specifically, the air pressure, $P$, is proportional to the difference between the input air mass, $M_i$, and the output air mass, $M_o$, which is given by the following expression:

$$ P \propto (M_i - M_o) \quad (18) $$

In the time-domain, the previous result is given by the following expression (where $C_i$ is the input air flow, $C_o$ is the output air flow and $k$ is the characteristic constant of the air pipe, which depends essentially on its internal volume):

$$ P(t) = k \cdot \int (C_i(\tau) - C_o(\tau)) d\tau \quad (19) $$

Given the integral dependence on the previous result, a initial operation condition must be defined. Therefore, the final model of an air pipe is given by the following expression:

$$ P(t) = P(t_0) + k \cdot \int_{t_0}^{t} (C_i(\tau) - C_o(\tau)) d\tau \quad (20) $$

3.3 Control Valves

The main function of a control valve is to control the air flow between two joint sections of an air circuit.

A control valve can be modeled in three steps. First of all, the dynamic behavior of the control valve is determined. Then, the air flow as a function of the control valve aperture and of the differential pressure between input and output sections (static behavior) is determined. Finally, the whole air flow provided by several independent control valves is determined.

The dynamic behavior of a control valve, $D(s)$, due to its internal structure, can be modeled as a first-order system, with static gain $k$ and a dominant pole located at $s = -\frac{1}{\tau}$, as given in expression (1).

The static behavior of a control valve is typically nonlinear. However, using the Bernoulli laws, the air flow, $C$, as a function of the control valve aperture, $A$, and of the differential pressure, $\Delta P$, can be determined through the following expression (where $k$ is the characteristic function of the control valve):

$$ C = k(A) \cdot \sqrt{\Delta P} \quad (21) $$

A characteristic function of a control valve is shown in figure 8.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{characteristic_function.png}
\caption{Characteristic function of a control valve.}
\end{figure}

Due to the quadratic form of the characteristic functions, these can be approximated by a second-order function given by the following expression:

$$ k(A) = a_2 \cdot A^2 + a_1 \cdot A + a_0 \quad (22) $$

Typically, an air/flue-gas circuit consists of several independent control valves for a better system operation management. Therefore, the total air flow, $C_t$, is given through the following expression (where $C_i$ is the air flow provided by the control valve $i$):

$$ C_t = \sum_i C_i \quad (23) $$

3.4 Furnace

The main function of a furnace is to burn the coal for the vaporization of the water inside the boiler.

As described in (Gonçalves, 1993), a furnace can be modeled in three steps. First of all, a formal description of the perfect gases is introduced. Following, all chemical equations that take place are written. Finally, the internal pressure as a function of the input and output air flows is determined.

Assuming that the internal pressure of a furnace is almost equal to the atmospheric pressure, the gases can be considered perfect gases, modeled by the following expression (where $P$ is the pressure, $T$ is the temperature, $V$ is the volume, $M$ is the mass, $\mu$ is the molecular mass and $r$ is the perfect gases constant):

$$ P = \frac{r}{V} \cdot \frac{M}{\mu} \cdot T \quad (24) $$

Assuming that the internal temperature of a furnace is almost constant, the time derivative of the internal pressure is proportional to the mass variation, as given by the following expression:

$$ \frac{dP}{dt} = \frac{r}{V} \cdot T \cdot \frac{1}{\mu} \cdot \frac{dM}{dt} \quad (25) $$

The air flow used in the burn process consists in a mixture of $m_{O_2} \%$ of oxygen and $m_{N_2} \%$ of nitrogen (per air mass unit). Therefore, the air flow, $C_a$, can be
seen as the sum of an oxygen flow, \( C_{O_2} \), and a nitrogen flow, \( C_{N_2} \), as given by the following expression:

\[
C_a = C_{O_2} + C_{N_2}
\]  

(26)

with:

\[
C_{O_2} = m_{O_2} \cdot C_a
\]  

(27)

\[
C_{N_2} = m_{N_2} \cdot C_a
\]  

(28)

Using the previous results, the mass variation is given by the following expression (where \( \mu_{O_2} \) is the molecular mass of the oxygen and \( \mu_{N_2} \) is the molecular mass of the nitrogen):

\[
\frac{1}{\mu} \frac{dM}{dt} = k_a \cdot C_a
\]  

(29)

with:

\[
k_a = \frac{m_{O_2}}{\mu_{O_2}} + \frac{m_{N_2}}{\mu_{N_2}}
\]  

(30)

The coal flow, \( C_c \), used in the burn process, consists in a mixture of \( c\% \) of carbon, \( h\% \) of hydrogen, \( s\% \) of sulfur, \( n\% \) of nitrogen, \( o\% \) of oxygen and \( w\% \) of hydrogen (per fuel mass unit). The chemical reactions that take place in the furnace are shown in the following table:

<table>
<thead>
<tr>
<th>Substance</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>( C + O_2 \rightarrow CO_2 )</td>
</tr>
<tr>
<td>Sulfur Dioxide</td>
<td>( S + O_2 \rightarrow SO_2 )</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>( N_2 + 2O_2 \rightarrow 2NO_2 )</td>
</tr>
<tr>
<td>Water</td>
<td>( 2H_2 + O_2 \rightarrow 2H_2O )</td>
</tr>
</tbody>
</table>

Using the previous chemical equations, the mass variation is given by the following expression (where \( \mu_{CO_2} \) is the molecular mass of the carbon dioxide, \( \mu_{SO_2} \) is the molecular mass of the sulfur dioxide, \( \mu_{NO_2} \) is the molecular mass of the nitrogen dioxide and \( \mu_{H_2O} \) is the molecular mass of the water):

\[
\frac{1}{\mu} \frac{dM}{dt} = k_c \cdot C_c
\]  

(31)

with:

\[
k_c = \frac{m_{CO_2}}{\mu_{CO_2}} + \frac{m_{SO_2}}{\mu_{SO_2}} + \frac{m_{NO_2}}{\mu_{NO_2}} + \frac{m_{H_2O}}{\mu_{H_2O}} - \frac{m_{O_2}}{\mu_{O_2}}
\]  

(32)

The mass variation due to the flue-gas flow, \( C_f \), resulting from the burn process, is given by the following expression:

\[
\frac{1}{\mu} \frac{dM}{dt} = -k_f \cdot C_f
\]  

(33)

Using all mass variation contributions, the total mass variation is given by the following expression:

\[
\frac{1}{\mu} \frac{dM}{dt} = k_a \cdot C_a + k_c \cdot C_c - k_f \cdot C_f
\]  

(34)

In normal operation conditions, the internal pressure variation is null and, consequently, the mass variation is also null (the sum of the air and coal flows equals the flue-gas flow), which result in the following expression:

\[
k_f = k_a \cdot \frac{C_a}{C_a + C_c} + k_c \cdot \frac{C_c}{C_a + C_c}
\]  

(35)

Typically, the air/coal flow ratio, \( r_{ac} \), is constant. Thus, the previous result can be calculated by the following expression:

\[
k_f = \frac{k_a \cdot r_{ac} + k_c}{r_{ac} + 1}
\]  

(36)

with:

\[
r_{ac} = \frac{C_a}{C_c}
\]  

(37)

Using all mass variation contributions, the internal pressure variation is given by the following expression:

\[
\frac{dP}{dt} = k \cdot (k_a \cdot C_a + k_c \cdot C_c - k_f \cdot C_f)
\]  

(38)

with:

\[
k = \frac{r}{V} \cdot T
\]  

(39)

Given the internal pressure variation and an initial operation condition, the final model of a furnace is given by the following expression:

\[
P(t) = P(t_0) + \int_{t_0}^{t} \frac{dP(r)}{dt} \, dr
\]  

(40)

4. SIMULATION

Any part of the air/flue-gas circuit can be simulated by the developed model. However, the air supplier subsystem is very interesting from the point of view of system stability, and consequently, has been chosen for simulation. Remark that, the air supplier subsystem is formed by an injection fan and an air pipe.

The air supplier subsystem will be simulated with two different types of plant data. First, analytical data (set of signals manually generated for specific proposes) will be applied to the subsystem model to verify its correct behavior. Then, real data will be used to test the subsystem under real operating conditions.

To simulate the air supplier subsystem based only on analytical data, the set-point for the air pipe pressure was changed for different values several times over a certain period.

The simulation results obtained for the air supplier subsystem with analytical data are shown in figure 9.

Simulation results show that the air supplier subsystem model is in agreement with the expected behavior, which states that to increase the air pipe pressure, the useful air flow provided by the injection fan must increase too, which can be done increasing its valve aperture. Note the integral dependence existing between the air flow and the air pressure.
To simulate the air supplier subsystem based only on real data, all real input signals were introduced in the model and its output was compared to the real output signal.

The simulation results obtained for the air supplier subsystem with real data are shown in figure 10.

Simulation results show that both signals (real and simulated) exhibit the same shape. However, some differences can be observed at particular instants. These differences can be explained taking into account the corruption caused by the additional noise present in the real signals and the limited precision of the used model. However, the results are suitable for fault detection and system diagnosis.

5. CONCLUSION

This paper describe a physical principles based model of the air/flue-gas circuit of a thermoelectric power plant unit. Simulation results obtained with the developed model have been compared with real plant data. It was concluded that the model may be used for FDI studies.

6. REFERENCES