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Dynamic Simulation of the Energy Recovery in an Incineration Plant

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Abstract−The context of this paper is energy recovery in an incineration plant. A dynamic model for the description of a drum unit is presented. In the first part, the physical system in question is presented. This description is performed by following the cycle of water within the system. The different devices of the network are presented, as well as the control valves and their roles. A complete list of the state variables used to represent the process is given. Secondly, we focus on the mathematical description of this system. Indeed, the set of equations representative of the process is rendered. This is a differential algebraic system composed of 6 ordinary differential equations and 113 algebraic ones. A predictor-corrector method (Gear's algorithm) is used to solve the system. The results of the model are shown in case of the turning off of the plant, when the turbine needs to be bypassed. Finally, an explanation of the observed yields of the model is given.

Key words: Incineration, Energy Recovery, Steam to Electricity, Modelling, Simulation

INTRODUCTION

Incineration plays a major role in the disposal of municipal waste in Europe and in France. A French governmental organization (ADEME 2001) has found that approximately 35% of the municipal waste produced by the French (25 million tons in 1998) was incinerated in 248 incineration plants. Because of the laws prohibiting rubbish dumping in European countries which came into effect in 2002, the number of incinerators is expected to grow, and so is the number of them able to recover energy from waste. However, the formation of toxic solid and gaseous by-products during the incineration of municipal waste, as well as the NIMBY (*Not In My BackYard*) syndrome, can lead to limitation in the use of incineration as well as to an increase in its cost. Thus, a better knowledge of the incineration processes is required. New achievements may then be used either by designers or operators of incinerators. In the latter case, the operating tools are real-time simulators, which can predict trends according to operating parameters. The building of such simulators is our aim.

More precisely, three French Laboratories (LGPP of *Pau*, LEPT of *Bordeaux* and LIPSI of *Biarritz*) in the South West of France have joined in for a project called SIMAPI (SIM*ulateur* A*quitain* de P*rocédés* d'I*ncinération*) in order to build such a tool. The upcoming virtual plant will include several models to represent the different technologies that might differ from one process to another (for example: grate fire furnace, rotary kiln, fluidized bed, dust-removing or gas cleaning technologies). It will also include an energy recovery section, which is usually performed by using a condensing turbine for electricity production, or a back pressure turbine for both heat and electricity production.

Presently, fluidized bed technology, has been modelled, allowing for dynamic and real-time fluidized bed incineration simulation [Marias, 1999; Marias et al., 2001a, b]. This technology has been chosen for the first step in the building of the virtual plant because its performance in terms of conversion of organic material, as well as low nitric oxide emissions, is expected to be very high. In addition, the control interfaces of the virtual plant have been designed (Figs. 1, 2, 3). In this paper, we focus on the energy recovery part of the virtual plant. More precisely, we present the mathematical model used to represent the behavior of the process water as it is raised to steam in the boiler, released in the turbine and then condensed in the aero-condenser (Figs. 2 & 3). Thus, some insights will be given on the system in question in order to present the different relevant components of the energy recovery section. Secondly, the mathematical model will be presented as well as the numerical method used to solve this DAEs system. Finally, some results of the model are presented in the case of the plant being turned off.

From an industrial point of view, this paper shows that our simulator is well suited to what can really happen when one or some of the operating parameters are modified, which can be very useful for teaching to operators how the process should be supervised.

THE SYSTEM IN QUESTION

The cycle of the process water is illustrated in Fig. 4. It is composed of a main loop and some auxiliary loops (de-superheating loop, funnel, heating of the feed tank and bypass of the turbine). The system depicted is incomplete. Isolating manual valves have been omitted from the unit, as well as drain and make up water loops. Of course this is a simplification, but the choice has been made to take into account the discriminating devices only. This cycle is an industrial one. More precisely, this is a cycle used on a fluidized incineration plant of 3.3t/h of municipal waste input.

1. The Main Loop

1-1. Physical System

The description of the main loop is performed starting from the condensate raising pump *PC01*. The process water, which is expelled from the pump, is at liquid state, a temperature of approximately 45 °C and a pressure of 2 bars. The water then flows across the feed

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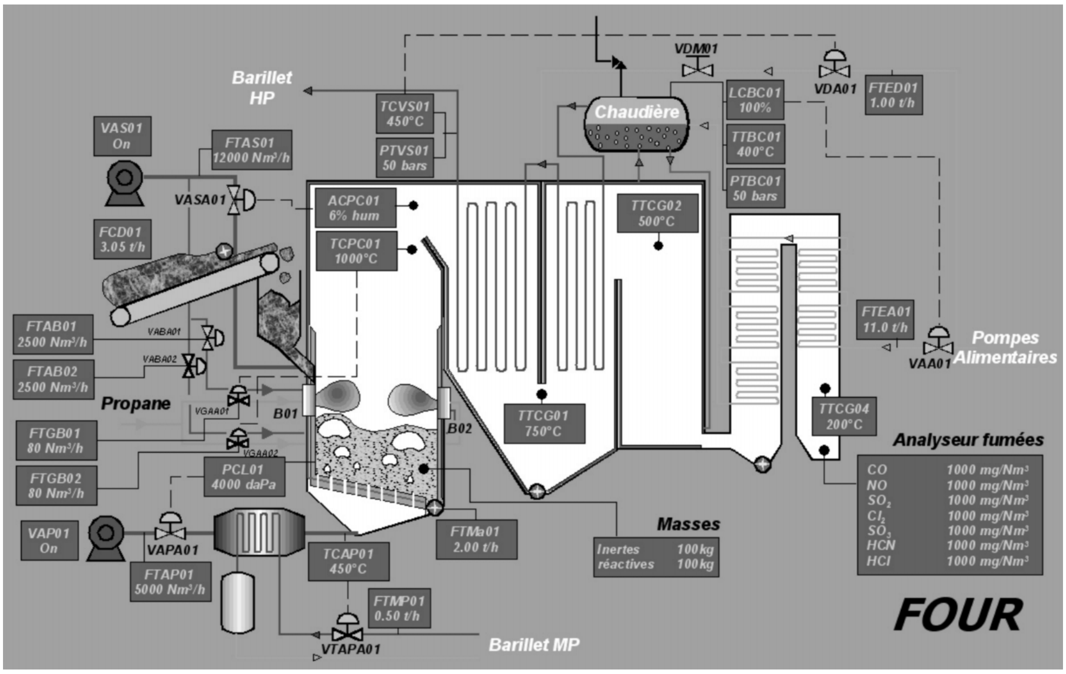

Fig. 1. Control interface of virtual plant (furnace view).

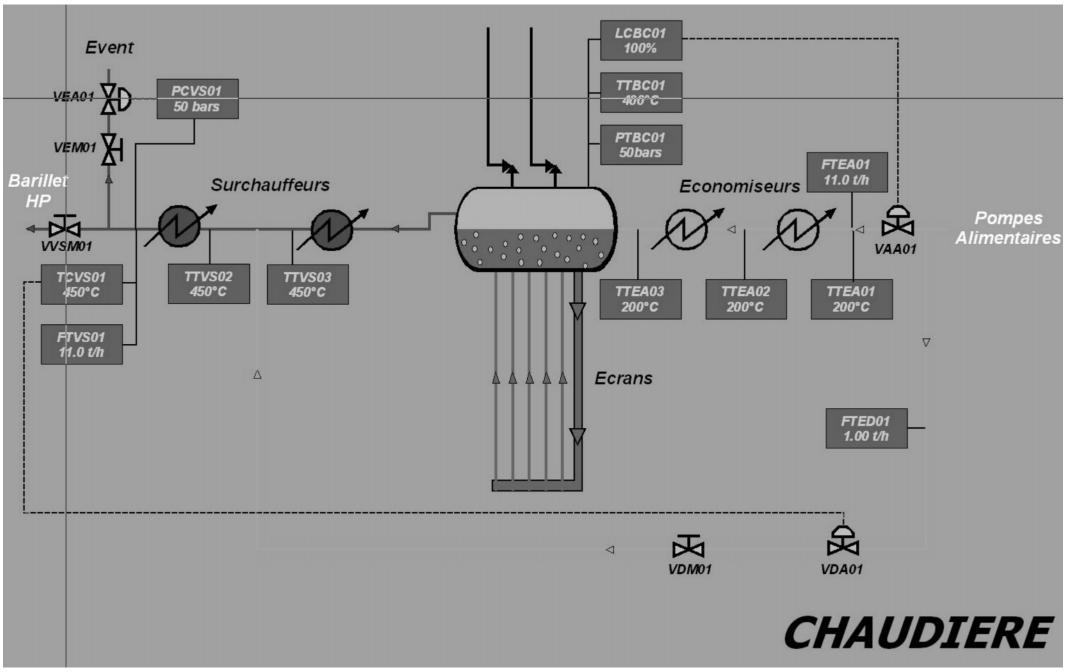

Fig. 2. Control interface of virtual plant (boiler view).

tank level control valve *VCCA01* and enters the feed tank *BA01*. In this vessel, the liquid water is raised to approximately 110 °C (by injection of steam at medium pressure) in order to de-gas the oxygen dissolved before the water enters the boiler. The water is then raised to a pressure of 45 bars by a feeding multi-staged pump *PA01*. Then, it flows across a two-stage economiser where its temperature reaches 190 C using the off-gases of the combustion chamber. The water then enters the steam drum where it is distributed in the cooling water tubes of the furnace. To simplify things, these water tubes and the steam drum have been combined into one device *BCh01* which should be a two phase drum receiving radiation and convection heat from the furnace. This is in that vessel that water is raised to saturated steam at approximately 45 bars and 260 °C before being superheated by the primary super heater *SUR01* to a temperature of 350 °C. It is then de-superheated to 340 °C (*N2*) by cooler liquid water coming from the de-superheating loop before it is re-superheated to 370 °C by the secondary super-heater *SUR02*. This de-superheating loop allows the control of the temperature of the steam

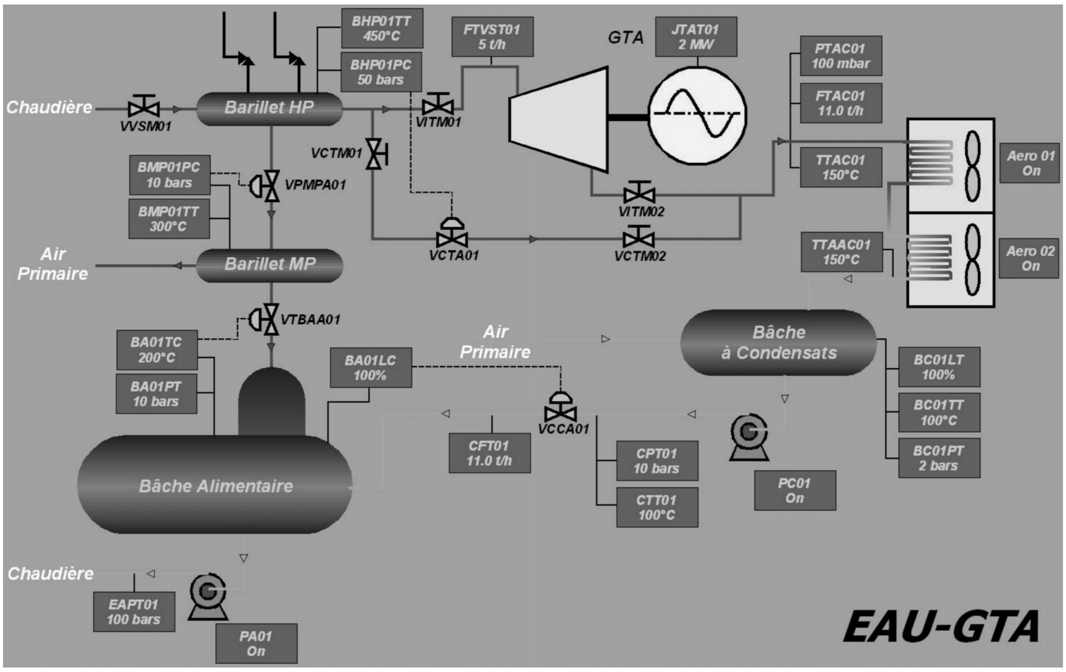

Fig. 3. Control interface of virtual plant (turbine view).

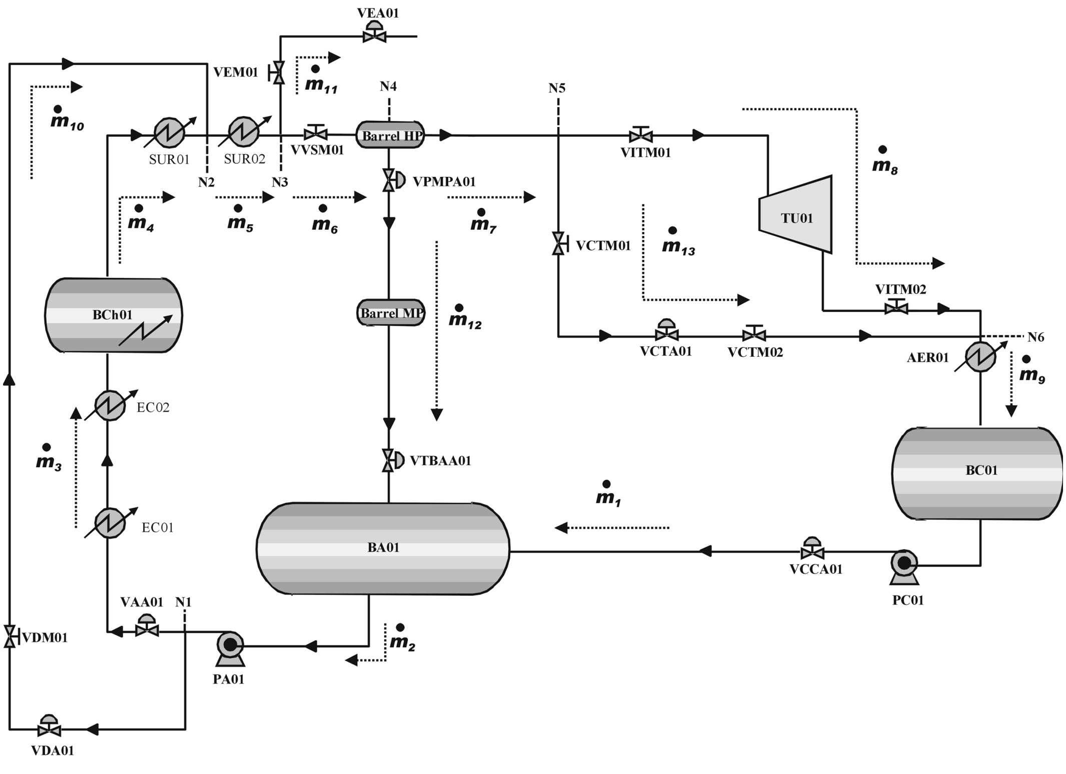

Fig. 4. Steam to electricity cycle in question.

entering the turbine. It then crosses a manual valve (*VVSM01*) before it enters the high pressure barrel. Next, it flows across the first isolation valve of the turbine (*VITM01*) and is released into the turbine (*TU01*) where thermal energy is converted into mechanical energy. The pressure of the exhaust steam is approximately 0.4 bar abs (under atmospheric pressure) while its temperature reaches 60 °C. It then flows across a manual valve (*VITM02*) before being condensed in the aero-condenser *AER01*. The liquid water finishes the loop by entering the condensate tank which is kept under atmospheric pressure by using a steam jet ejector which is not shown in Fig. 4.

1-2. Variables to be Computed

As shown in Fig. 4, there are 16 apparatuses on the main loop

(*PC01*, *VCCA01*, *BA01*, *PA01*, *VAA01*, *EC01*, *EC02*, *BCh01*, *SUR01*, *SUR02*, *VVSM01*, *VITM01*, *TU01*, *VITM02*, *AER01*, *BC01*) and two mixing nodes (*N2*, *N6*). On every apparatus, the enthalpy to weight, the density, the temperature and the pressure of the fluid have to be computed. Moreover, in each tank, the level of liquid needs to be calculated, and in the steam drum, we need to compute one more enthalpy to weight and one more density because both of the phases are important. Assuming that the state of water at the output of the aero condenser is boiling liquid, the quantification of the heat to be extracted from the device is also required. In the case of the mixing nodes, solely the enthalpy to weight is required. Finally, nine mass flow-rates are necessary to perfectly describe the main loop.

Table 1. State variables computed by the mathematical model

Fluid and apparatus	Enthalpy	Temperature	Pressure	Level or heat	Density
Liquid downstream *PC01*	h^l_{PC01}	T_{PC01}	P_{PC01}	-	ρ^l_{PC01}
Liquid downstream *VCCA01*	h^l_{VCCA01}	T_{VCCA01}	P_{VCCA01}	-	ρ^l_{VCCA01}
Liquid held within *BA01*	h^l_{PC01}	T_{PC01}	P_{PC01}	L_{BA01}	ρ^l_{PC01}
Liquid downstream *PA01*	h^l_{PA01}	T_{PA01}	P_{PA01}	-	ρ^l_{PA01}
Liquid downstream *VAA01*	h^l_{VAA01}	T_{VAA01}	P_{VAA01}	-	ρ^l_{VAA01}
Liquid downstream *EC01*	h^l_{EC01}	T_{EC01}	P_{EC01}	-	ρ^l_{EC01}
Liquid downstream *EC02*	h^l_{EC02}	T_{EC02}	P_{EC02}	-	ρ^l_{EC02}
Liquid held within *BCh01*	h^l_{BCh01}	T_{BCh01}	P_{BCh01}	L_{BCh01}	ρ^l_{PC01}
Steam held within *BCh01*	h^v_{BCh01}			-	ρ^v_{BCh01}
Steam downstream *SUR01*	h^v_{SUR01}	T_{SUR01}	P_{SUR01}	-	ρ^v_{SUR01}
Steam downstream *N2*	h^v_{N2}	-	-	-	-
Steam downstream *SUR02*	h^v_{SUR02}	T_{SUR02}	P_{SUR02}	-	ρ^v_{SUR02}
Steam downstream *VVSM01*	h^v_{VVSM01}	T_{VVSM01}	P_{VVSM01}	-	ρ^v_{VVSM01}
Steam downstream *VITM01*	h^v_{VITM01}	T_{VITM01}	P_{VITM01}	-	ρ^v_{VITM01}
Steam downstream *TU01*	h^v_{TU01}	T_{TU01}	P_{TU01}	-	ρ^v_{TU01}
Steam downstream *VITM02*	h^v_{VITM02}	T_{VITM02}	P_{VITM02}	-	ρ^v_{VITM02}
Steam downstream *N6*	h^v_{N6}	-	-	-	-
Boiling liquid downstream *AER01*	h^l_{AER01}	T_{AER01}	P_{AER01}	Q_{AER01}	ρ^l_{AER01}
Boiling liquid held within *BC01*	h^l_{BC01}	T_{BC01}	P_{BC01}	L_{BC01}	ρ^l_{BC01}
Liquid downstream *VDA01*	h^l_{VDA01}	T_{VDA01}	P_{VDA01}	-	$\rho^l V_{VDA01}$
Liquid downstream *VDM01*	h^l_{VDM01}	T_{VDM01}	P_{VDM01}	-	ρ^l_{VDM01}
Steam downstream *VEM01*	h^l_{VEM01}	T_{VEM01}	P_{VEM01}	-	ρ^l_{VEM01}
Steam downstream *VEA01*	h^l_{VEA01}	T_{VEA01}	P_{VEA01}	-	ρ^l_{VEA01}
Steam downstream *VPMPA01*	$h^v_{VPMPA01}$	$T_{VPMPA01}$	$P_{VPMPA01}$	-	$\rho^v_{VPMPA01}$
Steam downstream *VTBAA01*	$h^v_{VTBAA01}$	$T_{VTBAA01}$	$P_{VTBAA01}$	-	$\rho^v_{VTBAA01}$
Steam downstream *VCTM01*	h^v_{VCTM01}	T_{VCTM01}	P_{VCTM01}	-	ρ^v_{VCTM01}
Steam downstream *VCTA01*	h^v_{VCTA01}	T_{VCTA01}	P_{VCTA01}	-	ρ^v_{VCTA01}
Steam downstream *VCTM02*	h^v_{VCTM02}	T_{VCTM02}	P_{VCTM02}	-	ρ^l_{VCTM02}

Table 2. Mass flow-rates computed by the model

Description of the flow	Mass flow-rate
Flow leaving *BC01* and passing through *PC01* and *VCCA01*	$\dot{m}_1$
Flow leaving *BA01* and passing through *PA01*	$\dot{m}_2$
Flow passing through *VAA01*, *EC01*, *EC02* and entering *BCh01*	$\dot{m}_3$
Flow leaving *BCh01* and passing through *SUR01*	$\dot{m}_4$
Flow passing through *SUR02*	$\dot{m}_5$
Flow passing through *VVSM01* and entering *Barrel HP*	$\dot{m}_6$
Flow leaving *Barrel HP*	$\dot{m}_7$
Flow passing through *VITM01*, *TU01* and *VITM02*	$\dot{m}_8$
Flow passing through *AER01*	$\dot{m}_9$
Flow passing through *VDA01* and *VDM01*	$\dot{m}_{10}$
Flow passing through *VEM01* and *VEA01*	$\dot{m}_{11}$
Flow passing through *VPMPA01*, *VTBAA01* and entering *BA01*	$\dot{m}_{12}$
Flow passing through *VCTM01*, *VCTA01* and *VCTM02*	$\dot{m}_{13}$

Table 3. Role of the regulation valves

Valve	Role
VCCA01	Controls the liquid level in the feed tank
VAA01	Controls the liquid level in the steam drum
VDA01	Controls the temperature of the superheated steam entering the high pressure barrel
VEA01	Controls the pressure in the steam drum at the start up or the stopping of the process
VPMPA01	Controls the pressure in the medium pressure barrel
VTBAA01	Controls the temperature in the feed tank (de-gas of process water)
VCTA01	Controls the pressure in the steam drum

Thus, the full description of the main loop is performed through 81 variables. Tables 1 & 2 summarize the total number of variables in the mathematical model.

2. The De-superheating Loop

2-1. Physical System

A part of the process water leaving the feeding tank by-passes the boiler after being expelled from the feeding pump *PA01*. This by-pass allows for the control of the value of the temperature downstream the secondary superheater. So, this loop is quite simple because it is only made of pipes, a manual valve (*VDM01*) and especially a control valve (*VDA01*), which controls the flow circulating inside the loop in order to reach the desired requirements for superheated steam.

2-2. Variables to be Computed

Two apparatuses set up this loop (*VDA01* & *VDM01*). Thus, it is perfectly described by eight state variables (enthalpy to weight, density, pressure and temperature per device) plus one mass flow-rate.

3. The Funnel

3-1. Physical System

Once again, this is a very simple line composed of a manual (*VEM01*) and a control valve (*VEA01*). This loop is mainly used for the starting up of the unit, when low pressure steam leaves the secondary super-heater and is sent into the atmosphere.

3-2. Variables to be Computed

As in the case of the de-superheating loop, nine variables allow for the full description of this loop (two apparatuses set up this loop).

4. The Heating of the Feed Tank

4-1. Physical System

The de-gassing of the process water (required by the continuous addition of fresh water into the feed tank) is performed by using medium pressure steam which is first released from the high pressure barrel to the medium pressure one (P≈4 bars abs) using the control valve *VPMPA01*. This medium pressure steam is then used to heat the feed tank and the flow-rate entering the tank is controlled by the valve *VTBAA01* according to the vessel's temperature requirements.

4-2. Variables to be Computed

Similar to the de-superheating loop and to the funnel loop, eight state variables plus one mass flow-rate allow for the full description of the loop.

5. The by-pass of the Turbine

5-1. Physical System

This line is devoted to the control of pressure of the steam entering the turbine. The control valve *VCTA01* is opened, in case of a high value in the pressure of the high pressure barrel; however, it is closed when the excess pressure vanishes. This loop is composed of two manual valves (*VCTM01* and *VCTM02*) and the control valve *VCTA01*.

5-2. Variables to be Computed

Because this loop is composed of three valves, the number of state variables required for the description of the loop is 12. Moreover, knowledge of the mass flow-rate passing through this loop is required.

6. Summing-up

As stated in the previous paragraphs, and in Tables 1 and 2, the total number of variables to be computed is:

-81 in the main loop
-9 in the de-superheating loop
-9 in the funnel
-9 in the heating of the feed tank
-13 in the bypass of the turbine

Thus, the whole system is fully described when the value of the 121 variables is known.

7. Operating Parameters

Of course this industrial system is under numerical regulation. The role of each of the control valves is summed-up in Table 3. Nevertheless, during this first step in the modelling of the energy recovery section, no control loop has been taken into account. This case is characteristic of the manual working mode of all of the regulators of the unit. Yet, we have to specify the value of the opening of all the control valves (between 0 and 100%), as well as that of the manual ones. Of course, the opening of all the valves may be modified during the operation. Similarly, the values of the heat quantities received by the boiler, the economiser and the superheater may be modified during operation and are issued from the mathematical model devoted to fluidized bed incineration [Braianov et al., 2002].

MATHEMATICAL MODELLING

In this section, the governing equations of the numerical system are presented. Because of the numerous similarities that exist between the equations from one tank to another or from one valve to another, the choice has been made to rank the relevant equations by class of apparatus (except in the case of tanks where each set of equations is presented). In order to simplify the study, we have chosen to skip the description of thermal inertia for the shell of all the devices. Yet, they are supposed to behave as the fluid they hold. Moreover, we have not taken into account the pressure drop along the different pipes and the heat exchangers in the model. These pressure drops

Table 4. Configuration parameters for the system in question

Name	Notation	Value
Volume of condensate tank	V_{BC01}	6 m^3
Volume of feed tank	V_{BA01}	80 m^3
Volume of steam drum	V_{BCh01}	15 m^3
Isentropic efficiency of the turbine	η_{TU01}	80%

Table 5. Values of the flow-rate coefficient for the valves of the system

Valve	C_v (gal·mn^{-1})
VCCA01	7
VAA01	2.5
VVSM01	220
VITM01	500
VITM02	20000
VCTM01	350
VCTA01	50
VCTM02	50000
VDA01	0.2
VDM01	0.2
VPMPA01	5
VTBAA01	29
VEM01	20000
VEA01	25

have been grouped together in the different flow-rate coefficients of the valves. The configuration parameters (volume of tanks, isentropic efficiency of the turbine) as well as the flow-rate coefficient of the valves are reported in Tables 4 & 5. As will be shown in the following equations, constitutive equations are required by the model. Indeed, temperatures and density are required at different points in the system. This data is computed by using flashes at a given pressure and enthalpy by using the state equation NBS/NRC for pure water [Wagner and Kruse, 1998].

1. Tanks

Tanks are the only type of equipment where accumulation can occur. Thus, as we will see in the following paragraphs, only tanks will yield an ordinary differential equation. Basically, we can write different types of equation for each tank:

-balances (mass and energy)

-constitutive equations (equilibrium data, equation of state)

1-1. Condensate Tank

The temperature of the vessel should to be equal to the one of the boiling liquid according to the tank's pressure.

$$T_{BC01}=T_{equil}(P_{BC01}) \tag{1}$$

Mass and energy balances are written as follows (gas hold-up has been omitted):

$$V_{BC01}\frac{d(\rho^l_{BC01}L_{BC01})}{dt}=\dot{m}_9-\dot{m}_1 \tag{2}$$

$$V_{BC01}\frac{d(\rho^l_{BC01}L_{BC01}h^l_{BC01}-P_{BC01})}{dt}=\dot{m}_9h^v_{AER01}-\dot{m}_1h^l_{BC01} \tag{3}$$

The constitutive equation for the density of liquid held in the tank:

$$\rho^l_{BC01}=\rho^l_m(P_{BC01},h^l_{BC01}) \tag{4}$$

To conclude, as for the condensate tank, we can say that its mathematical modelling yields four equations.

1-2. Feed Tank

Mass and energy balances can be written as follows (once again, gas hold-up has been left out):

$$V_{BA01}=\frac{d(\rho^l_{BA01}L_{BA01})}{dt}=\dot{m}_1+\dot{m}_{12}-\dot{m}_2 \tag{5}$$

$$V_{BA01}\frac{d(\rho^l_{BA01}L_{BA01}h^l_{BA01}-P_{BA01})}{dt}=\dot{m}_1h^l_{VCCA01}+\dot{m}_{12}h^v_{VTBAA01}-\dot{m}_2h^l_{BA01} \tag{6}$$

Constitutive equations are used to compute temperature and liquid density:

$$h^l_{BA01}=h_m(P_{BA01},T_{BA01}) \tag{7}$$

$$\rho^l_{BA01}=\rho_m(P_{BA01},T_{BA01}) \tag{8}$$

The number of equations yielded by this tank is four.

1-3. Steam Drum

The pressure of the steam drum is computed assuming that there is equilibrium between the liquid and the vapor at the steam drum's pressure:

$$P_{BCh01}=P_{equil}(T_{BCh01}) \tag{9}$$

Mass and energy balances are written as follows:

$$V_{BCh01}\frac{(\rho^l_{BCh01}L_{BCh01})}{dt}=\dot{m}_3-\dot{m}_4 \tag{10}$$

$$V_{BCh01}\frac{(\rho^l_{BCh01}L_{BCh01}h^l_{BCh01}-P_{BCh01})}{dt}=\dot{m}_3h^l_{EC02}-\dot{m}_4h^v_{BCh01}+\dot{Q}^{op}_{BCh01} \tag{11}$$

where $\dot{Q}^{op}_{BCh01}$ stands for the heat received by the steam drum (this is one of the operating parameters)

Constitutive equations are used to compute the temperature and the density of the two phases:

$$h^l_{BCh01}=h_m(P_{BCh01},T_{BCh01}) \text{ (model of enthalpy for liquid)} \tag{12}$$

$$\rho^l_{BCh01}=\rho_m(P_{BCh01},T_{BCh01}) \tag{13}$$

$$h^v_{BCh01}=h_m(P_{BCh01},T_{BCh01}) \text{ (model of enthalpy for steam)} \tag{14}$$

$$\rho^v_{BCh01}=\rho_m(P_{BCh01},T_{BCh01}) \tag{15}$$

Hence, the modelling of the steam drum yields seven equations.

1-4. Summing-up

The total number of equations given by the mathematical description of the tanks is fifteen. Six of them are ordinary differential equations while the others are algebraic.

2. The Heat Exchangers

Because of the assumption that there is no pressure drop along the different exchangers, the output pressure is always equal to that of the input. This yields one equation per heat exchanger, except in the case of the aero condenser where it yields two: $P_{AER01}=P_{VITM02}$ and $P_{AER01}=P_{VCTM02}$. Moreover, one is able to write an enthalpy balance on every device of that class. Finally, at the output of each device, two constitutive equations have been written in order to compute the temperature and the density of the fluid in question. In the case of the aero-condenser, things are a little bit different. Firstly, an equilibrium equation is written, assuming that boiling liquid leaves the apparatus. This yields the temperature of the fluid leaving the device. Then, two constitutive equations are written in order to compute enthalpy to weight and the density of the fluid. The enthalpy balance yields the heat that should be extracted by the device.

We have chosen to illustrate the modelling of heat exchangers in the case of the superheater *SUR01*:

$$P_{SUR01}=P_{BCh01} \tag{16}$$

$$\dot{m}_{SUR01}h^{v}_{SUR01}=\dot{m}_{SUR01}h^{v}_{BCh01}+\dot{Q}^{op}_{SUR01} \tag{17}$$

where $\dot{Q}^{op}_{SUR01}$ stands for the heat received by the superheater (which is one operating parameter)

$$h^{v}_{SUR01}=h_m(P_{SUR01}, T_{SUR01}) \tag{18}$$

$$\rho^{v}_{SUR01}=\rho_m(P_{SUR01}, T_{SUR01}) \tag{19}$$

As a conclusion, and because there are five heat exchangers in our system, we can summarize the number of algebraic equations yielded by the model:

-sixteen for *EC01*, *EC02*, *SUR01*, *SUR02*

-six for *AER01*

Twenty two equations can be written here.

3. Valves

The main assumption used for the modelling of valves is that they are supposed to be isenthalpic. The four equations that can be written are the following:

-Pressure drop along the network: $P_X+\Delta P_X=P_{X-1}$ where P_{X-1} stands for the pressure at the input of the valve and ΔP_X represents the pressure drop across the valve (computed using the characteristics of the valve $\Delta P_X=f_X(\dot{m}_X, O_X, \rho^f_{X-1})$ where O_X denotes the opening of the valve (i.e., it is an operating parameter) and ρ^f_{X-1} the density of the fluid upstream the valve)

-Energy balance

-Two constitutive equations for temperature and density.

Given the number of fourteen valves in the system, 56 equations are written at this stage.

4. Pumps

The main assumption used for the modelling of valves is that they are supposed to be isothermal.

The four equations that can be written are:

-Characteristic of the pump $P_X=f_X(\dot{m}_X)$

-Temperature at the outlet of the pump equals inlet temperature

-Two constitutive equations for enthalpy and density.

Thus, the modelling of the two pumps yields eight algebraic equations.

5. Turbine

Basically, four equations are written for the modelling of the turbine:

-Pressure drop across turbine: $P_{TU01}+\Delta P_{TU01}=P_{VITM01}$ where ΔP_{TU01} stands for the pressure drop across the turbine computed using its characteristic equation $\Delta P_{TU01}=f_{TU01}(\dot{m}_8)$

-Enthalpy balance (using the isentropic yield of the device)

-Two constitutive equations for enthalpy and density.

6. Nodes

6-1. Splitters

Four splitters exist in the domain, namely *N1*, *N3*, *N4* and *N5*. At these particular positions solely mass balances are written, assuming that no material is accumulated at these points.

6-2. Mixers

Two mixers exist in the system, namely *N2* and *N6*. At these sites, mass and energy balances are written assuming no accumulation.

6-3. Summing-up

The modelling of the nodes in the system yields eight equations.

7. Pressure Specifications

Five more connectivity equations can be written. Indeed, they relate to the fact that apparatuses located just before the tanks are connected to it without any pressure drop. Thus, the following can be written:

$$P_{VCCA01}=P_{BA01} \tag{20}$$

$$P_{EC02}=P_{BCh01} \tag{21}$$

$$P_{AER01}=P_{BC01} \tag{22}$$

$$P_{VTBAA01}=P_{BA01} \tag{23}$$

$$P_{VDM01}=P_{SUR01} \tag{24}$$

8. Closure of the System

The total number of equations that we have written by now is 118. In order to close the system, three more equations have been written. We have chosen to write them as pressure specifications at particular points of the system:

-Pressure in the condensate tank *BC01* fixed by steam jet ejectors: $P_{BC01}=P^{fp}_{ejec}$

-Pressure in the feed tank imposed by the de-gas system: $P_{BA01}=P^{fp}_{deg\,as}$

-Pressure at the funnel equals atmospheric pressure: $P_{VEA01}=P^{fp}_{atm}$

9. Valves, pumps and Turbine Characteristics

In this section, the different functions encountered in the previous paragraphs are given. Dealing with the valve, the form of the equation is always the same in the liquid phase and in the vapor phase. Thus, the choice has been made to present the general equation for each of the phases as following. The values for the flow-rate coefficients are given in Table 5.

9-1. Valve Characteristic for Liquid

$$f_{valve}=\Delta P_{valve}=\frac{\rho^l_{up}}{1000}\left(\frac{3.6\times 10^5\dot{m}_{valve}}{0.8571C_{v,valve}\rho^l_{up}O_{valve}}\right) \tag{25}$$

where:

ΔP_{valve}: pressure drop across the valve [Pa]

ρ^l_{up} : density of the liquid upstream the valve $[kg\cdot m^{-3}]$

$\dot{m}_{valve}$: mass flow-rate of liquid across the valve $[kg\cdot s^{-1}]$

$C_{v,valve}$: flow-rate coefficient of the valve $[gal\cdot mn^{-1}]$

O_{valve}: opening of the valve [%]

9-2. Valve Characteristic for Steam

$$f_{valve}=\Delta P_{valve}=P_{up}-\sqrt{P^2_{up}-\frac{T_{up}\dot{m}^2_{valve}\times 1.3162\times 10^{16}}{C^2_{v,valve}O^2_{valve}}} \tag{26}$$

where:

ΔP : pressure drop across the valve [Pa]

P_{up} : pressure upstream the valve en [Pa]

T_{up} : temperature upstream the valve [K]

$\dot{m}_{valve}$: mass flow-rate of vapor across the valve $[kg\cdot s^{-1}]$

$C_{v,valve}$: flow-rate coefficient of the valve $[gal\cdot mn^{-1}]$

O_{valve}: opening of the valve [%]

9-3. Pump Characteristics

The behavior of the pumps has been approximated by a 2^{nd} order polynomial:

The raising of the condensate:

$$P_{out}=-3971\dot{m}^2-769.39\dot{m}+675972 \quad (27)$$

The feeding pump:

$$P_{out}=-46973\dot{m}^2-1950.7\dot{m}+10^7 \quad (28)$$

where P_{out} and $\dot{m}$ denotes the output pressure of the pump (Pa) and the mass flow-rate across the pump ($kg \cdot s^{-1}$), respectively.

9-4. Turbine Characteristic

The behavior of the turbine has been approximated by a linear law:

$$f_{TU01}=\Delta P_{TU01}=2.7\times10^6\dot{m}_{TU01} \quad (29)$$

where ΔP_{TU01} and $\dot{m}_{TU01}$ denotes the pressure drop along the turbine (Pa) and the mass flow-rate across the turbine ($kg \cdot s^{-1}$), respectively.

10. Solving of the Model

The mathematical model is composed of 121 non-linear equations. Among these, six are ordinary differential equations. The choice has been made to use a global algorithm to solve this DAEs set, which is of the form:

$$A\frac{dy}{dt}=G(y,t) \quad (30)$$

where the mass matrix A is singular. Problem (30) is then solved by using Gear's method [Gear and Petzold, 1984]. First, an explicit polynomial approximation is used at the prediction step; then an implicit approximation is used at the correction step. This iterative correction procedure is initialized at the predicted point. Both the explicit and the implicit polynomial approximations are built in the space of the state variables, not in the space of the derivatives as done when using classical predictor-corrector methods. Gear's method, which allows automatic step and predictor order management, has been proven to be very efficient for stiff system solution.

NUMERICAL RESULTS

In order to test the efficiency of the model, numerical results obtained when the system is turned off will be presented. The values of the heat powers received from the furnace are computed by using the fluidized bed model [Braianov et al., 2003]. In order to represent this, the sequence which is simulated is the following:

-Opening of *VCTA01* from 8 to 40% (bypass of the turbine)
-Closing of *VITM01* from 80 to 0% (isolation of the turbine)
-Closing of *VDM01* from 20 to 0% (stopping of the de-superheating)
-Stopping of heat the power received by heat exchangers (extinguishing of the furnace)

Such a sequence, and its consequence on the network, is depicted in Figs. 5 & 6. First, the opening of the bypass of the turbine leads to a decrease in the pressure drop of the steam system. This creates an increase in the mass flow-rate leaving the steam drum ($\dot{m}_4$) which in turns leads to a decrease in the pressure of the steam drum. This also induces a reduction in the mass flow-rate of vapor entering the

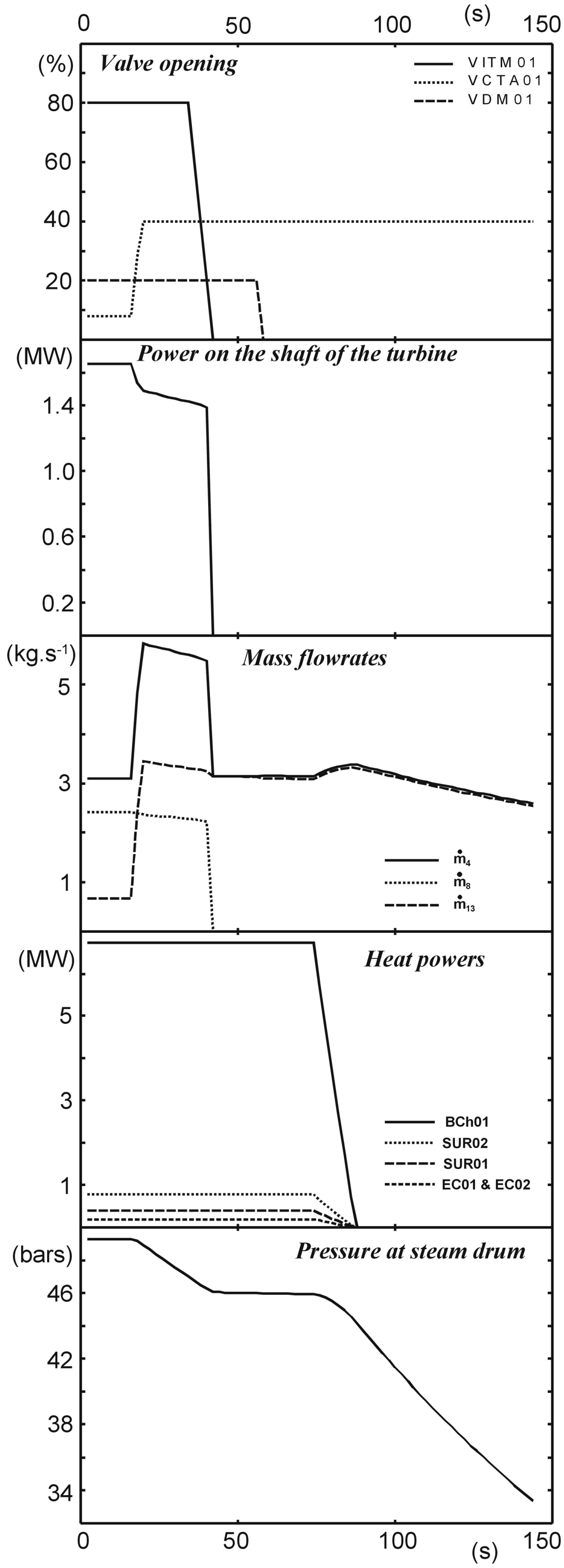

Fig. 5. Variation of operating parameters and consequent reply of the model (a).

turbine and then a reduction in the mechanical power available on the shaft of the turbine. Moreover, because more steam is bypassed from the turbine, the temperature entering the aero-condenser *AER01* in-

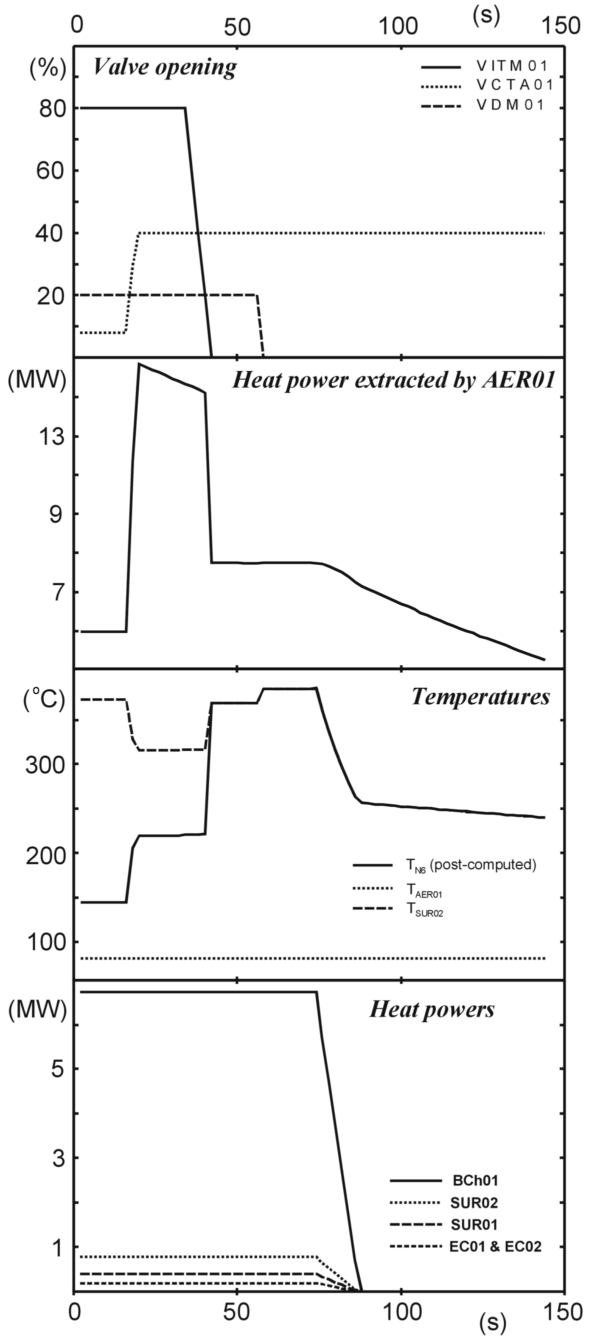

Fig. 6. Variation of operating parameters and consequent reply of the model (b).

creases. This effect, conjugated with the increase in the mass flow rate, leads to a doubling in the power to be extracted by *AER01*, which is quite important. Once the valve *VCTA01* has reached its final opening (40%) the diminution of pressure within *BCh01* leads to a slight decrease in the mass-flow rate of vapor leaving *BCh01*, and consequently in the heat to be extracted by *AER01*.

Before the extinguishing of the furnace, it is necessary that the turbine be isolated from the network. Indeed, the quality of the vapor (in terms of pressure and temperature at the input of the turbine) is expected to decrease. Thus, in order to protect this expensive device, it is necessary to stop feeding it. Such isolation is performed by closing the valve *VITM01*. As expected and as depicted in Fig. 5, this isolation induces a rapid decrease in the mass flow rate of the steam being turbined, and, as a consequence, a rapid decrease in the power available on the shaft of the turbine. This also creates a rapid increase in the pressure drop downstream the steam drum, and, consequently, a decrease in the mass flow-rate leaving *BCh01* and a stabilization of its pressure. Moreover, the reduction in the mass flow-rate entering the superheaters creates a rise in the steam's temperature. From this event, temperature at node 6 approximately equals the temperature downstream *SUR02* because there is no significant heat lost by the valves.

The closing of the de-superheating valve *VDM01* does not significantly modify the value of the previously represented variables. The main effect is that the temperature of the vapor leaving the superheater *SUR02* increases from 370 to 390 ºC (see Fig. 6).

The next event is the extinguishing of the furnace. This is simulated assuming that the thermal power received by the economisers, the steam drum and the super-heaters diminishes to zero in fifteen seconds. Of course, this time is short compared to the time that it would take to really decrease these values. Indeed, this thermal inertia of the furnace part of the system has been simplified, in order to keep the figure readable. The first noticeable effect is a slight and short increase in the mass flow rate of the steam leaving the steam drum and entering the bypass of the turbine (they are not strictly equal because of the mass flow-rate used for the heating of the feed tank). This slight increase in the mass flow-rate of steam is due to the quick reduction of the temperature of the steam downstream *SUR02* from 390 ºC to 240 ºC. Due to the form of the equation which is characteristic of valves, this induces a decrease in the global pressure drop of the steam network, and consequently, an increase in the mass flow rate leaving the boiler. Then, secondly, because of the reduction of the pressure at the steam drum, the mass flow rates slightly decrease to zero (not shown in the figure). Both effects of temperature decrease and the reduction of mass flow rates lead to a lowering of the heat to be extracted by *AER01*.

CONCLUSION

A dynamic model for the simulation of energy recovery in an incineration plant has been constructed. This model is representative of the steam to electricity cycle of an incineration plant of 3.3 t/h of municipal waste input. The main devices of the cycle have been taken into account. The mathematical formulation of the system leads to a system of 121 equations, 6 of them being ordinary differential ones. Gear's method allows for the solving of the system, even in the case of stiff behavior. Such stiffness might be encountered when operating parameters are suddenly modified. We have chosen to test the model on the case of the turning off of the plant, when the turbine needs to be bypassed in order to protect it.

Our model shows the manual way of working the unit. Indeed, none of the different control loops (level of liquid in the steam drum, pressure and temperature at the inlet of the turbine) have been implemented. We intend to add the control loops with their parameters in a future work.

Anyway, even at this stage, the tool we have built can be used for at least two purposes. The first one is linked to the training of operators who manage such a plant daily. With our tool, they can be trained in working conditions, but also in the start-up or the stopping of the unit. Given some specific scenarios (imposed by the teacher) they can be trained to react under specific conditions, and the teacher can analyze how the operator behaves, which is quite important. Secondly, such a simulator might be used for the design of new units or the revamping of old ones. Indeed, in the case of the incineration plant, the aero-condenser is often undersized. This might lead to light workload of the unit during summer months, for example. With our tool the designer can evaluate the heat power that should be extracted by the aero-condenser even in the worse cases, which should be quite useful for the computation of the exchange area for example.

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NOMENCLATURE

L : level of liquid [%]
$\dot{m}$: mass flow-rate [$kg \cdot s^{-1}$]
P : pressure [bars]
T : temperature [°C]
V : volume [m^3]

Greek Letter

ρ : density [$kg \cdot m^{-3}$]

Superscripts

fp : fixed parameter (constant for the model)
l : relative to liquid
v : relative to steam

Subscript

m : relative to a specific model (of enthalpy for instance)

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