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Modeling of a Tetra Pak Deaeration Process

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Abstract

An industrial deaeration process which is part of a liquid packaging line is examined. Experiments are made and evaluated. Based on the experiments, models are derived for the deaeration process. Process knowledge, physical as well as experimental are used for the modeling. The modeled and identified dynamics are simulated and tested. The results closely match the experimental data. Comparisons are made with the existing machine. Control proposals of the level and temperature loops are discussed.

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Contents

1. Introduction

1.1 Background

Almost every day we come into contact with one or more of Tetra Paks products. It can be packages for milk, juice, yoghurt or other liquid products. When we get these products, we expect them to have high quality so that they can be used in the way we want. High quality could imply that the product should last a given time without bacteria growth in a harsh environment. It can also mean that there should not be any miscoloured parts of the product, both to keep the customers trust and as an indicator of the quality.

Preprocessing of the liquids is done before they reach the customers. Examples are pasteurization and homogenization. Another processing step, not commonly known, can also be done, namely deaeration. In a deaeration process, oxygen from the liquid is boiled off, i.e., it is evaporated. Certain physical conditions must be fulfilled to have evaporation of oxygen from the liquid.

The purpose of the deaeration step is boil off oxygen whose presence is necessary for the aerobic bacterias. The more oxygen that leaves the liquid, the harder it will be for the remaining bacterias to stay alive. If the boiling takes place under normal conditions (high pressure, high temperature and normal oxygen content), proteins and vitamins will react with oxygen, resulting in a low level of bacterias but also in low levels of proteins and vitamins, which are important to the product quality. Instead, deaeration is done with lower pressure than the atmospheric. Thus, the temperature can also be lower. At lower temperatures, there are almost no reactions between proteins, vitamins and oxygen. Another effect of a lowered temperature , highly desirable, is an increased amount of aromas kept in the processed product. In a subsequent step, pasteurization, the rest of the bacterias (unaerobic) can be eliminated at higher temperatures, without the risk of reactions lowering the product quality. If there is no oxygen left, the reactions can not take place. These processing steps ensure that the bacteria activity is very low.

These processing steps are often done in close connection, to ensure that the product has a high quality when it is leaving the machine. Throughout the treatment of the liquids, some of the physical conditions must be controlled in order to be sure of what comes out of the machines.

1.2 Outline of the thesis

This thesis covers modeling of a deaeration process. Chapter 2 gives a thorough description of the entire packaging line. We also show the theoretical background for the modeling of the deaerator. The present control system is described. In chapter 3, we show examples of experiments we have done together with experimental conditions.

Chapter 4 contains models for the level loop and the temperature loop. The temperature loop is examined with the heat exchanger in mind. Some control proposals are discussed in chapter 5. We end the thesis with conclusions in chapter 6.

2. The Deaeration System

The deaerator is not an isolated system but part of a large production line. Deaeration together with pasteurization and homogenization are the main processing steps in the packaging line. These tasks are often done in close connection, one after the other. The order of the steps is important. If pasteurization would come before deaeration, the C-vitamins would be destroyed. With juice as the processed liquid, there would be no meaning to go on. Instead, we have the reversed order as can be seen in figure 2.1.

2.1 Liquid packaging line

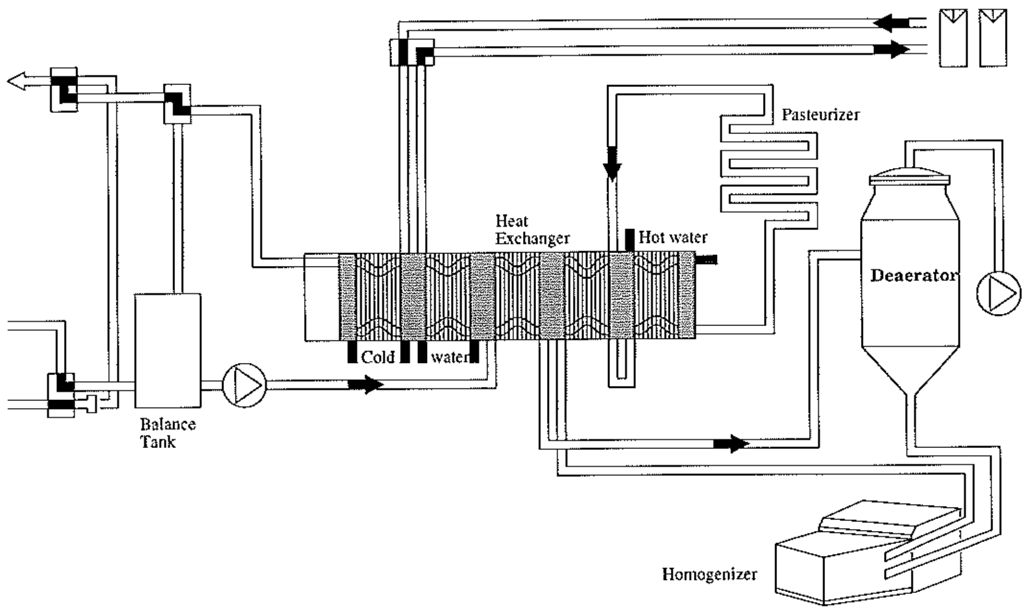

Figure 2.1 Schematic view of the liquid processing line, with balance tank, heat exchanger, deaeration, homogenization, pasteurization, packaging.

The liquid enters at the lower left end, into the balance tank. Its purpose is to provide liquid for the processing. There must always be liquid in the balance tank as it is vital that the machine never runs dry. If that would happen, the product quality would be endangered. The risk of machine breakdown is then also present. Because of this, there will be a big buffert in the balance tank, practically eliminating this risk. The liquid proceeds from this tank into the heat exchanger. There it is heated to the input temperature for the vacuum chamber (deaerator), about 50°C. For this, the heat exchanger needs energy input. This is to a great extent achieved through heat regeneration. The liquid further down the line needs to be cooled. It is routed through the heat exchanger where it leaves unnecessary warmth to the liquid that needs to be heated.

What comes out of the heat exchanger (the heated liquid), goes into the vacuum chamber. Inside of it, the physical conditions are very special because of its purpose, which is to boil off oxygen from the liquid. This will in turn reduce the level of aerobic bacterias. More about this in the following section.

After the deaerator, the liquid may enter a homogenizer. If present, its purpose is to generate a product with even-sized particles.

Pasteurization is the next, important step. The liquid, either from the deaerator or the homogenizer reenters the heat exchanger where it is heated to about 100°C. This is achieved with a hot water circuit, supplying energy to the heat exchanger. The purpose of the pasteurization step, is to eliminate as many bacterias (mostly unaerobic) as possible. The liquid is guided through a pipe system, maintaining a temperature a couple of degrees above the minimum pasteurization temperature.

The liquid reenters the heat exchanger one more time, to leave its excessive heat to the heat exchanger. The heat will be used for the heating of the liquid in the other side of the heat exchanger. On one side of the heat exchanger, the liquid is heated and on the other it is cooled. After cooling to about 15°C, the liquid goes to the packaging step. This temperature is about the same as in the balance tank. Any left-overs, unpackaged liquid, will reenter the balance tank or be discarded.

There is also a steam supply. It provides very hot water steam with high pressure. This constitutes a major part of the input energy.

2.2 Deaeration process

Deaeration takes place if the liquid is boiling. If the liquid is not to be aerated again, the process must be governed by certain physical conditions for the pressure and the temperature. Because of quality considerations, the temperature has to be quite low. This in turn affects the pressure, which must be lowered to allow boiling at lower temperatures. Thus, the process must be shielded from the outside world.

As the pressure inside the tank is quite low (about 10% – –25% of the atmospheric), the boiling temperature is also quite low. If a liquid enters the tank with a higher temperature than that, it will boil at the same time. To have continuous boiling, the product inlet temperature must always be higher than the boiling temperature. This process removes energy from the liquid and drops its temperature.

An understanding of the deaeration system includes many variables, such as pasteurization temperature, air pressure and steam capacity. Nevertheless, some of the variables are directly related to the process dynamics, which can be viewed in figure 2.2.

In order to know the dynamics of the system, it can be viewed upon in different aspects, resulting in a set of balance equations. In [1] the level, pressure and temperature dynamics are derived.

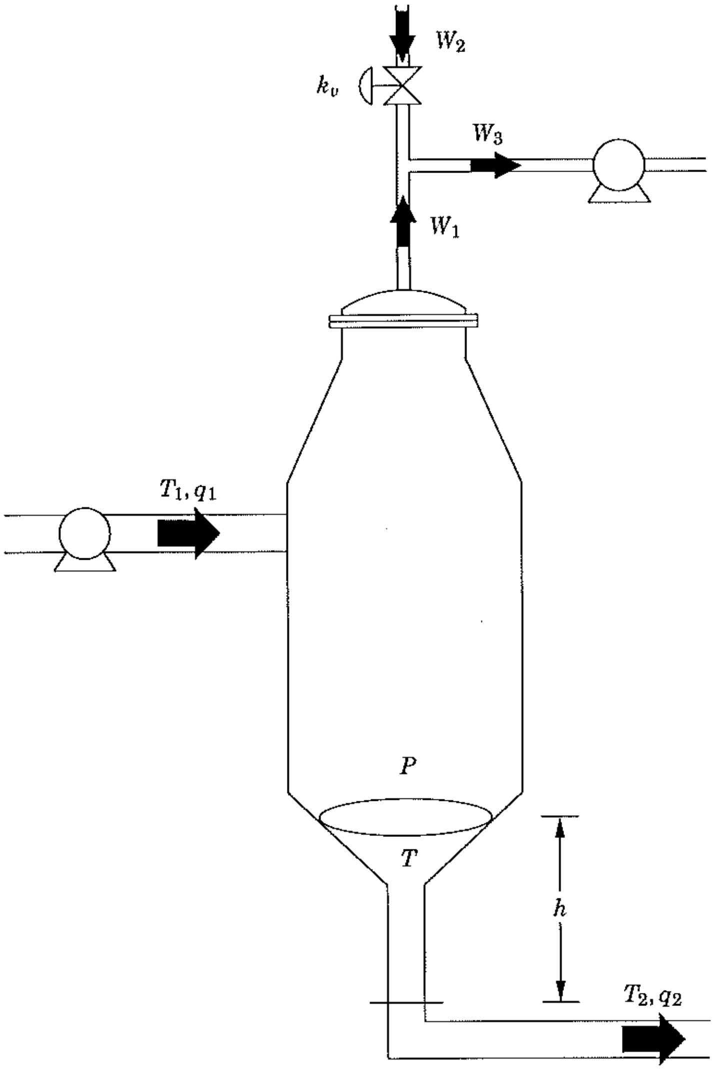

Figure 2.2 Deaeration process. The variables to be controlled are P, pressure inside the deaerator, T, liquid temperature and h, liquid level.

Process variables

$A(h)$	cross section area	C_p	liquid heat capacity
ΔH_{vap}	liquid vapor enthalpy	h	level
$\frac{dh}{dt}$	level change rate	k_p	vacuum pump gain
k_v	valve gain	M	gas molecular weight
m	mass	n_p	vacuum pump constant
p, P	pressure	P_{air}	air pressure
$\frac{dP}{dt}$	pressure change rate	q_1	inlet flow
q_2	outlet flow	R	perfect gas constant
ρ	liquid density	T	temperature
$\frac{dT}{dt}$	temperature change rate	T_1	inlet temperature
T_2	outlet temperature	$V(h)$	liquid volume
$V_g(h)$	gas volume	W_1, W_2, W_3	gas mass flow

Level dynamics

As the weight of the evaporated oxygen is neglectable compared to the the weight of inlet and outlet liquid flow, the mass balance equation becomes

$$A(h)\frac{dh}{dt} = q_1 - q_2$$

The cross section area is given by the radius and the level.

Pressure dynamics

A similar mass balance equation can be derived for the gas in the tank. Combined with the perfect gas law $pV = \frac{m}{M}RT$ and time differentiation, it gives

$$\frac{V_g(h)M}{k_v RT}\frac{dP}{dt} = -P + P_{air} - \frac{k_p n_p}{k_v} + \frac{W_1}{k_v} + \frac{PA(h)M}{k_v RT}\frac{dh}{dt} + \frac{PV_g(h)M}{k_v RT^2}\frac{dT}{dt}$$

This equation assumes models for the valve and the pump, which also can be found in [1].

Temperature dynamics

At evaporation, the tank temperature T, is closely related to the pressure P (almost linearly). This is modeled by the relation

$$T = T_{vap}(P)$$

Temperature can be viewed upon as energy. A temperature balance is then also an energy balance. This includes variables such as density and heat capacity for the liquid and the balance equation becomes

$$\frac{V(h)}{q_2}\frac{dT}{dt} = -T + \frac{q_1}{q_2}T_1 - \frac{A(h)T}{q_2}\frac{dh}{dt} - \frac{\Delta H_{vap}}{q_2 \rho C_p}W_1$$

Second / Third order system

During normal operation (evaporation), the system is of second order due to the algebraic relation between T and P. If the liquid stops evaporating, then this relation no longer holds. Instead, it is third-order dynamics. The same equations hold but without the W_1 term.

2.3 Existing control system

The deaeration process has two control loops, one for the level and one for the temperature. The level control loop, in figure 2.3, is according to the level dynamics equation described by a first order system. Therefore, a PI controller,

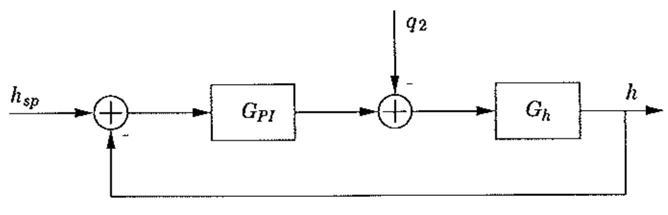

Figure 2.3 Level control closed loop for the liquid in the deaerator. The left block denotes the controller dynamics and the right denotes the process dynamics.

itself of first order, is enough to place the poles of the closed loop system and control the process. The controller is parameterized as

$$K\left(1+\frac{1}{T_i s}+T_d s\right)$$

with $K = 10, T_i = 45$ (and $T_d = 0$). In this configuration the outlet flow (q_2) is modeled as a load disturbance. A consequence of this is that the output from the PI controller becomes the inlet flow (q_1). This unfortunately makes it difficult to compare the measured PI output and the simulated PI output. The overall dynamics are nevertheless captured.

The temperature loop has a structure like figure 2.4. It consists of a temperature loop together with a pressure loop. The difference $T_1 - \delta T_{sp}$ is the input and the output is the outlet temperature T_2. For further information, look in appendix B.

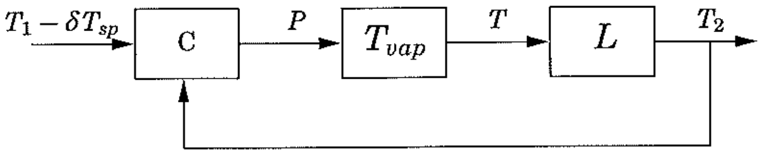

Figure 2.4 Temperature control loop for the liquid temperature in the deaerator. It has a pressure loop and a temperature loop.

3. Experiments

This part is the basis for the modeling and identification work to come. In this chapter, we show what kind of experiments we have done and plot some results.

The experiments have been done in closed loop configuration. The system was running under normal operating conditions. That is described with parameter values such as set-points (abbreviated *sp*) for important variables. Our starting point was $\delta T_{sp} = 3.0°C$ (flash temperature), $h_{sp} = 1.15$ m (level) and $q_{2sp} = 2500$ liters/hour (outlet flow).

We did step experiments around this operating point. Normal variations were between 1.5 and 4.5 degrees C for δT_{sp}. The level set-point was varied between 1.00 m and 1.40 m. The flow set-point was normally 2500 liters/hour but were also tried 4500 and 6600 liters/hour.

Many variables are logged during the trials. Among them are the level (h), the flow (q_2), pressure (P). The flash temperature (δT) is available as subtraction between the inlet and outlet temperature of the deaerator. See figure 2.2 for a view of the variables.

3.1 Level set-point changes (h_{sp})

These plottings show what influence level set-point changes have on the system. In figure 3.1, one can see that there are overshoots sometimes in the step responses. They are mainly due to problems with the pressure transmitter. At the moment, the transmitter can handle pressures down to -90 kPa. This is a differential pressure and corresponds to $P - P_{air}$. Converted to P, the measured pressure can approximately be as low as 10 kPa or 100 hPa.

The level changes disturb the temperature balance. It takes $15 - 20$ minutes for the temperature control to recover from a change in level.

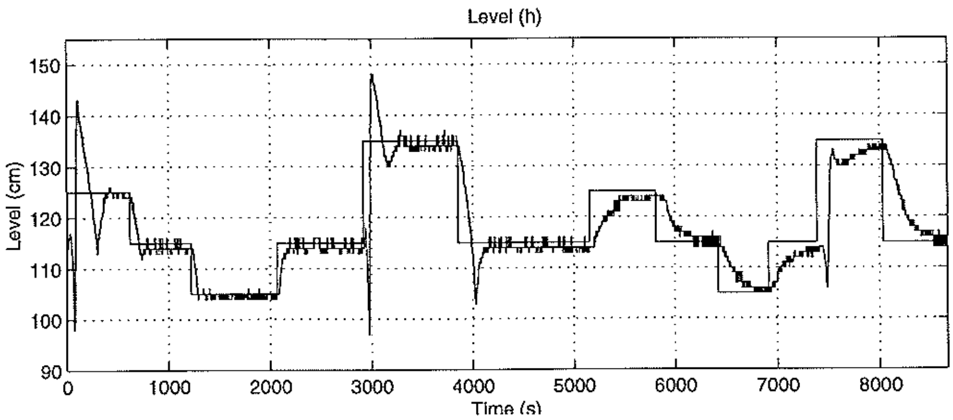

Figure 3.1 Experiment with step variations of h_{sp} between 105 cm and 135 cm. The set-point is shown together with the step response.

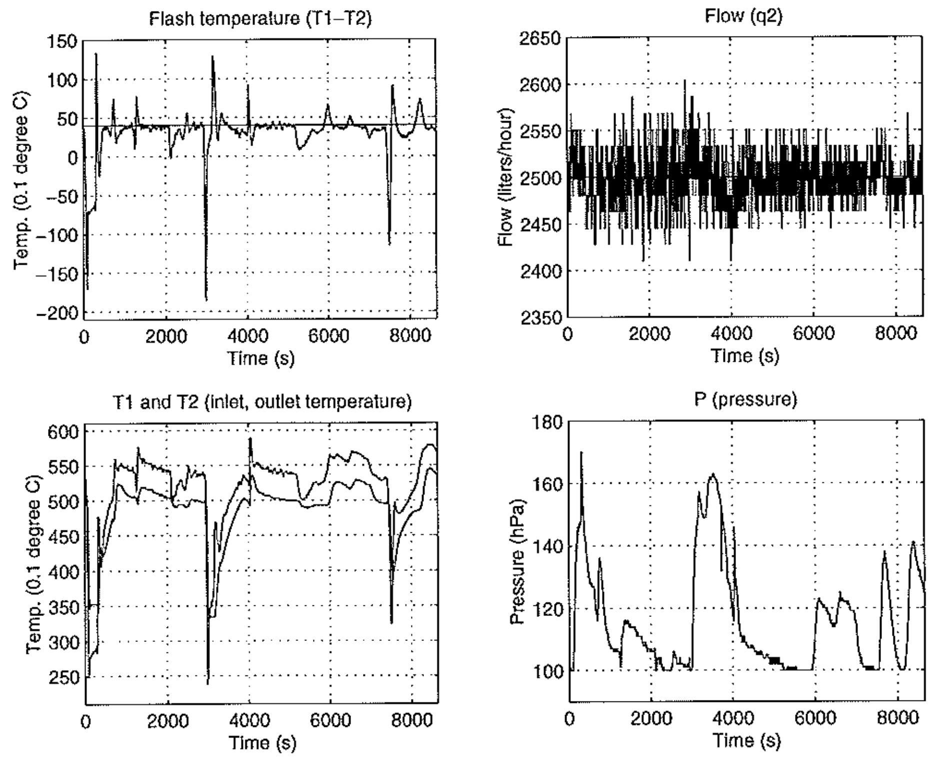

Figure 3.2 Experiment with step variations of h_{sp} between 105 cm and 135 cm. Flash temperature, temperature, flow and pressure plots.

3.2 Flow set-point changes (q_{2sp})

Here, we show an experiment with step variations of the flow. In flow context, the outlet flow (q_2) is referred to if nothing else is mentioned. It is the outlet flow that is logged. Currently the inlet flow is not logged. As can be seen in figures 3.3 and 3.4, there are only minor variations in the level, whereas δT, the flash temperature, varies more.

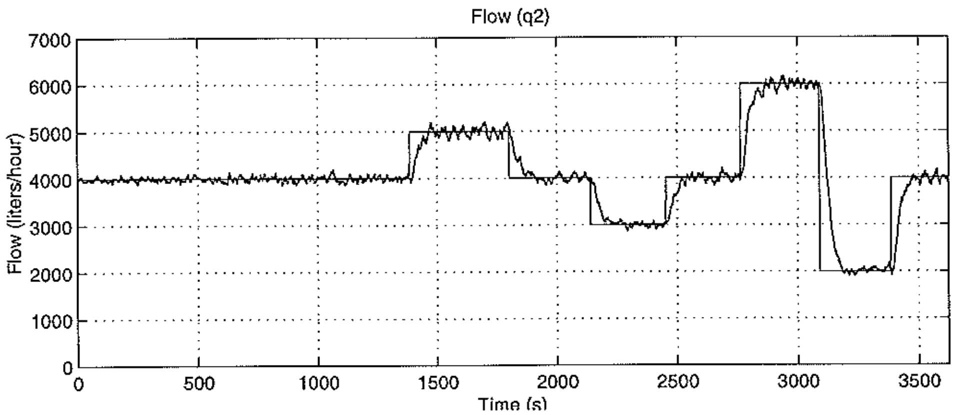

Figure 3.3 Experiment with step variations of q_{2sp} between 2000 liters/hour and 6000 liters/hour. The set-point is shown together with the step response.

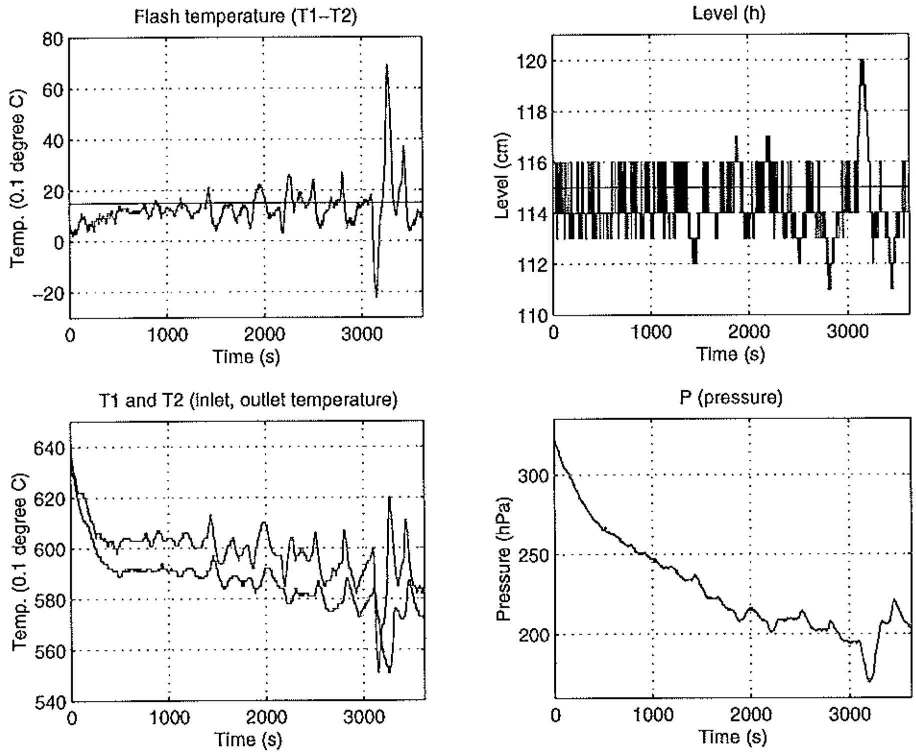

Figure 3.4 Experiment with step variations of q_{2sp} between 2000 liters/hour and 6000 liters/hour. Flash temperature, temperature, level and pressure plots

3.3 Flash temperature set-point changes (δT_{sp})

In figures 3.5 and 3.6, one can see that there is a problem between the times 2000 and 3000 seconds. The pressure saturates at 100 hPa and δT, the flash temperature does not reach its set-point. The reason for this is limitations in the pressure transmitter and its software.

An interesting thing is the oscillations in δT, the flash temperature. The apparent regularity indicates that there is a cause to look for. At the experiment start, before any changes are done, there is quite a long settling time for the system, about 30 minutes.

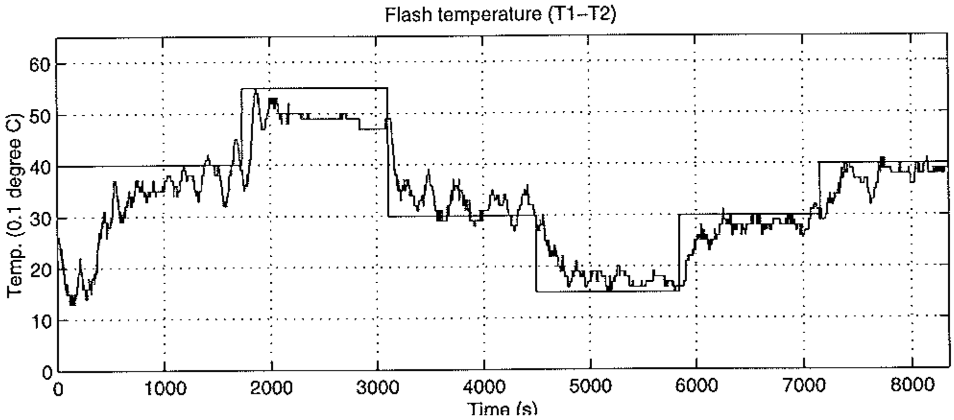

Figure 3.5 Experiment with step variations of δT_{sp} between 1.5°C and 5.5°C. The set-point is shown together with the step response

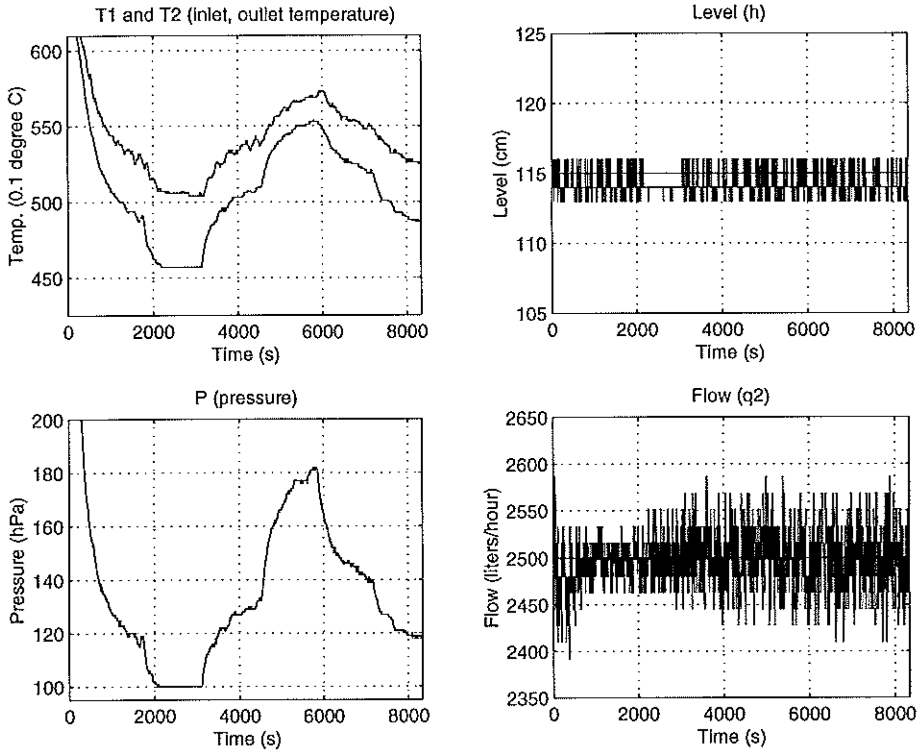

Figure 3.6 Experiment with step variations of δT_{sp} between 1.5°C and 5.5°C. Temperature, pressure, level and flow plots.

δT behaviour with different h_{sp} and q_{2sp}

When h_{sp} and q_{2sp} change, the δT behaviour also changes, as in figure 3.7.

With a low h_{sp}, the level controller variations in the flow are faster and with lower amplitudes than with a high h_{sp}. Consequently the δT oscillations decrease with the level set-point. A low h_{sp} also reduces the liquid volume inside the tank, i.e., the delay. In this way, the control action becomes faster.

A high q_{2sp} decreases the liquid permanence time inside the tank, i.e., the delay. Moreover, with a high flow the heat exchanger effects are reduced. Therefore, using a high q_{2sp} the control is much faster. High level and low flow increase the mixing effect between the inlet flow with $T_{vap}(P)$ and the flow inside the tank. $T_{vap}(P)$ changes can be observed on T_2 only with a delay depending on the mixing.

Using a 140 cm level and a flow of 2500 liter/hour the delay becomes too big, see fig. 3.8. In this case we can not know what is happening inside the tank observing the outlet temperature.

3.4 Summary

In this chapter we have described what kind of experiments we have done, together with example plots from the trials. The important variables are δT (flash temperature, $\delta T = T_1 - T_2$), h (level) and q_2 (flow). They have been measured and logged together with about 20 other variables.

A normal operating point is around $\delta T = 3.0$°C, $h = 115$ cm, $q_2 =$ 2500 liters/hour. The flow has three normal settings, 2500, 6600 and 8000

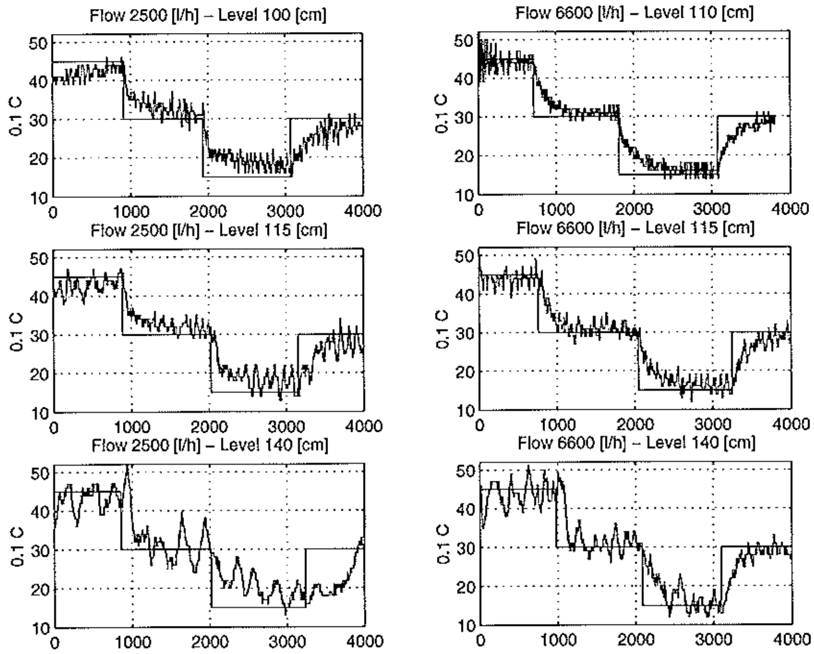

Figure 3.7 Experiments with step variation of δT_{sp} with different h_{sp} and q_{2sp}. The levels are 100, 115 and 140 cm. The flows are 2500 and 6600 liters/hour.

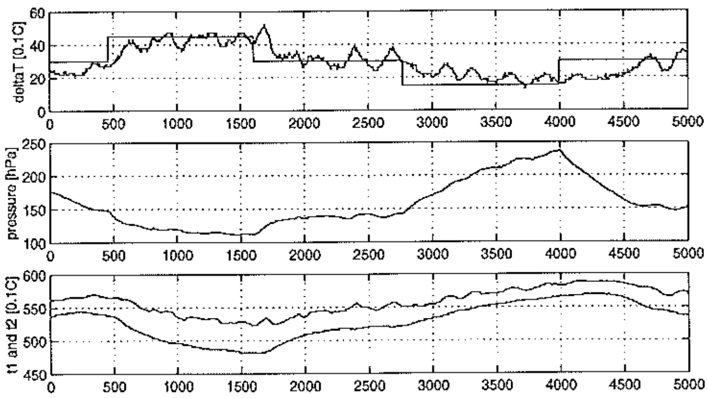

Figure 3.8 Experiment with step variation of δT_{sp}, h_{sp} = 140 cm and q_{2sp} = 2500 liters/hour

liters/hour. Due to restrictions with the hot water steam, we could not test the highest flow. Instead, we tried 4500 liters/hour. The level was varied between 100 cm and 140 cm. At the end of one test, level changes from 100 cm to 90 cm were tried. The PID output and especially the level varied very much during this trial. It turned out that the controller could not handle this task. The reason for this is that the low level gives so small time delay that the controller can not keep up with that pace.

Different values of δT boil off different amount of oxygen. It has been found by Tetra Pak that low values work but higher values work even better. Unfortunately we did not measure the oxygen content in the vapor. However, we varied the δT_{sp} between 1.0°C and 10.0°C (the last value from the bypass test). This gave a good view of the temperature dynamics.

4. Modeling of the Deaeration Process

In this chapter we present models for the level and temperature loops. We identify and validate the models using experimental data obtained as described in chapter 3. The models are derived using physical knowledge of the process together with standard identification methods, [2] and [3]. The heat exchanger influence on the temperature loop is examined.

4.1 Level loop

While the control task for the level loop is simpler than for the temperature loop, it is still important. The level must be controlled such that the machine does not run dry (damaging the machine and endangering the product quality). The normal liquid level is about $115-125$ cm, relative to the measuring

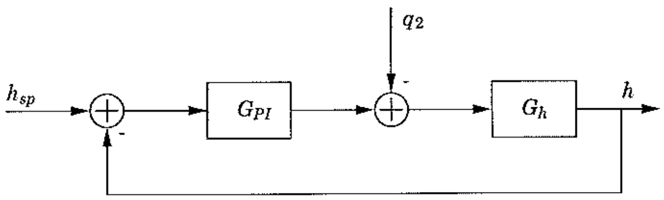

Figure 4.1 Level control closed loop for the liquid in the deaerator. The left block denotes the controller dynamics and the right denotes the process dynamics.

device. We started to do step changes of the level around this point, down to 100 cm and up to 140 cm. With the result from these experiments, we started to identify a mathematical model of the level control loop, in figure 4.4.

Identification

The level dynamics equation on page 7 is first order. The PI controller for the level is also of first order. This gives a second order model for the open loop level system. The data is filtered before it is used. The result can be seen in figure 4.2. The open loop model is clearly good in reproducing the data. This result applies for the open loop configuration in figure 4.3. The model in continuous time from the identification is

$$\tilde{G}_h = \frac{0.0025s + 0.0006}{s^2 + 0.025s + 0.0006} \cdot e^{-3s}$$

It is simple, but captures most of the process dynamics, see figure 4.2 (lowest part). Therefore, we split the open loop transfer function into the closed loop configuration as can be seen in figure 4.1. This gives the PI controller block and the level transfer function block seen in figure 4.4. It is modified from the original result to have better performance. This is observed simulating the closed loop system with different transfer functions. The closed loop model is

$$G_{PI} = K\left(1 + \frac{1}{T_i s}\right) = 10\left(1 + \frac{1}{45s}\right)$$

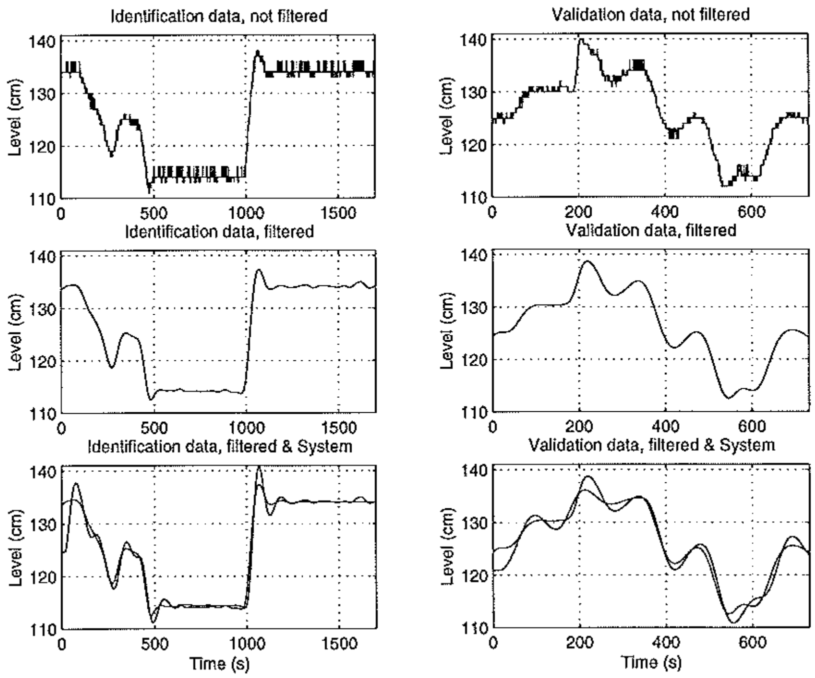

Figure 4.2 Identification and validation data for the level control loop. The data sets are filtered. The lower plots show the identified model compared with the filtered data.

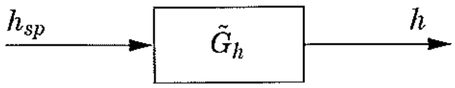

Figure 4.3 Level control open loop model. The transfer function $\tilde{G}_h$ describes the open loop behaviour.

$$G_h = \frac{0.001}{s + 0.004} \cdot e^{-3s}$$

It is this model, seen in figure 4.4, that is used further on.

Simulink simulation

The Simulink model in figure 4.4 is now tested on the data set d0320a. The result is plotted in figure 4.5. The simulated output, dashed line, is close to the original output, solid line. In the simulation, the input is the same as in the Tetra Pak trial. One directly sees that there are large overshoots that are not captured by the simulated system. The reason for this lies in the trials,

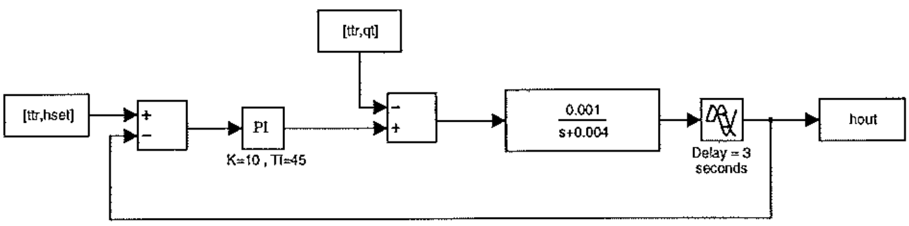

Figure 4.4 Level closed loop Simulink model. The PI block represents the controller dynamics. The time delay and its preceding block represents the process dynamics.

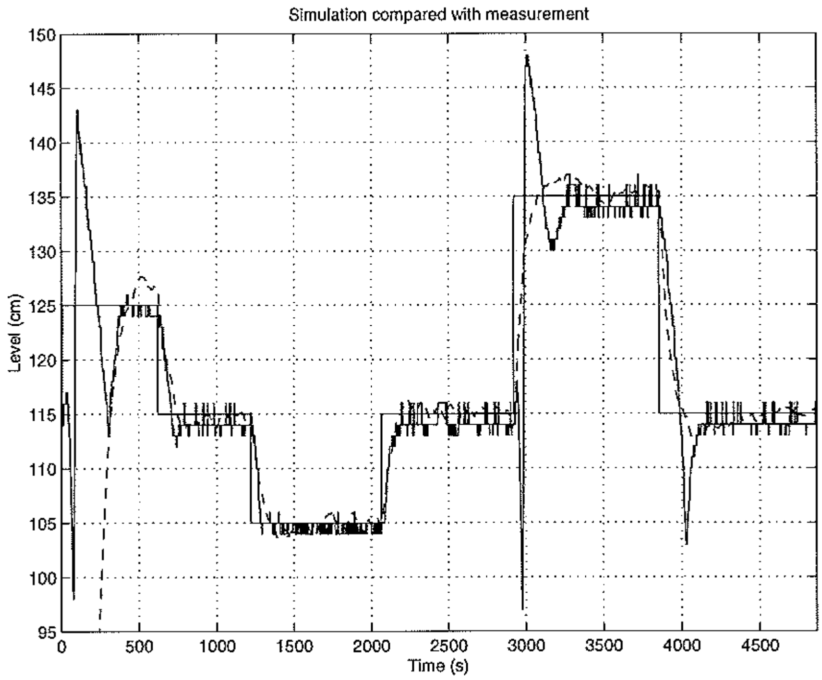

Figure 4.5 Simulation with closed loop level control. The dashed line denotes the simulated behaviour. The solid line is measured data from Tetra Pak. The quantization effects in the measured data can be seen as 1 cm deviations from the set-point.

more exactly the pressure transmitters that saturated or gave faulty results.

4.2 Temperature loop

The temperature control loop is used to control the deviation between the inlet temperature T_1 and the tank temperature T. The deviation is necessary to provide the deaeration process with energy.

The model structure

From the temperature dynamics point of view, the vacuum chamber can be considered as a system with one input, the δT_{sp}, and one output, the tank temperature. It is approximated with the outlet temperature T_2. The existing control system for the tank temperature T, is a cascade loop with an inner pressure loop and an outer loop for compensating the fluctuation in the inlet and outlet temperatures.

The liquid is evaporating during normal operation. The tank temperature T is then determined by the vapor temperature for the current pressure P

Figure 4.6 Temperature control open loop. Input is δT_{sp}. Output is T_2. T_1 is ideally constant. V.C. denotes the vacuum chamber.

through the relation $T = T_{vap}(P)$. It can be considered as almost linear in the operation area.

Therefore, to obtain the set-point we have to choose the right value for the pressure. In that way we can characterize a first control loop for the pressure and an internal dynamic between the control output and the pressure.

The tank temperature can be obtained directly from the pressure. Its value is not available through measurement devices. We must consider the outlet temperature instead. Therefore, we have another internal dynamic between the pressure and the outlet temperature. It is characterized by the pressure-temperature relation $T = T_{vap}(P)$ and by T coming out time delayed.

Identification and validation data

The vacuum chamber can operate in lots of different configurations, depending on the level, the flow and the flash temperature set-point (δT_{sp}) . Our first problem was to choose good parameter settings for running the experiment and collect in the data.

The suggested liquid level during normal operation is 115 cm, whereas there are three different flows: 2500, 4500, 6600 liters/hour, for the different production needs. The δT_{sp} can vary from 1.5°C to 5.5°C because of different desires for the deaeration percentage.

We have used the experiments d0303a and d0407a, respectively for the identification and validation . In both of them we have a constant liquid level of 115 cm and a constant flow of 2500 liters/hour (the lowest). That flow is the easiest to handle but also the worst for what is concerning the transport time delay. With these parameters fixed, we have run the experiments doing step changes of δT between 1.5°C and 4.5°C.

Internal dynamics identification

We identified the mathematical models for the two internal dynamics separately. As results we obtained two first order transfer functions in continuous time, one for the PID output-pressure dynamic:

$$\frac{-0.0411}{s + 0.0126}$$

with a time constant of about 80 seconds, and one for the pressure-outlet temperature dynamic, that has a time constant of 106 seconds.

$$\frac{0.0117}{s + 0.0094}$$

The temperature transfer function agrees with the theory in which the time constant was estimated to be approximately 120 seconds. The pressure transfer function is really slower than expected. In fact, theoretically the pressure loop seemed to give almost immediate response. This is not a big problem because this difference from the theory is probably due to the pressure valve and the pressure measurement devices reaction times.

Simulink model and simulation for the internal dynamics

As an identification confirmation, we have run the identified transfer functions in Simulink for verifying them in a normal situation of use. We obtained good results.

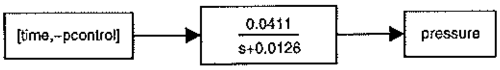

Figure 4.7 Simulink model. Transfer function between controller output (pcontrol) and pressure (P).

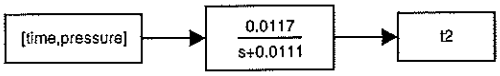

Figure 4.8 Simulink model. Transfer function between pressure (P) and outlet temperature (T_2).

The simple Simulink models shown in figure 4.7 and 4.8, are tested with the same data used in the identification process. The simulated outputs are showed in figure 4.9, together with the data from the Tetra Pak trials. In the simulation curves, we can see that the curves are quite close. Since there is agreement between the two simulations for what concerns the simulation behaviour in relation with the real data, we can suppose that this is due to same non-linearity inside the two dynamics. For the temperature dynamic this is easy to understand because we know that the relation between pressure and tank temperature, $T_{vap}(P)$, is non-linear.

In the case of the pressure dynamics, it is not so easy to understand from where the non-linearity comes from. The simulated curve is below the experimental, when the controller works with "high" pressure. It is still below when

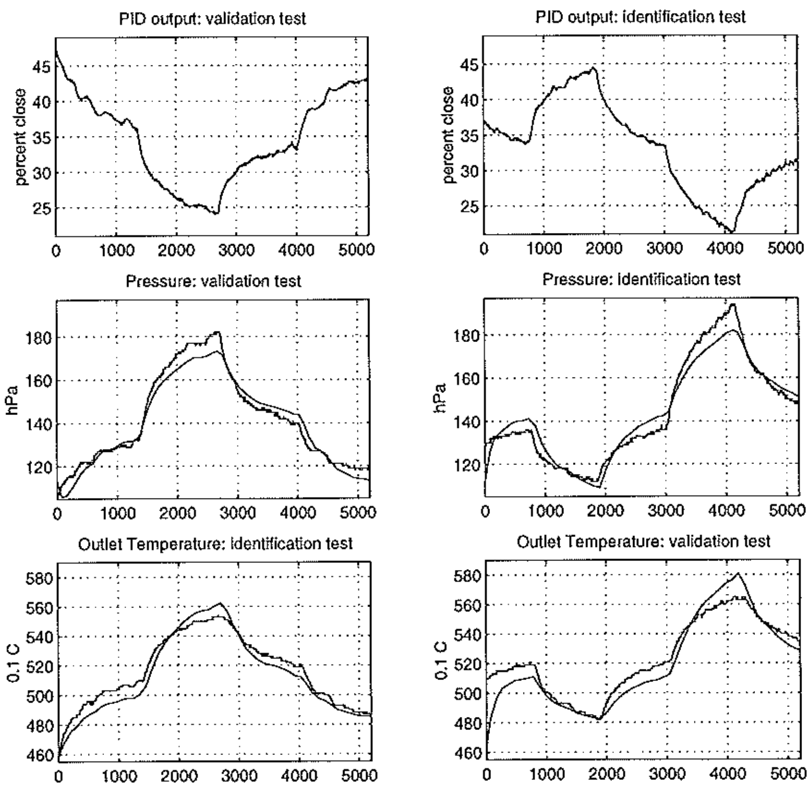

Figure 4.9 Comparison between measured data and simulated data. The smooth curves are simulated data. The jagged curves are measured data.

it works at "low" pressure. It seems that the pressure is easier to increase than reduce. This probably depends from a non-symmetry in the control action. When the controller tries to put up the pressure, the pressure valve does most of the work whereas most of the work is done by the vacuum pump when the controller tries to put the pressure down.

Simulink model for the control loop

We have inserted the internal dynamics in the existing control loop to obtain a model for the complete system. For more information about the model, see appendix B.

In this model, we have the PID controller

$$G_{PID} = K\left(1 + \frac{1}{T_i s} + T_d s\right) = 2\left(1 + \frac{1}{20s} + s\right)$$

We also have the linear approximations of the function T_{vap} and its inverse P_{vap} and a filter that works as an approximation of the time delay L.

Simulink simulation

We have tested the Simulink model using the identification data as inputs. The results, showed in figure 4.10, can be considered as satisfactory. The simulated PID output signal shows oscillation not present in the real PID output. However the most important signals, the pressure and most of all the temperature, have a behaviour very close to reality.

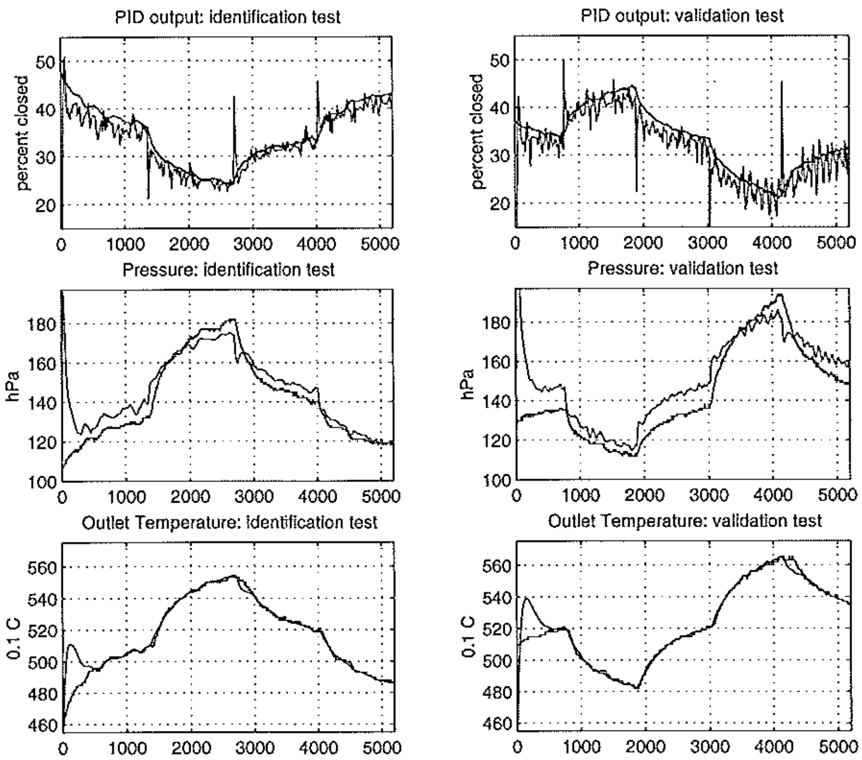

Figure 4.10 Comparison between Simulink model output and measured data. The model gives the smoothest curves.

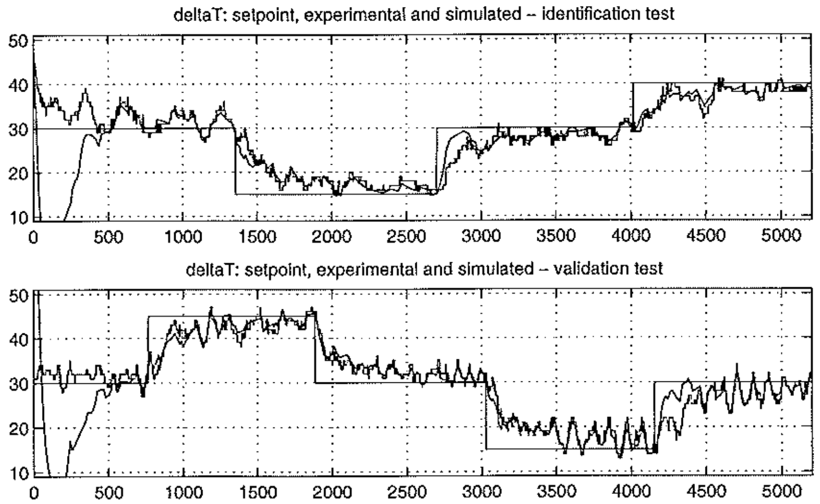

Figure 4.11 Comparison between δT from the Simulink model and δT from measured data. The δT_{sp} is also plotted as a number of steps.

The model is even better, observing the simulated δT, obtained as difference between the real inlet temperature and the simulated outlet temperature. Its plot, showed in figure 4.11 proves that the model can capture most of the process dynamics.

Unfortunately this model is not suitable for control design. The reason is that the inlet temperature depends from the outlet temperature.

The inlet temperature problem

The good results showed in figure 4.11 are obtained by the model considering the real inlet temperature as input. In this way the model can not be used, because we can not simulate the temperature loop with different values of the δT_{sp} if we must use real data as inlet temperature. What happens then, if we consider a constant inlet temperature? In this case the simulation result is completely different from the experimental, as can be seen in figure 4.12. The Simulink model response is much faster than the real model. This means that there is some other kind of relation between the inlet temperature and the outlet temperature besides the one that we have in the vacuum chamber.

This is confirmed analysing the behaviour of T_1 and T_2. As we can see in figure 4.13, instead of being constant, the inlet temperature follows the outlet temperature. This involves a slowing down in the control action.

As we are going to see in the next section, this added dynamic is due to the heat exchanger. Inside it, the inlet and the outlet flows are in opposition

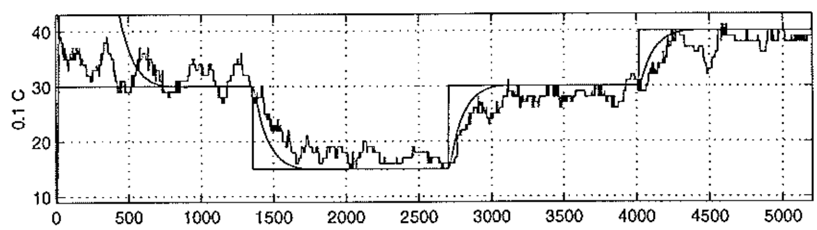

Figure 4.12 Simulated model behaviour when constant inlet temperature is assumed. The oscillating signal is measured data.

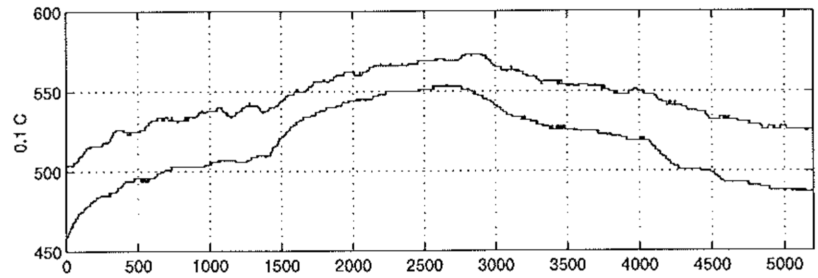

Figure 4.13 Temperature gap between T_1 and T_2. The inlet temperature is on top. It follows the outlet temperature.

in the energy exchange.

Model validation with a constant inlet temperature experiment

We verified the existence of a dynamic outside the vacuum chamber. Then we checked if the model was useful to describe the internal dynamics, running an experiment in which the inlet temperature was constant.

In the experiment d0408a we obtained an almost constant inlet temperature, around 54°C, bypassing a part of the heat exchanger. We sent the liquid directly from the balance tank to the vacuum chamber, without letting it go through the heat exchanger. In this case the experimental results are comparable with the simulated obtained using the experimental δT_{sp} as the only input. We considered the inlet temperature constant in the δT calculation. It can be seen in figure 4.14.

This means that we can use the Simulink model in section 4.2 to simulate the vacuum chamber individually outside the packaging line, but not if we consider it as part of the system.

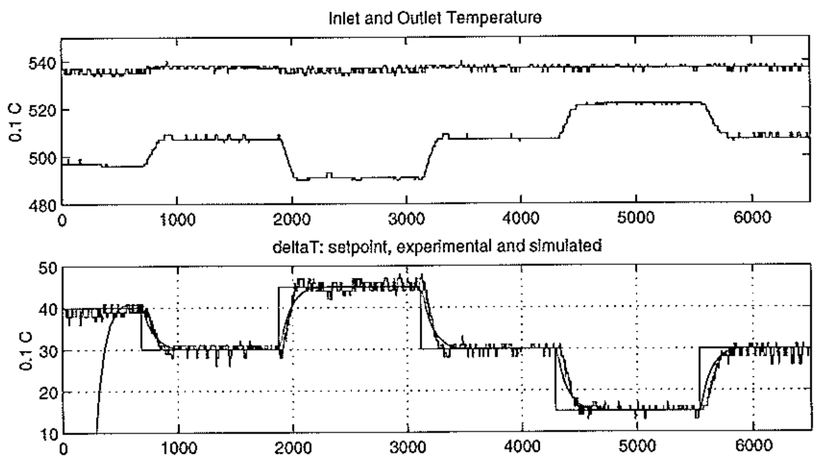

Figure 4.14 Temperatures from test with constant inlet temperature. A major part of the heat exchanger was bypassed. The result was a fairly constant inlet temperature. It is on top in the upper plot.

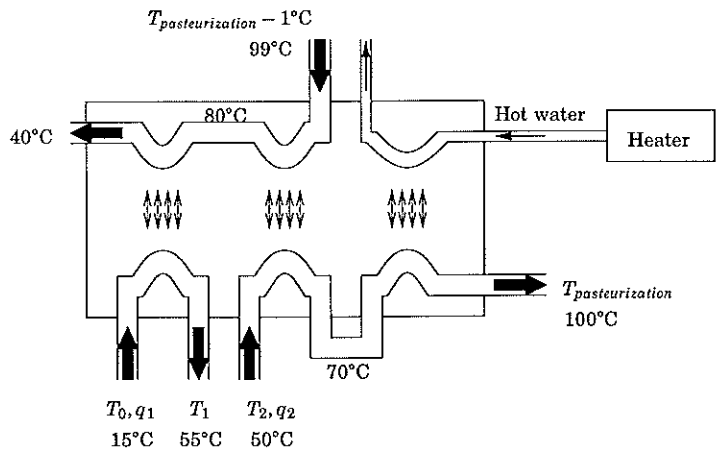

Figure 4.15 Simplified part of the heat exchanger. Heat transfer is denoted with two-way arrows. One-way arrows represents liquid flow direction.

4.3 Temperature loop with heat exchanger

The temperature control loop adjusts the pressure inside the vacuum chamber so that there can be a gap, δT, between the inlet and the outlet temperature. If the inlet temperature is constant, the control action is quite fast, as in figure 4.14. Instead, if an outlet temperature decrease involves an inlet temperature decrease, and vice versa, as happened in our system, in figure 4.13, the control action is slowed down, as can be seen in figure 4.12.

This undesiderable dynamic is due to the heat exchanger. The amount of heat avaliable to heating the inlet flow, depends on the outlet flow temperature.

The heat exchanger

In a heat exchanger the inlet flow with low temperature is heated by conduction through a warm flow of a special liquid. The amount of exchanged energy between the warm and the cold flow is directly depending from the heat exchange duration and from the temperature gap between the two flows. Therefore the outlet temperature from the heat exchanger can be regulated choosing the heating flow temperature or the cold flow permanence time inside the exchanger. The warm flow looses energy during the heat exchange, decreasing its temperature. Thus two cold flows will be heated in different ways if inserted in the heat exchanger in different positions with regard to the heating flow direction. The first, exchanging heat with an high energy flow, could be brought to a temperature higher than the second flow, that exchange heat with a colder flow. In our system both the inlet and the outlet vacuum chamber flows go through the heat exchanger. The inlet flow, coming from the balance tank with temperature T_0, around 15°C, have to be heated to the normal vacuum chamber temperature T_1, that is around 55°C. The outlet flow at temperature T_2 must be heated to 100°C, the pasteurization temperature.

The outlet flow heating is obtained in two steps. First the flow is heated using the warm flow coming back from the pasteurization to an intermediate temperature, around 70°C. Then it is brought to the pasteurization temperature with an appropriate heating flow, controlled through a specific heater to maintain this temperature constant. The inlet flow is heated using the energy left in the flow coming back to the pasteurization after the first outlet flow heating step.

Because of the heat exchanger work, as consequence of a T_2 variation, we have an opposite variation in the amount of heat exchanged between the inlet flow and the flow coming back to the pasteurization. Therefore if we have a T_2 reduction we also have a reduction in the energy left to heat the inlet flow, i.e. a T_1 reduction.

This explain why the inlet temperature follows the outlet temperature, and consequently why the temperature control loop inside the packaging machine work slower than using it alone with a constant inlet temperature.

The new model structure

There is temperature dynamic inside the heat exchanger. The inlet temperature T_1 becomes a function of the outlet temperature T_2. This can be reported in the model putting a feedback dynamic between the output and input.

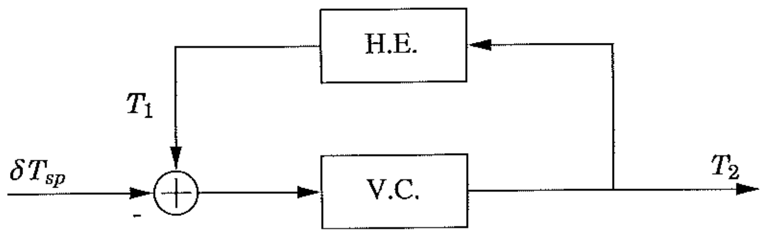

Figure 4.16 Temperature loop with feedback through the heat exchanger. T_1 depends on T_2.

Feedback dynamic identification

We have used the same data set for $T_2 \rightarrow T_1$ dynamic identification as before. We obtained a first order transfer function in continuous time:

$$\frac{0.0227}{s + 0.0325} \cdot e^{-55s},$$

with a time constant of about 30 seconds and a 55 second time delay. The time delay is quite big. It can be explained considering that the flow with temperature T_1 needs time to go the route between the heat exchanger and the vacuum chamber. The outlet flow also needs time to go from the vacuum chamber to the heat exchanger. This means that the temperature T_1 at the vacuum chamber entrance feels the effect of the outlet temperature T_2 with a delay that is the sum of the two delays.

Simulink model for the feedback dynamic

As identification confirmation, we have run the Simulink model shown in figure 4.17 with the same data used in the identification process. The simulated output and the experimental data plotted together can be observed in figure 4.18. We can see that the simulated model is quite good in reproducing the real data.

Simulink model for the vacuum chamber with feedback dynamic

The Simulink model in figure 4.18 can be used to describe the dynamic between outlet and inlet temperature. It can be inserted as a feedback between output and input in the existing Simulink model for the control loop.

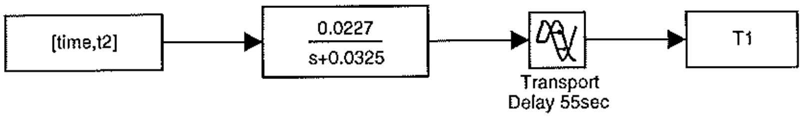

Figure 4.17 Simulink model for the dynamic between T_2 and T_1. The model respresents the feedback in figure 4.16.

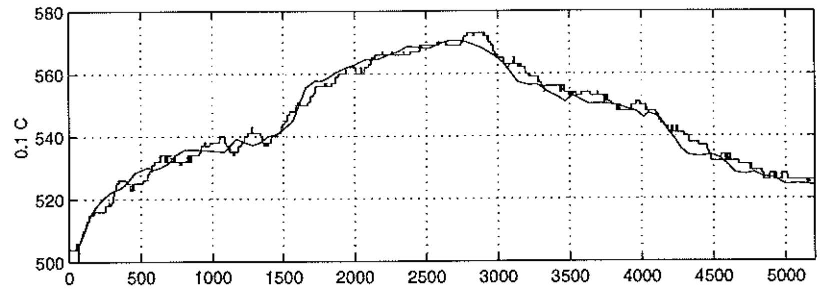

Figure 4.18 Comparison between simulated T_1 and measured T_1. The smoothest curve is the simulated.

For further information about the Simulink model, see appendix B.

The Simulink model tested using the identification data, shows a long convergence time. It is most of all due to the delay in the feedback. But after this time we can say that the simulated data and the real data have almost the same behaviour, as in figure 4.19. The model results are really good for the simulated δT, obtained as difference between the simulated T_1 and the simulated T_2. In fact, as we can see in figure 4.20, the two signals time contants are almost the same. That is contrary to what happen using the Simulink model without feedback, figure 4.12.

Therefore, from this point of view, the new Simulink model can be used to simulate the vacuum chamber when it runs inside the packaging line. This model can be used for control design if we do not consider the oscillations.

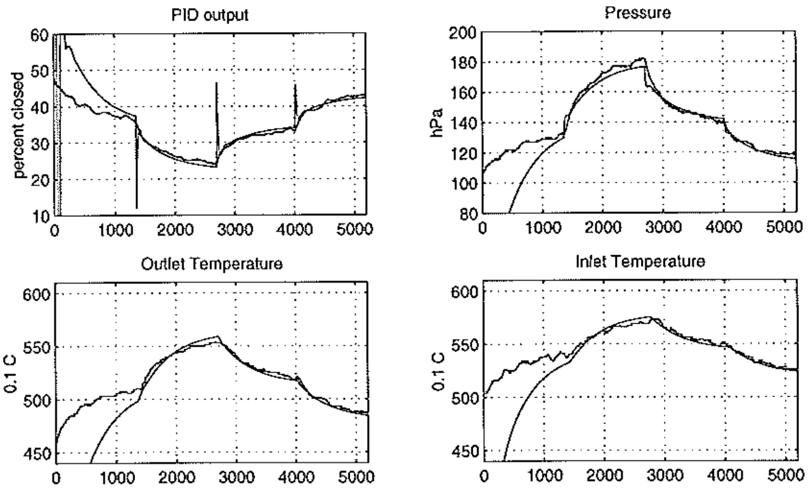

Figure 4.19 Comparison of Simulink model and measured data. The smoothest curves are the simulated.

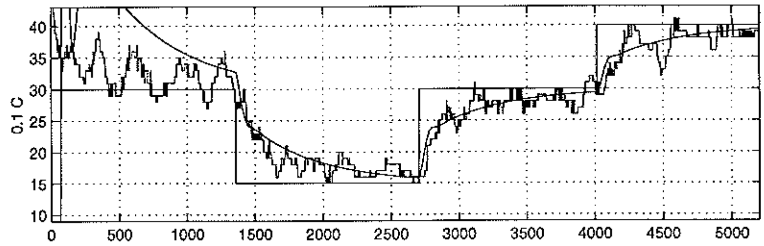

Figure 4.20 Comparison between δT from the simulated model and measured data. The smoothest is are the simulated. Two dynamics are seen in the simulated curve. The first part is similar to figure 4.12, i.e. fast response. The second part is slower due to the heat exchanger dynamics.

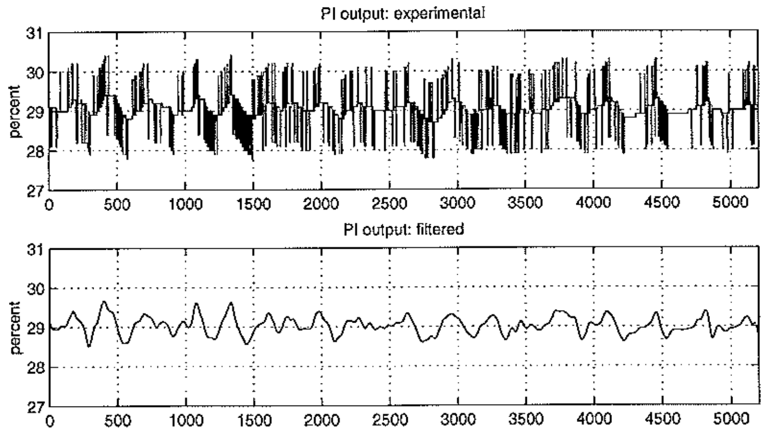

Figure 4.21 Level controller output, unfiltered and filtered. Same experiment as figure 4.20.

The inlet flow problem

With the Simulink model including heat exchanger, we can capture the principal δT dynamics almost perfectly, but we loose the fast dynamics. The simulated signal is smooth whereas the real signal show lots of oscillation, see figure 4.20.

The inlet flow is controlled to have a fixed value for the liquid level in the tank. During normal operation the level set-point is constant. Because the outlet flow set-point is constant, the inlet flow was also considered constant. In reality, the outlet flow is not constant but varies around the set-point. Consequently the inlet flow also varies because of the level control, see figure 4.21.

An inlet flow variation determines a variation in the liquid permanence time inside the heat exchanger. This involves a variation in the exchanged heat amount in the inlet temperature T_1. Therefore, the T_1 oscillation characteristics are determined principally by the level control loop that modifies the inlet flow.

4.4 Temperature loop with extended heat exchanger

The level control loop varies the inlet flow to maintain the liquid level in the tank constant. This variation in the flow involves a heating process variation that also determines an inlet temperature variation. Therefore, the feedback

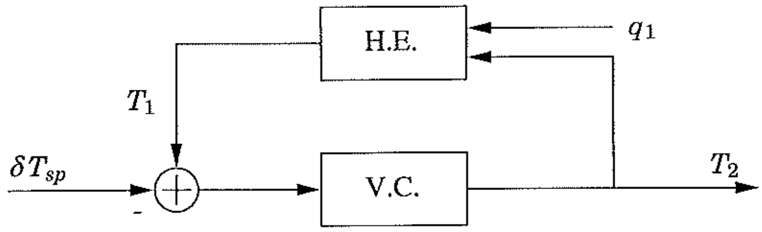

Figure 4.22 Temperature loop with extended feedback through the hear exchanger. T_2 and q_1 (the level control signal actually used) are used as inputs. The output is T_1.

dynamic that produces the inlet temperature must have two inputs, the outlet temperature and the inlet flow.

New heat exchanger identification

For the identification we have used an output error structure, with two inputs, the outlet temperature and the level control signal and one output. We had to use the level control signal instead of the inlet flow because it was not logged during the experiment.

The best identification results were obtained choosing a first order dynamic between T_2 and T_1, according with the previous results, and a third order dynamic for the level control signal. The new identified transfer function in continuous time is:

$$\frac{-(0.0015s^2 + 0.0047s + 0.0047)}{s^3 + 0.0983s^2 + 0.0132s + 0.0005}$$

That transfer function, using the level control as input, produces the output shown in figure 4.23 that added to the slow dynamic gave the oscillations.

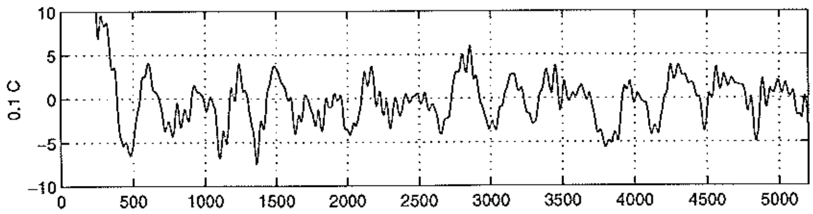

Figure 4.23 Oscillation in the deaerator inlet temperature. The cause is heat exchanger dynamics.

Simulink model for the heat exchanger

The new Simulink model for the heat exchanger is obtained adding the outputs from the two identified dynamics, figure 4.24.

The simulation results compared with the experimental data, see figure 4.25 show that the model is able to capture most of the system dynamics.

Simulink model for the vacuum chamber with the extended heat exchanger

For more information about the Simulink model obtained for the vacuum chamber considering the heat exchanger effects, look in appendix B.

The simulation results for the identification data set, figure 4.26 and figure 4.27, show that the model is now able to capture the δT oscillations.

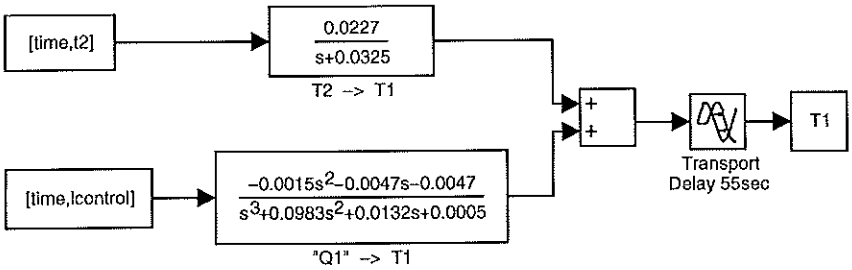

Figure 4.24 Simulink model for the extended heat exchanger dynamics.

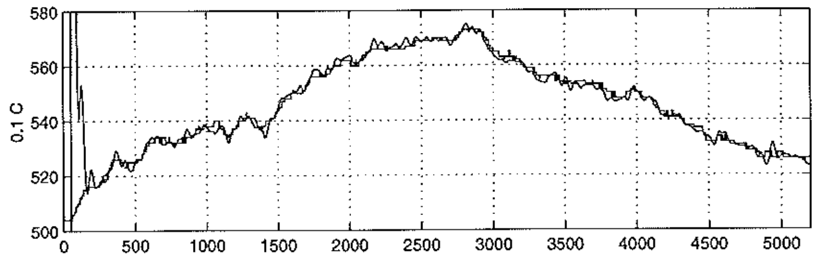

Figure 4.25 Comparison between T_1 from simulation with extended model and measured data.

The oscillations observed on δT are not a bad temperature control effect. They result from having T_2 instead of T. In fact, T_1 presents some oscillation over the principal dynamic. This is due to the level control action, whereas T_2 is smoother because of the mixing during the permanence in the tank. This show that we can not consider T almost equal to T_2 when the inlet temperature varies fast. The oscillations do not come from any internal dynamic. Instead, they can be considered as an external disturbance. This means that the model with heat exchanger, in section 4.3, is suitable for control design.

4.5 Temperature loop at different operating conditions

The identified dynamics and the Simulink models obtained in this chapter are referring to a level of 115 cm and a flow of 2500 liters/hour. Changing these values the system behaviour also change, as seen in chapter 3.

The Simulink models can be used for different sets of data changing the dynamics inside it. The transfer functions for some parameter sets can be found in appendix A.

The model step response simulations, figure 4.28 and figure 4.29, show that the temperature loop control is faster when it runs with a low level. This gives a shorter delay inside the tank. Use of a high flow is convenient for the vacuum chamber with heat exchanger, see figure 4.30. When it works separately, a low flow is better, see figure 4.31.

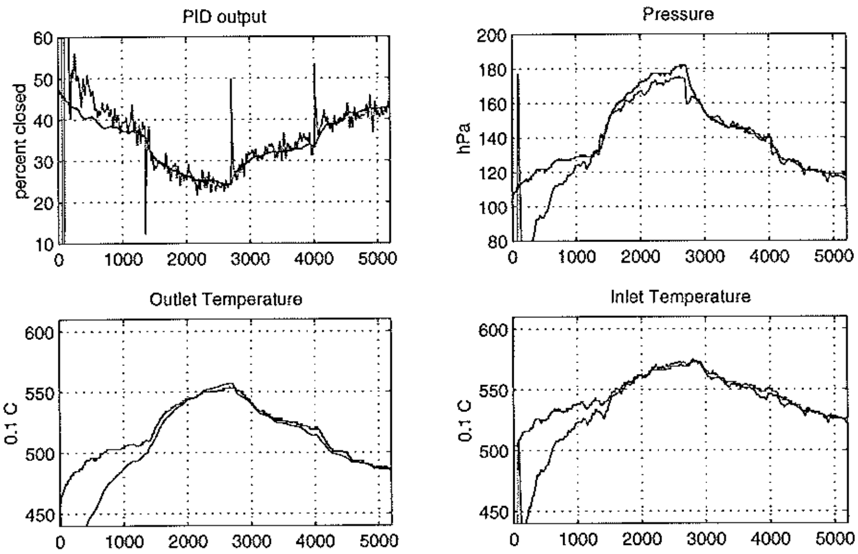

Figure 4.26 Comparison between simulated and measured data. The smoothest curve is the simulated.

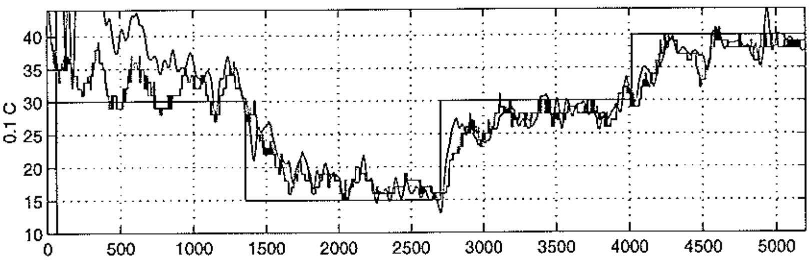

Figure 4.27 Comparison between δT from measured data and from simulation. The smoothest curve is the simulated. It captures most of the oscillations.

4.6 Summary

We have adressed different aspects of modeling and identification in this chapter. Above all, we have analysed the temperature loop with and without the influence of the heat exchanger. The result is that it has significant influence of the temperature loop. This is mainly noticeable in the deaerator inlet temperature. As could be seen in the bypass experiment, where a major part of the heat exchanger was bypassed, the inlet temperature was then much more stable than before.

While that approach gives good results, the present control system is also analysed. According to the theory, that system is faster than the true system. Taking the heat exchanger into account, we show models that capture the behaviour better than the existing control model.

The level loop is simpler than the temperature loop, but must still be treated seriously. Without proper control the machine can run dry endangering the product quality and damaging the machine. We show that the present level control system is good, and a mathematical model of it. The pressure transmitter related overshoots when changing the level, have caused some problems. Not in identification because we worked with a good part of the data, but in simulation where the model gives responses for a system without malfunctioning parts.

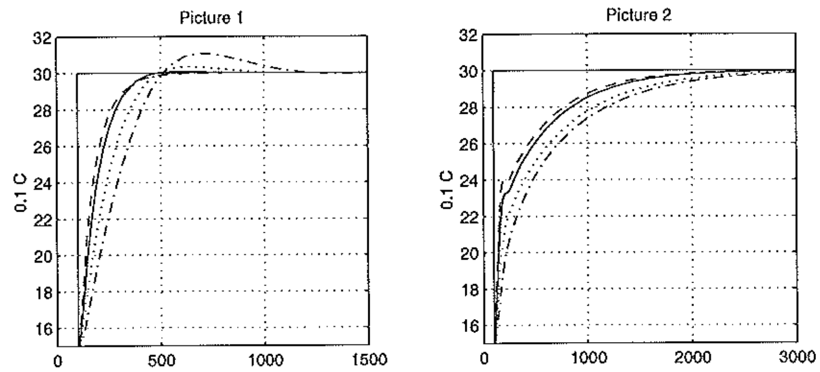

Figure 4.28 Step response simulation with flow of 2500 liters/hour and levels of 100 (—–), 115 (–), 130 (–·) and 140 (···) cm. Picture 1: without heat exchanger. Picture 2: with heat exchanger

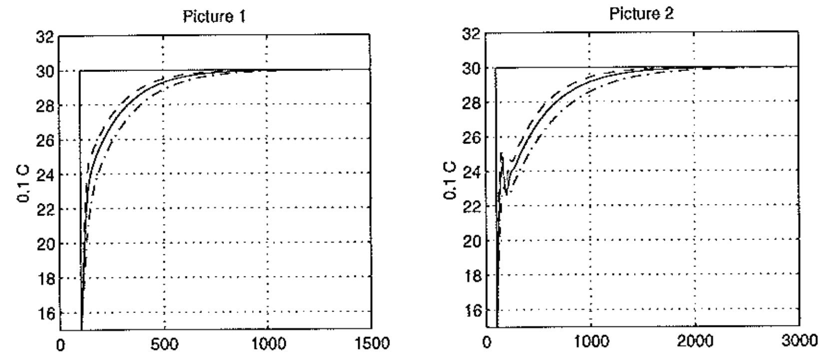

Figure 4.29 Step response simulation with flow of 6600 liters/hour and levels of 100 (—–), 115 (–) and 140 (–·) cm. Picture 1: without heat exchanger. Picture 2: with heat exchanger

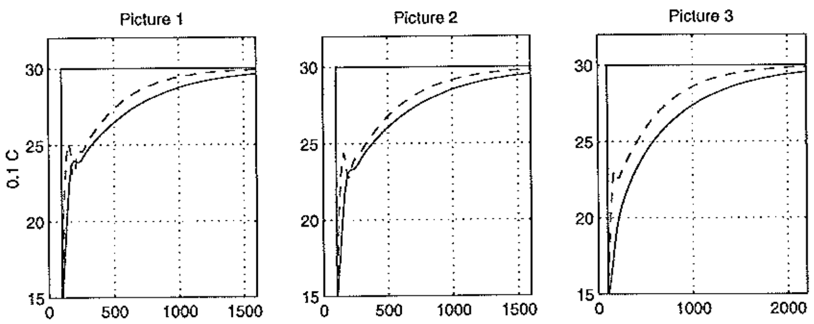

Figure 4.30 Step response simulation with heat exchanger. Picture 1: level 100 cm, flows 2500 (–) and 6600 (—–) liters/hour, Picture 2: level 115 cm, flows 2500 (–) and 6600 (—–) liters/hour, Picture 3: level 140 cm, flows 2500 (–) and 6600 (—–) liters/hour

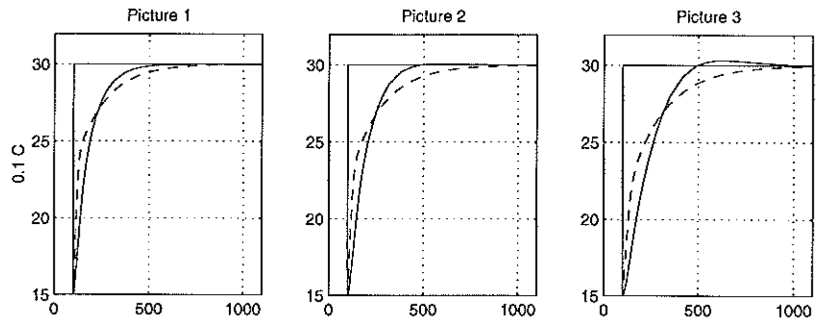

Figure 4.31 Step response simulation without heat exchanger. Picture 1: level 100 cm, flows 2500 (–) and 6600 (– –) liters/hour, Picture 2: level 115 cm, flows 2500 (–) and 6600 (– –) liters/hour, Picture 3: level 140 cm, flows 2500 (–) and 6600 (– –) liters/hour

5. Control Proposals

In this chapter we present some control ideas and discuss what they result in. This is mainly relevant for the machine we have tested. Some other machines have a controller for the deaerator inlet temperature, in contrast to the machine we tested, TA Drink Aseptic. This is a matter of cost; quite often customers are satisfied without such a controller.

The control designs that we suggest are discussed in [4].

5.1 Level loop

Changes in process parameters can occur, e.g. one of many subsequent filling machines can be stopped. In that case the level controller must direct the process back to normal conditions. Start-up and operation impose different demands on the process.

We found that the level controller also has influence on the temperature loop. It is reasonable that a level change affects the flash temperature. Its balance becomes disturbed and it takes some time before it is recovered. Unexpectedly, we also found that the level controller affects changes in the δT_{sp} (flash temperature set-point), as explained in section 4.4.

This calls for a desire to have different controllers for different conditions. We have tested different parameters for the level controller (PI) during the trials. We increased the damping and got good results.

Basis for changes

The behaviour of the closed loop system, in figure 2.3, can to a certain extent be examined theoretically. The blocks will together form the closed loop transfer funtion G_{cl}.

$$G_{PI} = K\left(1 + \frac{1}{T_i s}\right), \quad G_h = \frac{b}{s+a}$$

The poles of G_{cl} are

$$p_{1,2} = -\frac{a+Kb}{2} \pm \sqrt{\frac{(a+Kb)^2}{4} - \frac{Kb}{T_i}}$$

The poles determine the speed (frequency) and damping of the transfer function and thus its behaviour. The present level controller works good. However large steps result in large overshoots. This suggests an increased damping in the closed loop system.

Trials with changed parameters

Three trials with different controller parameters were done. An example is showed in figure 5.1. The second and third controller from the left are slower than the original. They also have more damping and thus less overshoot in their step responses.

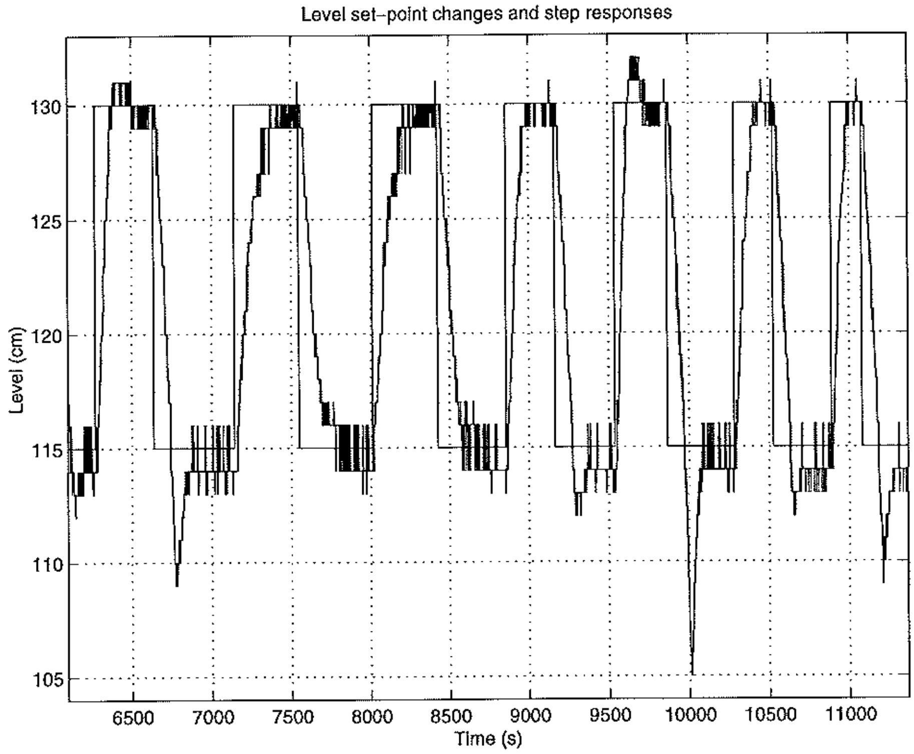

Figure 5.1 Experiment with new controller parameters. New controller for each set of steps; seven controllers tried. The leftmost is the original one. From left to right the PI controllers are: (K, T_i)=$(10, 45)_1$, $(14, 90)_2$, $(15.3, 83)_3$, $(14.3, 57)_4$, $(10, 35)_5$, $(16, 56)_6$, $(15, 45)_7$

Results

Comparison of controllers can be made looking at step responses for different controller parameters. It can be complemented by calculating the damping and frequency limit for the corresponding values of K and T_i. This suggests increased damping. Considering only the level, the present controller runs good.

Sometimes set-point changes result in large overshoots. The largest change is in start-up. This suggests one controller for set-point changes and another during operation. The oscillations in δT, explained in section 4.4, support this. For this a slow controller would remove the fast oscillations but keep the slow trends. A fast controller would remove the trends but probably have the fast oscillations.

Therefore, gain-scheduling is an interesting approach. Two level controllers, one designed for set-point changes and the other for normal operation, could be used. A reduced tolerance in level measurements would aid this. The level control loop influences on the temperature control loop must be considered.

5.2 Temperature loop

As we have seen in chapter 4 the temperature control loop works rather good if the inlet temperature is constant. When the vacuum chamber is considered part of the packaging line, the inlet temperature follows the outlet temperature. This slow down the control action and increase the convergence time.

Moreover, we have observed that oscillations in the inlet flow involve oscillations in the inlet temperature and then oscillations in the measured $\delta T (= T_1 - T_2)$.

Oscillations

The oscillations depend on the inlet flow. This flow depends on q_2 and mostly on the level control signal. The outlet flow is not constant but varies around the set-point. Consequently the level also varies, and the level controller changes the inlet flow to keep h around the set-point.

To reduce the oscillations we must have the inlet flow as steady as possible. We can obtain improvement in these ways:

- The outlet flow controller works with a quite big tolerance. This implies wide oscillations in q_2 and in h. Using a better controller the outlet flow would be more steady.
- The tolerance of the level measurement devices is one centimeter. We have the same tolerance for the level set-point. The error signal will then always be large. This involve wide variations in the control signal. Using a less tolerance, for example 0.1 cm, it would be easier for the controller to keep the set-point and the control signal would be more steady.
- The level controller have to be quite slow. A fast controller implies big overshoots. These are dangerous when we try to decrease the h_{sp} because we risk to run dry. With a slow control action we obtain a control signal with slow oscillations because the controller react gradually to the impulses in the error signal (due to the measurement tolerance). Using a slow PI when we want to have h_{sp} variations and a fast PI during normal operation the inlet flow would be more steady. The same result could be obtained also using a PID to choose appropriately the poles in the two situations,

In these ways we can reduce the oscillation in the inlet temperature. But since we do not measure the internal temperature T, we can not know for certain the conditions inside. Therefore, we can not say if we really have δT oscillations and most of all how the control loop reacts to these oscillations.

It would be very interesting to measure the internal temperature T to verify the internal behaviour. We would probably discover that the flash temperature is almost constant if compared to the measured δT.

Convergence time

There are two dynamics in δT set-point response. The fast depends on the deareator. The slow depends on the heat exchanger. The convergence time is the sum of the deaerator and heat exchanger times. Rearranging the heat exchanger as in figure 5.2 could be a way to eliminate the undesirable dynamic between T_1 and T_2. In fact the inlet flow is heated with a warm flow having constant temperature. In this way the inlet flow will be constant, independently of the T_2 behaviour. This heat exchanger configuration need more energy than the existent, both for heat the outlet flow to the pasteurization temperature and for the cooling before packaging. Nevertheless we could obtain a response comparable with the response obtained using the Simulink model in section 4.2.

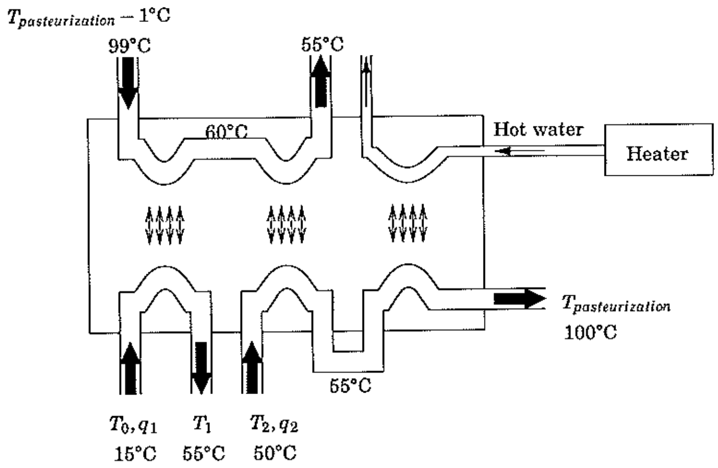

Figure 5.2 Suggestion of modified heat exchanger. Original configuration in figure 4.15. Heat transfer is denoted with two-way arrows. One-way arrows represent liquid flow direction.

Measuring T would improve the convergence time. We could then remove the delay L in the temperature loop (figure 2.4). The control action could then be speeded up.

Gain scheduling is proposed here as well. Different operating conditions motivate different controllers. This would speed up the convergence time. As above, the scheduled variables would be h and/or q_2.

5.3 Summary

We have discussed control proposals. The level loop works better with more damping in the set-point step responses. We have tested different controllers. In figure 5.1 controllers with higher damping are tested showing good results.

The level loop influences the temperature loop. This is seen in step response convergence time and oscillations in T_1 and δT. We suggest strategies to reduce this dependence. They include gain scheduling and reduced measurement tolerance. Rearrangement of the heat exchanger is discussed. Access to T instead of T_2 is interesting. It would give the true condition inside the tank.

6. Conclusions

The main part of the report consists of modeling of the control loops in the deaeration process. When we started the work we had a theoretical description of the dynamics in the deaeration system and the derived control models. The accuracy of those models had not been examined since experimental data were not available.

We have collected experimental data and estimated the model parameters. With them, we have run extensive simulations of the models, obtaining results that can be summarized as:

- Accurate models of the deaeration process
- Important to include the heat exchanger in control design
- Probable control improvements with gain scheduling
- Is T_2 a good approximation of T?

Accurate models of the deaeration process

With the experimental data we have identified the dynamics in the vacuum chamber. The obtained dynamics were used to evaluate the existing control systems, i.e. temperature and level control loops.

Simulation results show that the found model are not suitable for control design because they do not take the packaging line effects into consideration.

We did an experiment in which we bypassed a major part of the heat exchanger. This verified that the model can be used to simulate the vacuum chamber when it works separately, outside the packaging line.

Important to include the heat exchanger in control design

The influence of the heat exchanger can be seen when comparing experimental data from the bypass trial with other data. Therefore, we have identified the dynamic between the deaerator outlet and inlet temperature. We have inserted this as a feedback between T_2 and T_1 in the existing model.

With this model we show two temperature dynamics. One depends on the deaeration process and the other on the heat exchanger.

We explain the δT oscillations and show that they mainly depend on the level control signal. It contains oscillations which are passed on to the inlet flow and thereby the liquid permanence time in the heat exchanger. These oscillations can be viewed upon as external disturbances.

This allows simulation of the vacuum chamber inside the packaging line. The model with heat exchanger is therefore suitable for control design.

Probable control improvements with gain scheduling

We have identified models at different operating conditions. Simulated and experimental results show that the deaeration process behaviour changes when the operating conditions vary. This means that control improvements can probably be obtained using these models in design of gain-scheduled controllers.

During the experiments, we have seen that the control loops affect each other. Particularly, the inlet temperature depends on the level control signal. This suggests using appropriate level controllers in different operating steps.

In normal operation, the signal should be stable and during h_{sp} changes, there should be no overshoot. Control design should take this into consideration.

Is T_2 a good approximation of T?

T_1 depends on T_2. How much can we trust the approximation of T with T_2? When T is almost constant, the difference is probably small. When T varies fastly, the delay inside the tank is too long for comparisons od the temperatures. This causes errors in the temperature feedback, figure 2.4. Although difficult, measuring T would be interesting.

6.1 Future work

The obtained models can be considered sufficient to describe the system. The attention can then be focused at improving the control action and build a software pilot plant. Future work is suggested to consist of the following steps:

- Control design using simulation model
- Model library for deaerators and heat exchangers

Control design using simulation model

Control design could be made with the models. They accurately desribe the deaeration process dynamics. The model with heat exchanger feedback from T_2 to T_1 should then be used.

Model library for deaerators and heat exchangers

More long term work consists of developing a model library for different machine configurations. That would allow simulation and control design using machine-specific models.

7. References

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A. Temperature loop at different operating conditions

Different sets of data change the temperature loop models. This appendix show transfer functions for different operating conditions. Changing the transfer functions, the model dynamics also change. Each transfer function represents dynamics for pressure, temperature and heat exchanger. K_{vest} denotes the controller output.

	Pressure	*Temperature*	*Heat exchanger*
	$K_{vest} \rightarrow P$	$P \rightarrow T_2$	$T_2 \rightarrow T_1$
Flow 2500 liters/hour			
• Level 100 [cm]			
	$\frac{-0.0573}{s+0.0161}$	$\frac{0.0159}{s+0.0114}$	$\frac{0.0229}{s+0.0329}$
• Level 115 [cm]			
	$\frac{-0.0411}{s+0.0126}$	$\frac{0.0117}{s+0.0094}$	$\frac{0.0227}{s+0.0325}$
• Level 130 [cm]			
	$\frac{-0.0352}{s+0.0108}$	$\frac{0.0067}{s+0.0072}$	$\frac{0.0164}{s+0.0234}$
• Level 140 [cm]			
	$\frac{-0.0248}{s+0.0062}$	$\frac{0.0039}{s+0.0049}$	$\frac{0.0131}{s+0.0186}$
Flow 6600 liters/hour			
• Level 100 [cm]			
	$\frac{-0.1073}{s+0.0258}$	$\frac{0.0536}{s+0.0370}$	$\frac{0.1002}{s+0.1719}$
• Level 115 [cm]			
	$\frac{-0.1031}{s+0.0255}$	$\frac{0.0401}{s+0.0335}$	$\frac{0.0570}{s+0.0977}$
• Level 140 [cm]			
	$\frac{-0.0788}{s+0.0197}$	$\frac{0.0238}{s+0.0263}$	$\frac{0.0232}{s+0.0399}$

B. Reference to Tetra Pak

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