Steam Generator Modeling Using Thermofluid Matlab-Simulink Library

F. Betchine
Automatic laboratory of Setif
LAS - Algeria -

A. Lamamra
Automatic laboratory of Setif
LAS - Algeria -

Abstract

The modeling of process engineering systems is still an open field because of its complexity. These processes have a highly non-linear behavior mainly due to the mutual interaction of several phenomena of various kinds and the combination of technological components that implement the laws from different disciplines (mechanical, thermal , chemical). Even if these types of processes are present in a many industries with risk (nuclear, chemical, etc...), which require for their knowledge and control models more precise and usable.

The aim of this work is to create a model in Matlab-Simulink, of the steam generator situated at Lille 1 University, such a process occurred in many risky process, is characterized by multidomain energy.

Key words-- Modeling, Matlab-Simulink, Steam Generator, Condenser, boiler, expansion.

1. Introduction

The steam generation process is widely used in process engineering. Furthermore, such phenomena occur in many risky processes such as nuclear and chemical, it is why their modeling is needed.
Because of the complexity of the thermodynamic phenomena which govern the dynamic behavior of thermal power plants, the modeling problem is still with a great interest.

2. Process description

Let us consider the supervision of the pilot process schematically shown on fig 1. The test plant designed to be a scale-model of part of a power station is a complex non linear system. This installation is mainly constituted of four subsystems: a receiver with the feedwater supply system, a boiler heated by a 60 KW resistor, a steam flow system and a complex condenser coupled with a heat exchanger.

The feed water flow is pressurized via the feed pump which is controlled by a relay to maintain a constant water level inside the steam generator. The heat power is determined based on the available accumulator pressure P7. The expansion of the generated steam is realized by three valves in parallel connection. V5 is a controlled valve, which allows passing around the steam flow to the condenser. V6 is automatically controlled to maintain proper pressure to the condenser. In an industrial plant, the steam flows to turbine for generating power, but at the test stand, the steam is condensed and stored in a receiver tank and returned to the steam generator [5],[6].

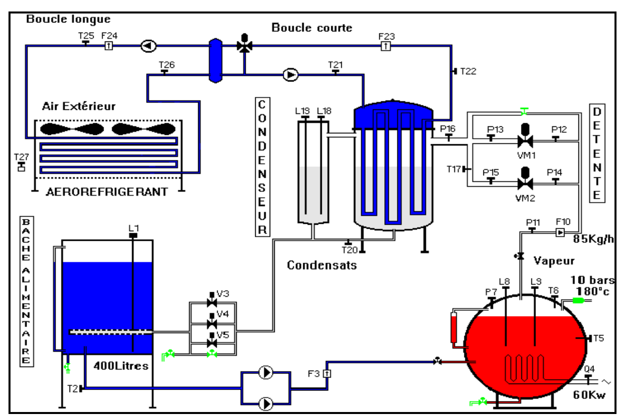

Fig 1. Schematic of the pilot process

2.1. The feedwater system

It consists of a pump, a pipe and a tank receiver (Fig 2):

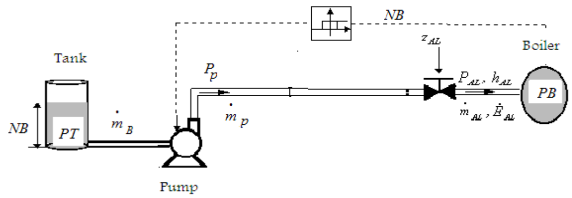

Fig 2. Feedwater system

The tank is initially full of water at ambient temperature, and therefore under-saturated: the pressure and temperature are independent. The pressure at the bottom of the tank depends only on the volume or mass:

$$P_T = \rho_T.g.N_T = \rho_T.g.\frac{V_T}{A_T} = \frac{\rho_T.g}{A_T}\frac{m_T}{\rho_T} = \frac{g.m_T}{A_T} \qquad (1)$$

Where $P_T, \rho_T, g, N_T, V_T, A_T, m_T$ refer to the pressure, density of water, gravity, and water level in the tank, the volume of water, the tank section and the mass of water.

The input and output Enthalpy flows of the storage tank are expressed as a function of temperature T_{in}, the specific enthalpy H_{AL}, the input and output mass flow $\dot{m}_{in}$, and $\dot{m}_{out}$:

$$\dot{H}_{in} = \dot{m}_{in} c_p T_{in} \qquad (2)$$

$$\dot{H}_{out} = \dot{m}_{out}\frac{H_{AL}}{m_{AL}} \qquad (3)$$

The mass flow refueled by the pump $\dot{m}_{AL}$ is determined as the intersection between the pump and the pipe characteristics ($\dot{m}_{PA}$ and $\dot{m}_{AL}$) which are given by the following equations [3],[6]:

$$\begin{cases} \dfrac{\dot{m}_P}{\rho_{AL}} = -8{,}33*10^{-10}\Delta P_P + 9{,}722*10^{-4} \\ \dfrac{\dot{m}_P}{\rho_{AL}} = \sqrt{\dfrac{(P_P - P_B)10^5}{K_D(zv_1)}} \end{cases} \qquad (4)$$

ρ_{AL} is the water density equal to 1000 kg/m^3.

ΔP_P is the difference between the output pressure P_P and the input pressure P_T of the pump:

$$\Delta P_P = 10^5(P_P - P_T) \qquad (5)$$

$K_D(zv_1)$ is the flow nonlinear characteristic of the pipe identified experimentally and depending on valve V1 position ZV1. b_1 is a Boolean variable based on the reference (L_{B_ref}) and the actual (L_B) water level inside the boiler. It depends also on the dead zone Δ, of the "on-off" controller.

2.2. The boiler

The boiler belongs to the class of saturated fluid accumulator, as it is shown in fig 3:

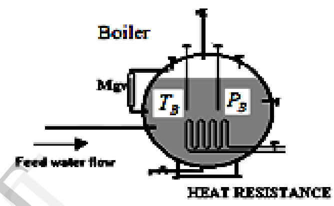

Fig 3. The boiler

The energy conservation equation is given by (6):

$$\frac{d(H_B)}{dt} = \dot{H}_B = \dot{Q}_{TH} + \dot{H}_{AL} + \dot{E}_W - \dot{H}_{VD} \qquad (6)$$

H_B is the total enthalpy in the boiler

We assume that the fluid in the boiler exits as a saturated, homogeneous mixture of vapor and liquid at uniform pressure P_B, the mixture is characterized by the steam quality X (dryness fraction) in the boiler

The pressure P_B and the steam quality X in the boiler, are determined solving the mixture equation:

$$\begin{cases} h_B = \dfrac{H_B}{m_B} = h_v(P_B).X + h_l(P_B).(1-X) \\ v_B = \dfrac{V_B}{m_B} = v_v(P_B).X + v_l(P_B).(1-X) \end{cases} \qquad (7)$$

Where h_l and h_v represent water and steam saturation specific enthalpy, v_l and v_v specific volumes. All are thermodynamic functions of pressure [3]:

$$h_v = -0.74P^2 + 17.21P + 2680$$

$$h_l = -0.0243P^4 + 0.8487P^3 - 11.9P^2 + 99.97P + 347$$

$$v_v = -5.3*10^{-5}P^5 + 0.00207P^4 - 0.0032P^3 + 0.2498P^2 - 1.03P + 2.166$$

$$v_l = -3.59*10^{-7}P^3 + 1.2456*10^{-5}P^2 + 1.03*10^{-3}$$

The temperature T_B is determined then by the following thermodynamic relationship $T_B = f(P_B)$:

$$T_B = -0.4594P_B^2 + 12.72P_B + 99.003$$

2.3. Steam expansion

The steam expansion system is shown in fig 4:

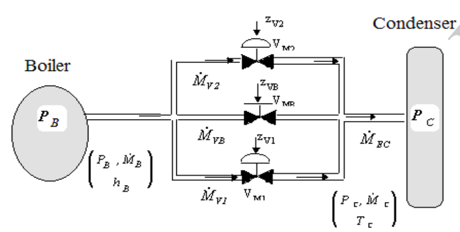

Fig 4. The steam expansion system

The expansion of generated steam is realized by three valves in parallel connection. VM1 is a manually controlled valve, simulating that corresponds in an industrial plant to pass around the steam flow to a condenser. VM2 is automatically controlled to maintain proper pressure to the condenser. The bypass valve VMB, normally closed allows simulating a leakage pressure in the system.
In an industrial plant, the steam flows to turbine for generating power, but at the test stand, the steam is condensed and stored in a receiver tank for returning to the boiler.

The flow of under-saturated liquid through the three parallel valves is given as follows:

$$\begin{cases} \dot{m}_1 = K_{v1}(z_{v1}).\sqrt{(P_B - P_C)\dfrac{P_C}{T_B}} \\ \dot{m}_2 = K_{v2}(z_{v2}).\sqrt{(P_B - P_C)\dfrac{P_C}{T_B}} \\ \dot{m}_B = K_{vB}(z_{vB}).\sqrt{(P_B - P_C)\dfrac{P_C}{T_B}} \end{cases} \quad (8)$$

$K_{v1}(z_{v1})$, $K_{v2}(z_{v2})$ and $K_{vB}(z_{vB})$, Are the pressure drop coefficients in the corresponding valve, these coefficients are nonlinear functions of the position z of the flap valve.

2.4. The condenser

The condenser of the steam generator is one of the most complex components; Figure represents a schematic diagram of this component. Its role is to transform the dry steam coming from the steam expansion system to liquid.

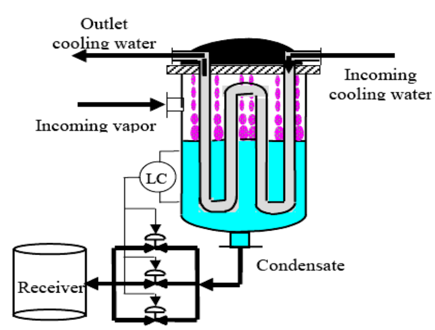

Fig 5. Condenser schematic

The steam coming from the expansion system to the condenser is condensed over the vertical tubes through which the cooling water flows. The tubes are split into three parts: at the input to the condenser in touch with the steam, within the condensate and then again in contact with the steam at the output from the condenser. There the water outflow (condensate) is controlled by three valves, in order to keep its level constant.
Steam phase
The mass of saturated steam coming from the boiler is given by:

$$M_{cv} = \rho_v * V_{cv} \quad (9)$$

V_{cv} : Volume of steam (m^3).

ρ_v : Mass density of steam Kg/m^3.

$$\rho_v = \frac{\int\left(\dot{M}_{ec} - \dot{M}_{ct}\right)dt}{\left(\frac{\partial \rho_v}{\partial T}\right) * V_{cv}} + \rho_{v0} \quad (10)$$

$\dot{M}_{ec}$: Entering steam flow Kg/S.

$\dot{M}_{ct}$: Condensate flow Kg/S.

ρ_{v0} : Initial mass density of steam Kg/m^3.

The volume of steam in the condenser V_{cv} is :

$$V_{cv} = V - S_c * N_{cond} \quad (11)$$

V : Total volume of the condenser (m^3).

S_c : Horizontal section of the condenser (m^2).

N_{cond} : Level of liquid in the condenser (m).

$$N_{cond} = \frac{M_l}{\rho_l * S_c} \quad (12)$$

Where M_l is the liquid mass:

$$M_l = \int\left(\dot{M}_{ct} - \dot{M}_{vd}\right) * dt + M_{l0} \quad (13)$$

$\frac{\partial \rho_v}{\partial T}$: Partial derivative of saturated steam density is evaluated from saturated steam tables[5]:

$$\frac{\partial \rho_v}{\partial T} = 4.59*10^{-11}T_{cv}^4 + 1.59159*10^{-9}T_{cv}^3 + 8.0471*10^{-7}T_{cv}^2 + 1.1346*10^{-5}T_{cv} + 1.90366*10^{-4} \quad (14)$$

The specific enthalpy of the steam in the condenser is obtained from thermodynamic tables

$$h_{cv} = -3*10^{-7}T_{cv}^5 + 2.0766*10^{-4}T_{cv}^4 - 7.0061*10^{-2}T_{cv}^3 + 8.9607*T_{cv}^2 + 1.18506*10^3 T_{cv} + 2.5202*10^6$$
(15)

☒ *Liquid phase*

The condensate flow is:

$$\dot{M}_{ct} = \frac{\rho_l * (\rho_l - \rho_v) * g * e_x^3 * \pi * d_t * n_t}{3 * \mu_l} \quad (16)$$

ρ_l : Mass density of the liquid (Kg/m^3).

ρ_v : Mass density of the steam (Kg/m^3).

μ_l : Dynamic viscosity of the liquid ($Kg/m.s$).

d_t : Tubes' diameter (m).

n_t : Number of tubes.

e_x : The height of the condensing film it is extracted from a Nusselt type formula:

$$e_x = \left(\frac{4 * \mu_l * (l - N_{cond}) * (T_{cv} - T_{vt}) * \lambda_l}{g * \rho_l * (\rho_l - \rho_v) * [L_v + 0.68 * c_{tv} * (T_{cv} - T_{vt})]}\right)^{1/4}$$
(17)

λ_l :Thermal conductibility of the condensate ($W/(m.^\circ c)$).

T_{vt} : Temperature entering steam (°C).

c_{tv} : Specific heat of the metal tube in vapor section ($J/(Kg.^\circ c)$).

L_v : Latent condensation heat (J/Kg).

$$L_v = -3.4*10^{-11}T_{cv}^4 + 4.421*10^{-11}T_{cv}^3 - 1.545403*10^{-6}T_{cv}^2 - 2.21406*10^{-3}T_{cv} + 249716*10^6 \quad (18)$$

The pressure of the liquid is:

$$P_{cl} = N_{cond} * \frac{g*\rho_l}{10^5} + P_{cv} \quad (19)$$

The flow of outlet liquid

$$\dot{M}_{vd} = M_{ct} - \sum b_i * \sqrt{\rho_c * \frac{P_{cl} - P_{ls}}{K_{dv}}} \quad (20)$$

Specific enthalpy of outlet liquid (J/kg) is given by:

$$h_{vd} = c_l * T_{cl} \quad (21)$$

c_l : Specific heat of the liquid ($J/(Kg.^\circ c)$).

T_{cl} : Temperature of outlet liquid (°C).

☒ *Mixture equation* [2] [3]:

$$\begin{cases} h_{cv} = h_v(P_{cv})*X + h_l(P_{cv})*(1-X) \\ \frac{1}{\rho_v} = v_v(P_{cv})*X + v_l(P_{cv})*(1-X) \end{cases} \quad (22)$$

2.5. The discharge valves

The level of the condensate is controlled by means of three on–off valves placed in parallel between the condenser and the tank. These valves keep the condensate level L_C within 0.5 l of a given set point.

It is considered that the inertia of the valves is negligible. They have the same coefficient drop pressure K_{DC}.
The flow of each branch is determined by Bernoulli's law because the liquid is assumed incompressible:

$$\dot{m} = \sum_{i=1}^{3} b_i.K_{DC}(P_{sc} - P_B) \quad (23)$$

Or:

$$\dot{m} = \sum_{i=1}^{3} b_i.\rho K_{DC}\sqrt{P_{sc} - P_B} \quad (24)$$

Depending on whether the flow is laminar or turbulent.

3. Modeling hypotheses

The steam generator is modeled by considering the following hypotheses [1], [5]:

- The water and the steam in the boiler are supposed to be in thermodynamic equilibrium, due to their homogenization;
- The boiler mixture is under an uniform pressure; where the effect of the superficial pressures of the steam bubbles is neglected.
- The variables are localized on the real system.
- The steam generator is not correctly insulated, where the heat losses are by conduction towards external environment.
- The fluid in the feeding circuit is considered incompressible because the water is taken at the ambient temperature.

4. process model

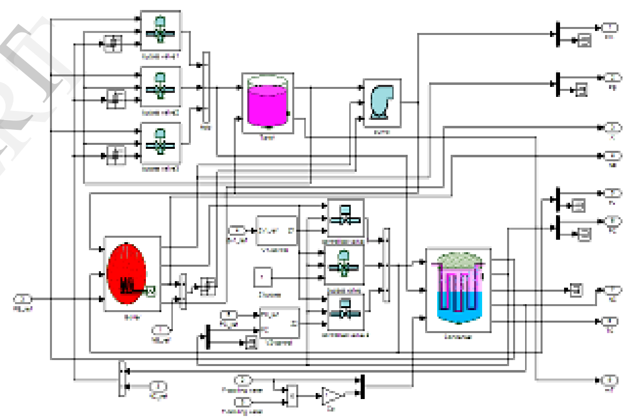

Fig 6. Process model

5. Simulation Results

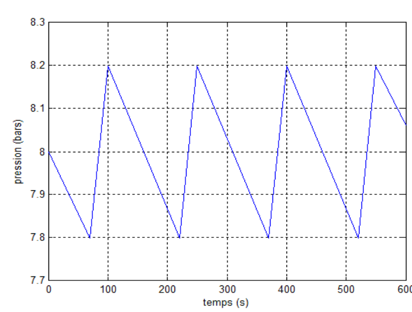

Fig 7.a. boiler pressure

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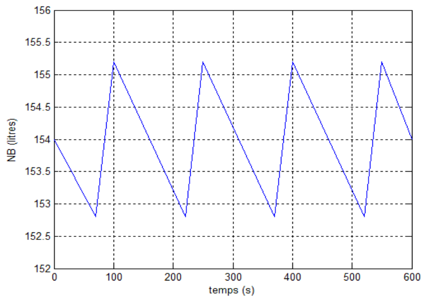

Fig 7.b. water level in the boiler

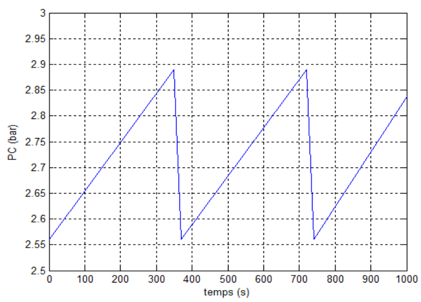

Fig 8.a. Condenser pressure

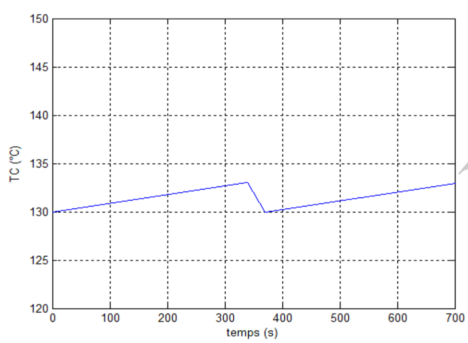

Fig 8.b. condensate temperature

The global Matlab-Simulink model "Fig 6" of the process is validated through comparison between the model outputs (simulation results) and those of the Bondgraph model [1], [4].
The simulation results for the pressure and water level inside the boiler are given in "Fig. 7.a" and "Fig. 7.b".
Simulation results for the pressure, outlet coolant temperature of the condenser are given in "Fig 8.a" and "Fig 8.b".
As can be seen from "Fig. 7.a", the level in the boiler continues to drop (because of the generated steam flowing into the condenser). After a long time , when the level falls below the lower threshold specified by a setpoint, the pumps are switched on to fill the boiler up to the upper threshold specified by the aforementioned setpoint.

It can be seen from "Fig. 7.b" that the stored condensate initially heats up due to mixing with the high temperature just condensed liquid phase flowing from the U-tubes. The heat transfer from stored condensate to submerged tubes increases with increase in condensate level. Consequently, the stored condensate temperature attends a dynamic steady state.

Conclusion

The Matlab-Simulink model of the steam generator has been developed. The global behavioral model is then simulated and the results are compared to the Bond graph model simulation results and Matlab - simulink library realization (that had been compared to experiments observation) . The steam generator model shows acceptable coherence with the process behavior.

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