Development of a Real-Time Simulator for A Three-Effect Falling Film Evaporator

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Summary

The aim of the project was to create a real-time simulator of a falling film evaporator located in the Collage of Science at Massey University to allow operators to be trained on using the system. This aim was broken into two objectives: the development of a simulink model in Matlab Simulink and secondly the design of control system databases and control screens in Fix32.

A specification was initially laid out for these two objectives. A design of the real-time simulator was then made, based around the specifications. The real-time simulator was implemented and then tested to ensure that the initial specifications were met. The final evaporator simulator was an executable file embodying the simulink model controlled by control screens.

The Simulink model was developed based on an existing mathematical model of the falling film evaporator that was solved in Matlab M-file format. Two steps occurred while developing the Simulink model. First was converting the existing M-file model into Matlab simulink blocks. The second step involved making improvements to the simulink model.

The design of control system database and control screens followed, based around the specifications. The control system database was developed using the Fix32 "Database builder" and included database blocks and chains. Inputs and output blocks were created and configured to match the variables being sent to and from the Simulink simulation. The control screens were designed, based on the existing industrial screens. The pictures of

preheaters, effects, feed water tank, steam pipelines, steam valve and pumps were redrawn to match the real plant as close as possible.

After the creation of the simulink model, the steady-state simulation initialisation values were determined and adjusted through the test. The final test was made by running the Simulink model in conjunction with the modified Fix32 control system. The final test proved that the Real-time simulator was created successfully.

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1 Introduction

1.1 Background

1.1.1 A Falling-film evaporator

Evaporation is an important process used in the chemical industry, which concentrates a solution containing dissolved or suspended solids by boiling off the solvent. A large proportion of the energy used in industry is given to this process. It is a very appropriate process to study due to its wide use and energy intensity[3].

In a modern evaporation system the evaporator acts as the main process unit in the evaporation process for drying a number of products. Good evaporator control is particularly important because of its widespread use, especially in the New Zealand dairy industry, and the direct effect of better control on energy efficiency and a more consistent product.

The evaporator used in this thesis is a pilot-scale, three-effect, falling-film evaporator that resides in the College of Sciences, Massey University. This system is a scaled version of the type of process used in the dairy industry and was built to provide a platform for research into process identification and control.

1.1.2 Falling-film evaporator existing model

To study problems before the control is implemented on the real system a process model was previously created by a number of researchers[2,3,4]. This existing model can be used to test and refine the performance of the control strategy.

The existing model was completed by Russell (1997)[4] as a suite of Matlab m-files.

1.1.3 Real-time simulator modeling

In order to obtain real time simulation results, a new dynamic mathematical model was created and solved in Matlab Simulink. The model is the mathematical expression of the process. It expresses most of the important dynamic characteristics performance of the process. It would be used by the simulator (a program package that contains dynamic mathematical model and Fix32 SCADA system) and would act as the real process to be run by the operator. In order to provide the best training for the operator the simulation must run behind Fix32, the SCADA package that the operator would use to run the real plant. The real control screens and control database would be used as for the real plant.

The development of the real-time simulator can give lots of benefits to the industry. For example, by running the real-time simulator, the simulation results can display directly on the control screen and the process engineer can change the simulation settings directly. These properties can give the process engineers and operators a better understanding of the characteristics of the evaporator.

In order to obtain a graphical and real-time simulation environment, a real-time simulator was created during this project. This real-time simulator provided a better operation platform to make the simulation running more like a real plant. In addition the equations and parameter settings used in the original dynamic model were improved to make the simulation more accurate.

The real-time simulator was also designed as a control design tool, which could be used to simulate and compare various control strategies. For this reason the real-time simulator contained ordinary differential equations and algebraic relationships and parameters were lumped where appropriate.

Other reasons for doing this project include:

- The real-time simulator could provide off-line operator training. Operators or students can easily gain an understanding of the characteristics and responses of the process.
- The process engineer who wants to apply different operating strategies could use this real-time simulator to determine the effects without the danger of disrupting the actual process.
- The real-time simulator could also be used as a process-monitoring tool by running it in parallel with the plant and noting differences between the two.

1.1.4 SCADA package and Fix32 software

Supervisory Control and Data Acquisition (SCADA) packages are used in industry to monitor and control processes. A SCADA package is a multitasking environment that provides two basic functions: supervisory control and data acquisition. It receives data from the process, performs supervisory control functions, displays information to the operator and receives requests, stores trending data and sends set-points to the process.

Fix32 is an example of a multitasking SCADA system widely used in the industry. It provides process monitoring and control, data collection and graphic display functions.

1.2 Objectives

This project sought to develop a real-time simulator, which contains a falling-film evaporator Simulink model linked to SCADA control screens. The Simulink model was developed based on an existing mathematical model of the falling-film evaporator that was solved in Matlab M-file resident in the College of Sciences, Massey University.

The control screens are used to display the simulation results from the Simulink model and to change the settings of the parameters in the Simulink model.

For this reason the thesis is broken into two parts: developing the real-time mathematical model in Matlab Simulink and designing control screens in the FIX32 SCADA package. Once these two tasks are completed the real-time simulator is converted into executable code which connects with the control screens. The results of the combined testing are reported at the end of this thesis in chapter 6.

To develop the falling-film evaporator Simulink model, two steps must occur. The first step is converting all the M-files of the old model into Simulink blocks. The second step involves making improvements to the Simulink model.

This work has the following objectives:

- To develop a modeling methodology to convert existing m-file model into Simulink block.
- To improve and correct any mistakes made in the existing m-file model.
- To develop control screens that duplicates those of the real process.
- To build a database for the control screens. The database contains all the results that are received from the real-time Simulink model and all the changes of the parameters made by the operator. All the changes will be sent to the Simulink model directly.

2

Industrial Falling-film Evaporators

OVERVIEW

Before developing the real-time simulator, the principle of the falling-film evaporator and relevant technology were studied in order to obtain a better understanding of the plant. This chapter introduces industrial evaporators and provides a brief overview of their function and operation. A description of the falling-film evaporator at Massey University is discussed. Finally an existing model of the falling-film evaporator is given with details of some of the important differential equations.

2.1 Industrial Evaporators

The first multi-stage and vapour recompression evaporator was built in the latter part of the 19^{th} century. Today multi-stage evaporators with vapour recompression are widely used to improve the energy efficiency of the process. There are four types of evaporators mainly used in industry. They are described as follows:

Forced-circulation evaporator gives high heat transfer coefficients, positive circulation and relative freedom from scaling at the expense of high operating costs and long residence times. It is best applied to crystalline products and corrosive or viscous solutions.[1]

Horizontal tube evaporator needs very little headroom. It can provide good heat transfer and low cost. It is primarily used for seawater evaporation to produce fresh water.

Short-tube vertical evaporator is relatively inexpensive. It provides good heat transfer at high temperature but is not so good at low temperature. The hold-up time of the product is relatively high. It is suitable for processing clear or non-corrosive solutions[1].

Long-tube vertical evaporator includes the ***climbing- (or rising-) film evaporator*** and the ***falling-film evaporator.*** Both of them provide good heat transfer with small temperature differences between the liquid and the steam. The falling-film evaporator especially provides good heat transfer at both high and low temperature. It has a short residence time and this makes it very useful for heat-sensitive products such as orange juice and milk. However, it needs a large amount of headroom and is unsuitable for processing salting or severely scaling liquids.

There are a number of other types of evaporators such as ***plate evaporator, centrifugal evaporator and agitated thin-film evaporator.***

2.2 Falling-film Evaporator Description

The falling-film evaporator in the College of Sciences at Massey University is a scaled down version of the falling-film evaporators found within the dairy industry. It was designed to handle liquid feeds of 180-200 liters/hour with an evaporation rate of 30 litres/hour. In practice, the evaporation rate is in the range of 40-60 litres/hour. The

College of Science evaporator contains three effects with two preheaters and a water-jet condenser. Table 2-1 shows the design temperature and pressure operating conditions in the evaporator at steady state.

Table 2-1: Design operating temperatures and pressures.

Stage	Product temperature (°C)	Pressure of vapour in shell (kPa abs.)
Effect 1	70	50
Effect 2	60	32
Effect 3	45	20
Preheater 1	35	5
Preheater 2	70	50

A schematic of the College of Science falling-film evaporator is shown in appendix 1. In the plant the second preheater is heated with externally supplied steam as is the first effect. The vapour produced in the third effect is transferred to the first preheater. No vapour recompression is used in the process.

Figure 2-1 shows a single effect of the falling-film evaporator. Each effect contains only one evaporation tube. Through a simple nozzle the liquid is pumped into the effect and is distributed around the tube over a distribution plate. Both of the preheaters are shell and tube heat exchangers, which have three tubes passes in each.

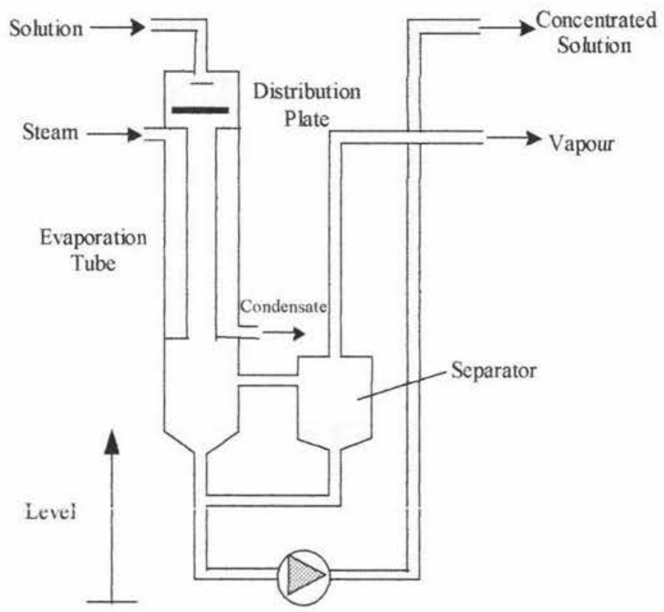

Figure 2-1 A single effect of the falling-film evaporator

The falling-film evaporator has a total of 20 measured variables, which include seven temperatures, five pressures, four flows and four liquid levels. Their positions on the process are shown in appendix 1.

2.3 Falling-film Evaporator Existing M-file Model

The existing falling-film evaporator m-file model was developed by a number of researchers[2,3,4]. The model has a total of 10 input variables. They are the temperature of the external steam supply, the ambient temperature, the ambient pressure, the temperature of the product leaving the feed tank, speed of the effect pumps, speed of the feed tank pump and product flowrate.

In the most recent model (1) the plant was split into eight sub-systems. Figure 2-2 shows the sub-systems in each effect. Each sub-system is described in the following sections. All the details of equations are shown in appendix 3.

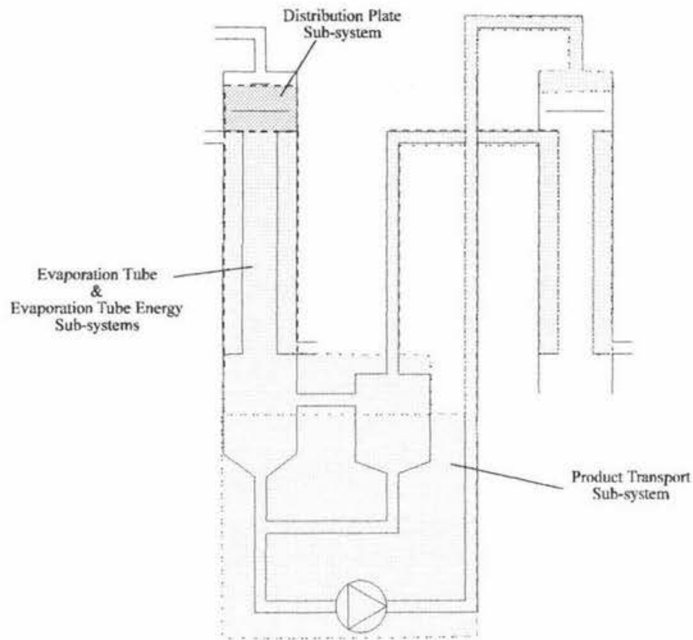

Figure 2-2: Sub-system boundaries in an effect

Figure 2-3 shows a diagram representation of the evaporator model. This gives a clear view of the connection of each sub-system.

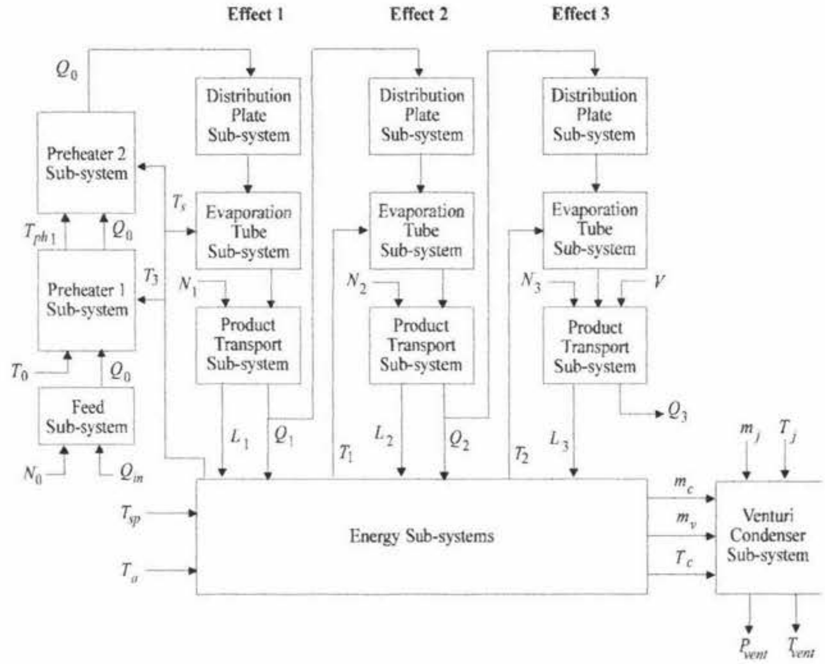

Figure 2-3: A diagram representation of the evaporator model

Distribution plate sub-system

This sub-system models the flow of solution through the distribution plate and into the evaporation tube. The distribution plate is considered as a mixed tank with perforations which allow the liquid to distribute evenly into the evaporation tube.

Evaporation tube sub-system

This sub-system models the mass flow of the liquid out of the evaporation tube which is obtained by performing a mass balance over the evaporation tube sub-system and the mass of vapour produced in the evaporation tube.

Before modeling the evaporation tube sub-system two assumptions are made:

- The heat flow across the tube is considered to be uniform.

- The fall velocity of the liquid film is assumed to be constant.

Product transport sub-system

This sub-system models the flow of product from one effect to the next. It involves the reservoir of liquid concentrate, the pipework connecting the effects and the distribution nozzle in the downstream effect. The temperature changes that occur through the product transport system are also modeled.

Evaporation tube energy sub-system

This sub-system models the heat transfer in the evaporation tube sub-system. This includes the heat received from the heat steam, heat lost to the surroundings and heat lost to the downstream effect from the condensation of the vapour.

Each effect is formed by these sub-systems. In addition the effects are related to the following sub-systems.

Feed sub-system

This sub-system models the flowrate of the liquid, which is pumped from the feed tank into the first effect through the preheater tubes.

Preheater sub-system

This sub-system models the temperature of the liquid out of each preheater. It includes the heat transfer in the preheaters. Russell[4] used a discrete first order differential equation to represent the old model. This differential equation is not very suitable for the sub-system.

Venturi condenser sub-system

The sub-system models the suction pressure produced by the venturi condenser and the rise in cooling water temperature due to the condensate and vapour exhaust stream. [1]

External steam input sub-system

The sub-system models the temperature of the external steam input.

3

Methodology for developing the Real-time Simulator

OVERVIEW

This chapter provides an explanation of the methodology used for developing the real-time simulator. This development was separated into two parts: the development of the real-time simulator model and the development of the SCADA control system. It begins by briefly introducing the software used, defines the specifications of the simulator and then describes the development procedure.

3.1 Software tools

Three software packages were used in developing the real-time simulator model. They were Simulink, its associated Real-time Workshop and the Microsoft Visual C++ 5.0 compiler.

The Simulink software package is provided by Mathworks[8] (Natick, Massachusetts) as a graphical environment for the Matlab software package. Using Simulink blocks, the process engineers can convert any M-files made in Matlab into Simulink and provide a graphical representation of the Simulation.

The Real-time Workshop is an additional package that can convert a Simulink model into C code and then use a compiler such as Microsoft Visual C to compile the generated code into a standalone application. The application can execute in real-time with temporal resolutions ranging from microseconds to hundredths of a second. A pseudo-real time template was developed at Massey University to handle tempered resolutions of hundredths to hundreds of seconds.

The Fix32 SCADA package was used as the real-time simulator SCADA control system.

3.2 Simulator Model Specifications

In its training role, the real-time simulator must match the real plant as closely as possible in order to give process engineers and operators a better understanding of the characteristics of the evaporator. This includes the development of a better graphical man-machine interface.

The real-time simulator must correctly represent the existing M-file model. The M-files must be converted into Simulink accurately and the steady state initial values must be carefully selected from the existing M-file model.

In order to gain better responses (i.e. closer to the responses of the real plant) to operator actions, some improvement should be applied to the real-time simulator. This includes modifications made to some of the differential equations and adjustments made to the steady state values and time constants.

3.3 Methodology

The real-time simulator consists of control screens and a Simulink model. The development of the control screens includes two parts: drawing graphical man-machine interfaces and building the database.

Three steps were employed in developing the Simulink model: converting the existing model into a Simulink model, testing the Simulink model and compiling the Simulink model into a standalone application running along side Fix32.

The control screens were developed using the Fix32 SCADA package. Fix32 provides the "Draw" environment that allows development of graphical man-machine interfaces. This was used to build control screens similar to that used in industry.

The database for the simulation was developed using the Fix32 "Database builder". Input and output blocks were created and configured to match the variables being sent to and from the Simulink simulation. The tagnames of these blocks were used to match Simulink variables with the blocks in the database.

The Simulink model was converted by choosing Simulink blocks to perform the same actions as the m-file commands. For example the "Function" blocks were used to perform the calculation functions of each m-file, the "Relational operator" blocks were used to convert the "greater", "less" or "equal" commands in each m-file.

In each m-file, groups of commands and equations were used to calculate different functions. Depending on the number of commands and equations and the relationship between each particular function, one or more groups of these commands and equations were converted into one Simulink sub-system. For example, the group of commands and equations for calculation of the product flowrate through the effect 1 distribution plate were converted into "CalcQd1" Simulink sub-system. Each m-file was converted into one Simulink sub-model that included a number of sub-systems. The Falling-film Evaporator Simulink model was then completed by connecting all the sub-models together.

After the Simulink model was completed, initial values of the time constants and state parameters were obtained from the trials data of the existing m-file model, some needed to be adjusted.

After defining the initial values of time constants and state parameters, the black box testing methodology was employed to test the model in order to gain the initial values of input and output variables. This was done by setting all the inputs to their steady state values and running the simulation until the outputs had reached steady state. This allows the simulator to be started at steady state each time.

After the test, the Real-Time Workshop (RTW) software from the Mathworks was used to convert the Simulink model into C code. This was then compiled into a stand-alone application. As part of this process, C code files were included to allow information to be passed between the stand-alone application and the Fix32 database using the Easy Database Access (EDA) code library from Intellution.

Finally, the compiled real-time simulator is connected with the control screens and both of them are tested together. This involved tests to make sure that information was being passed correctly as well as steady state tests to ensure that the model was correctly responding to inputs from the control screens.

4

Real-time Simulator Modifications

OVERVIEW

This chapter describes all the changes made to convert the existing model to Simulink, create the links to the control screens, improve simulation accuracy and robustness as well as improve the design and performance of the control screens. The full real-time simulator will be described later in chapter 5.

4.1 Simulink Model Modifications

In the existing m-file model some differential equations did not accurately represent the evaporator process. For example the calculation of the outlet temperature of preheater 1 and preheater 2. Also, some corrections have been made such as the calculation of the mass of condensate produced in the first preheater shell per residence time. These will affect the settings of the model parameters and the simulation results. All the other simplifications or mistakes were corrected during development of the Simulink model.

In order to make the Simulink model simpler and clearer, all the constants and the system initial conditions were put into the initial condition sub-model. This makes the constants and system initial conditions easier to maintain.

The "FromFix" driver and "ToFix" driver are also introduced into the Simulink model. These drivers enable the Simulink model to communicate with the control screens. Inputs from Fix32 entered the simulation via the "FromFix" block and the converse for the "ToFix" block.

All these changes are detailed in the following sections.

4.1.1 Preheater Sub-model modification

Two major modifications were made to the preheater sub-model: a new differential equation was used to represent the outlet temperature of the preheater, and the correction of the differential equation for the mass of condensate produced in the first preheater shell per residence time.

Changes made to the outlet temperature of the preheater

The equation (4.1) listed below is a discrete first order equation and is assumed to represent the dynamic relationship of the preheater output temperature in the existing m-file model (T_{ph}).

$$T_{ph}(z) = \left(\frac{1-\eta_{ph}}{1-\eta_{ph} z^{-1}} \right) \overline{T}_{ph}(z) \qquad (4.1)$$

Where $\overline{T}_{ph}$ is the steady state temperature and $\eta_{ph}<1$.

The term η_{ph} is a function of the system time constant, $\tau_{c(ph)}$

$$\eta_{ph} = e^{-\left(t_s / \tau_{c(ph)}\right)}$$

Where t_s is the sampling time.

In equation (4.1) $\overline{T}_{ph}(z)$ is the steady state representation for the preheater output temperature. In this equation the distance along the preheater tube and the time of the liquid through the preheater tube are not being considered as system variables. Also the liquid velocity is not being considered. For these reasons a first order dynamic was added to the equation used in the existing m-file model to achieve the right type of response.

The steady state temperature for the first preheater, $\overline{T}_{ph1}$, is

$$\overline{T}_{ph1} = T_{e3} - \left(T_{e3} - T_0 + \frac{U_{lossph1} A_{sph1} (T_{e3} - T_a)}{\rho_{ph1} c_{ph} Q_0} \right) e^{\frac{-U_{ph1} A_{ph}}{\rho_{ph1} c_{ph} Q_0}} \tag{4.2}$$

and for preheater 2:

$$\overline{T}_{ph2} = T_s - \left(T_s - T_{ph1} + \frac{U_{lossph2} A_{sph2} (T_s - T_a)}{\rho_{ph2} c_{ph} Q_0} \right) e^{\frac{-U_{ph2} A_{ph}}{\rho_{ph2} c_{ph} Q_0}} \tag{4.3}$$

In order to get a better mathematical description of the preheater output temperature, a new differential equation was introduced to the Simulink model to replace the discrete first order equation. This equation was developed by making energy balances around infinitesimal cross sections of the preheater tubes. The temperature of the liquid in the tubes $T(x,t)$ varies with distance along the preheater tube and time. The following partial differential equation is produced for the temperature of the liquid in the preheater tube. [2]

$$\frac{\partial T(x,t)}{\partial t} + v(t)\frac{\partial T(x,t)}{\partial x} = \frac{h_0 A_c}{\rho C_p V_c}(T_e(t) - T(x,t)) \tag{4.4}$$

The affect of the liquid velocity on the heat transfer coefficient was also considered. This equation was solved by linearisation and integral transformation in the Laplace domain. The linearised partial differential equationis given by the following.

$$\frac{\partial T(x,t)}{\partial t}+[\frac{\partial T(x,t)}{\partial x}]^0 v(t)+v^0\frac{\partial T(x,t)}{\partial x}=\frac{h_0 A_c}{\rho C_p V_c}(T_e(t)-T(x,t)) \quad (4.5)$$

$$[\frac{\partial T(x,t)}{\partial x}]^0=\frac{1}{v^0\tau_{Tc}}[T_e^{\,0}-T^0]e^{-\frac{x}{v^0\tau_{Tc}}} \quad (4.6)$$

Where the time constant is given by:

$$\tau_{Tc}=\frac{\rho_c C_p V_c}{h_o A_c}$$

The solution of this equation is given by the following transfer function.

$$T_2(s)=-\frac{\tau_c(T_e^0-T_1^0)e^{\left(\frac{-\tau_c}{\tau_{T_c}}\right)}}{v^0\tau_{T_c}}\frac{\left[1-e^{(-\tau_c s)}\right]}{\tau_c s}v(s)+\frac{1}{\tau_{T_c}s+1}\left[1-e^{\left(\frac{-\tau_c}{\tau_{T_c}}\right)}e^{(-\tau_c s)}\right]T_e(s)+e^{\left(\frac{-\tau_c}{\tau_{T_c}}\right)}e^{(-\tau_c s)}T_1(s) \quad (4.7)$$

This model can be extended to include the effect of fluid velocity on the heat transfer coefficient. The following relationship is assumed for the heat transfer coefficient.

$$h_0=h_0^0 v^b \quad (4.8)$$

The substitution of this into the partial differential equation produces the following transfer function for the outlet preheater temperature.

$$T_2(s) = (bv(s)^b - 1)\frac{\tau_c (T_e^0 - T_1^0) e^{\left(\frac{-\tau_c}{\tau_{T_c}}\right)}}{v^0 \tau_{T_c}} \frac{\left[1 - e^{(-\tau_c s)}\right]}{\tau_c s} v(s) + \frac{1}{\tau_{T_c} s + 1}\left[1 - e^{\left(\frac{-\tau_c}{\tau_{T_c}}\right)} e^{(-\tau_c s)}\right] T_e(s) + e^{\left(\frac{-\tau_c}{\tau_{T_c}}\right)} e^{(-\tau_c s)} T_1(s)$$

(4.9)

This transfer function was used in the Simulink model to replace the discrete first order function. An example of the preheater 1 output temperature Simulink block is shown in figure 4-1. The left side performs difference calculations of the transfer function and provides three system inputs and system constants.

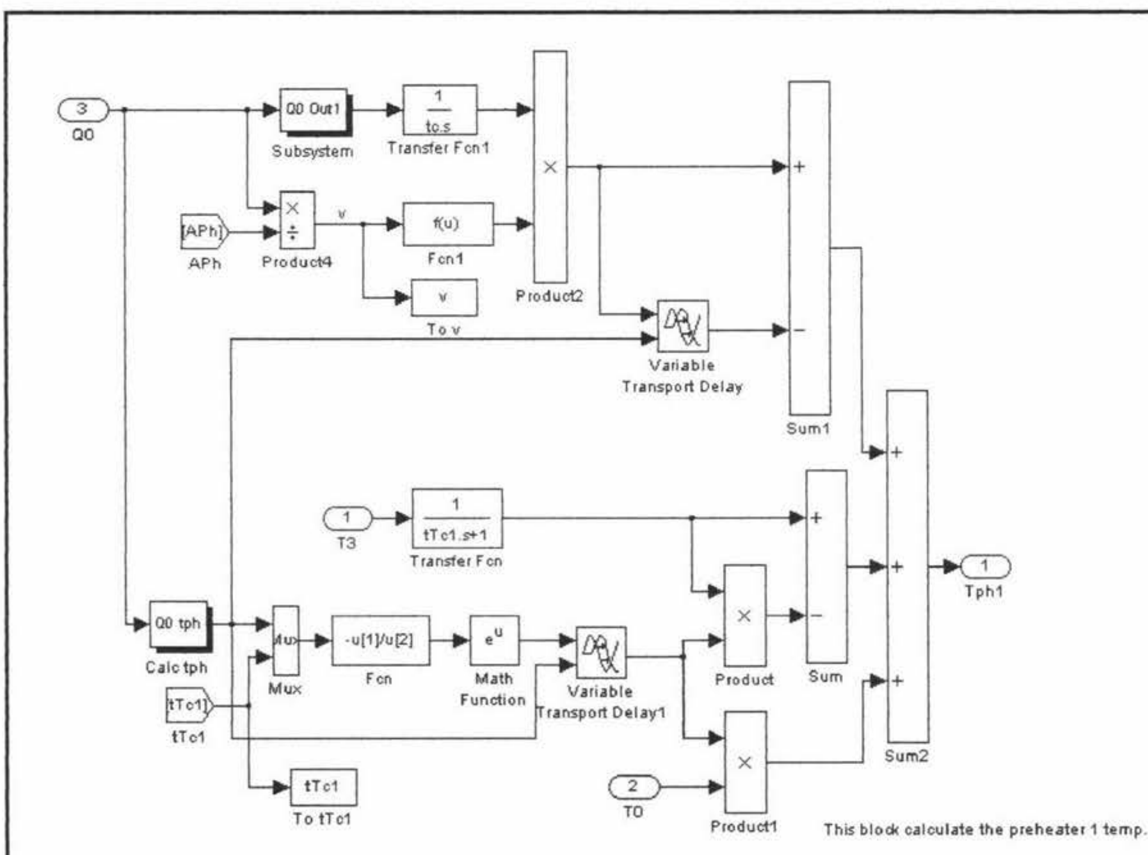

Figure 4-1 Preheater 1 outlet temperature

Changes made to the calculation of mass of condensate produced in the preheater 1 shell

The old model equation (4.10) that defines the mass of condensate produced in the first preheater shell per residence time does not correctly include the influence of the heat losses. These are considered significant so a better version derived in the following paragraphs.

$$\frac{dM_{cPh1}}{dt} = \frac{q_{Ph1}}{r_{Ph1}} - \frac{q_{Ph1d}}{r_{Ph1d}} \qquad (4.10)$$

Where q_{Ph1} is heat transfer in preheater 1

$qloss_{Ph1}$ is heat loss into surrounding

q_{Ph1d} is heat transfer in preheater 1 with time delay

r_{Ph1} is latent heat of vaporisation

r_{Ph1d} is latent heat of vaporisation with time delay

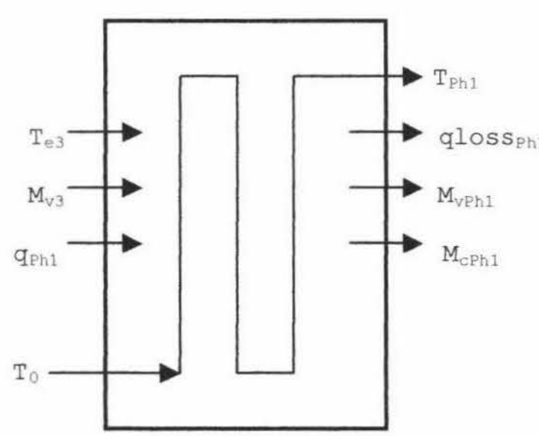

Figure 4-2 Preheater 1

In the preheater 1 sub-system the input liquid is pumped from the feed tank and the output liquid into preheater 2. The heating vapour is from the effect 3 evaporation tubes. Figure 4-2 shows the preheater 1 sub-system. The inputs to the system are: temperature of product leaving the feed tank (T_0), temperature of product in the effect 3 evaporation tube (T_{e3}), heat transfer into preheater 1 (q_{Ph1}) and preheater 1 outlet temperature (T_{Ph1}). The outputs from the system are: mass of vapour produced in the effect 3 evaporation tube (M_{v3}), heat loss in the surrounding ($qloss_{Ph1}$), mass flow of vapour from preheater 1 (m_{vPh1}) and mass of condensate produced in the first preheater shell (M_{cPh1}).

Considering the mass balance over preheater 1, then the mass of vapour into the preheater 1 shell is:

$$M_{v3}(t) = m_{vPh1}(t) + M_{cPh1}(t) \tag{4.11}$$

The transport of vapour from the effect 3 evaporation tube and into preheater 1 has a time delay (τ_e). Considering this time delay and assuming constant mass flow of vapour from preheater 1, then the mass of vapour into the preheater 1 shell is:

$$M_{v3}(t-\tau_e) = m_{vPh1}(t) + M_{cPh1}(t-\tau_e) \tag{4.12}$$

subtracting equation (4.11) and (4.12):

$$M_{cPh1}(t) - M_{cPh1}(t-\tau_e) = M_{v3}(t) - M_{v3}(t-\tau_e) \tag{4.13}$$

as $$\frac{dM_{cPh1}(t)}{dt} = M_{cPh1}(t) - M_{cPh1}(t-\tau_e) \tag{4.14}$$

then $$\frac{dM_{cPh1}(t)}{dt} = M_{v3}(t) - M_{v3}(t-\tau_e) \tag{4.15}$$

By performing an energy balance over the preheater 1 sub-system, the mass of vapour into the preheater 1 shell is:

$$M_{v3}(t)r_{Ph1}(t) = q_{Ph1}(t) + qloss_{Ph1}(t) \qquad (4.16)$$

to give
$$M_{v3}(t) = \frac{q_{Ph1}(t) + qloss_{Ph1}(t)}{r_{Ph1}(t)} \qquad (4.17)$$

The substitution of equation (4.17) into equation (4.15) produces the following differential equation for the mass of condensate produced in the first preheater shell per residence time.

$$\frac{dM_{cPh1}(t)}{dt} = \frac{q_{Ph1}(t) + qloss_{Ph1}(t)}{r_{Ph1}(t)} - \frac{q_{Ph1}(t-\tau_e) + qloss_{Ph1}(t-\tau_e)}{r_{Ph1}(t-\tau_e)} \qquad (4.18)$$

then
$$\frac{dM_{cPh1}}{dt} = \frac{q_{Ph1} + qloss_{Ph1}}{r_{Ph1}} - \frac{q_{Ph1d} + qloss_{Ph1d}}{r_{Ph1d}} \qquad (4.19)$$

Where $qloss_{Ph1d}$ is heat loss to the surroundings with time delay

As can be seen by comparing equation (4.19) and (4.10), equation (4.10) contains the missing term, $qloss_{Ph1d}$. The corrected equation (4.19) is used in the Simulink model.

Other changes made to the preheater sub-model

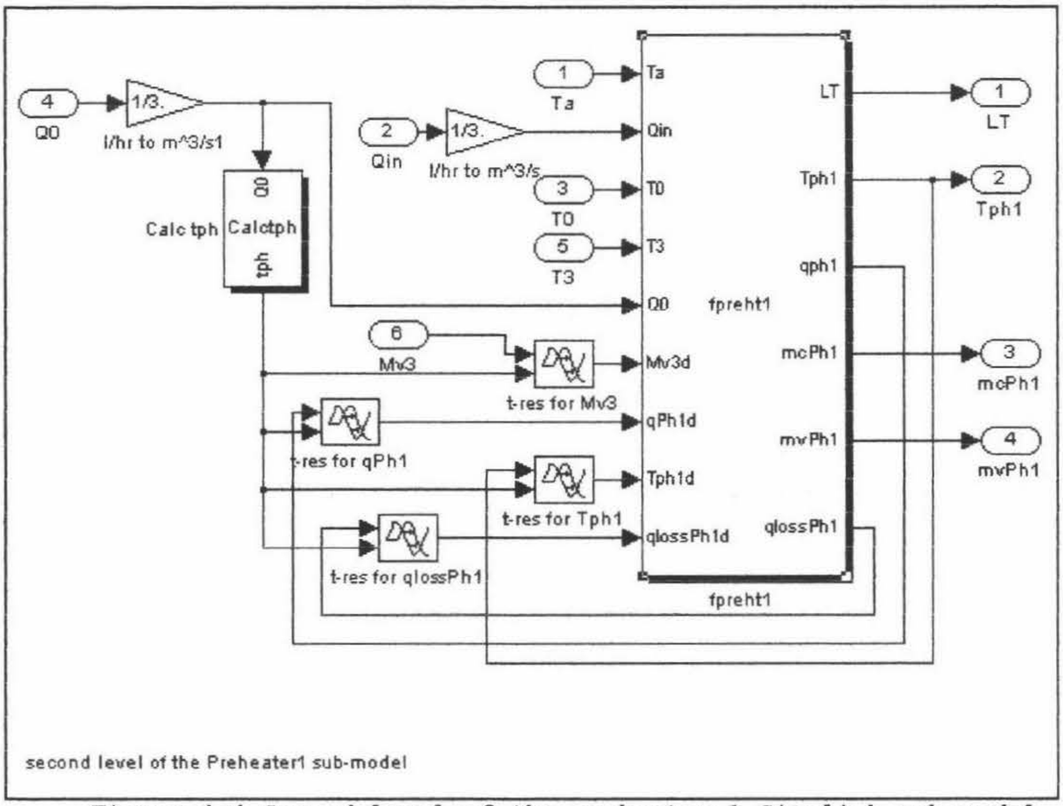

Figure 4-4 Second level of the preheater 1 Simulink sub-model

- An additional system input, $qloss_{Ph1}$, is provided to the preheater 1 Simulink sub-model. Figure 4-4 shows the preheater 1 Simulink sub-model.

- As the system input T_a (ambient temperature) for the preheater 2 sub-system is not in use, this input was deleted from the preheater 2 Simulink sub-model.

- The calculations of liquid density, ρ_0, and heat loss to the surrounding, $qloss_{Ph2}$, are not necessary. The preheater 2 Simulink sub-model does not provide these calculations.

4.1.2 Initial condition sub-model modification

In order to make the Simulink model simpler and clearer, an additional initial condition sub-model was provided in the evaporator Simulink model. This sub-model includes an "initial inputs" sub-model, a "sub-systems" sub-model and a "constant" sub-model. These sub-models are described below. They contain all the constants and system initial conditions. By collecting all the initial conditions and constants together they can be more easily managed.

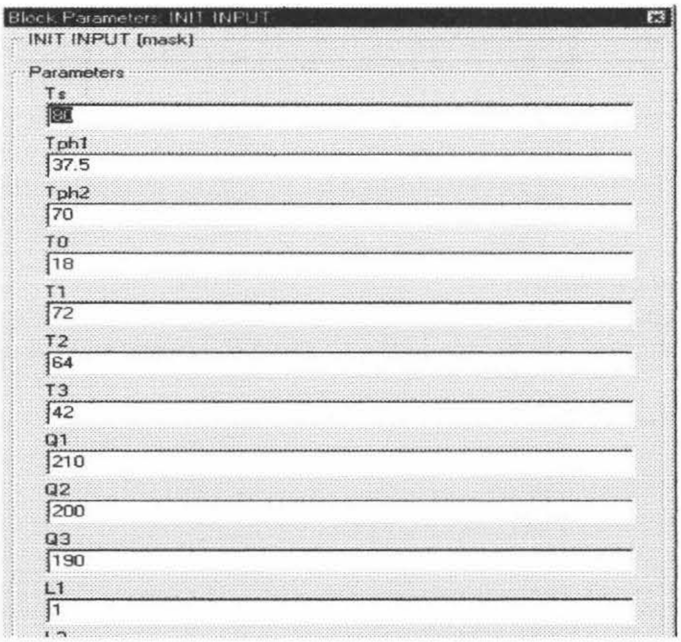

Figure 4-5 an example of initial inputs sub-model mask

- "Initial inputs" sub-systems contain all the initial values used to calculate state derivatives. Each value is easily changed from the block mask. An example of the block mask is shown in figure 4-5.

- "Sub-systems" sub-model contains all the initial calculations for each Simulink sub-model. Figure 4-6 shows an example of "sub-systems" sub-model. In the block each function block performs a difference calculation. Each "From" block inputs each variables value to the "function" block and each "Goto" block outpust the result of the "function" block to the variables.

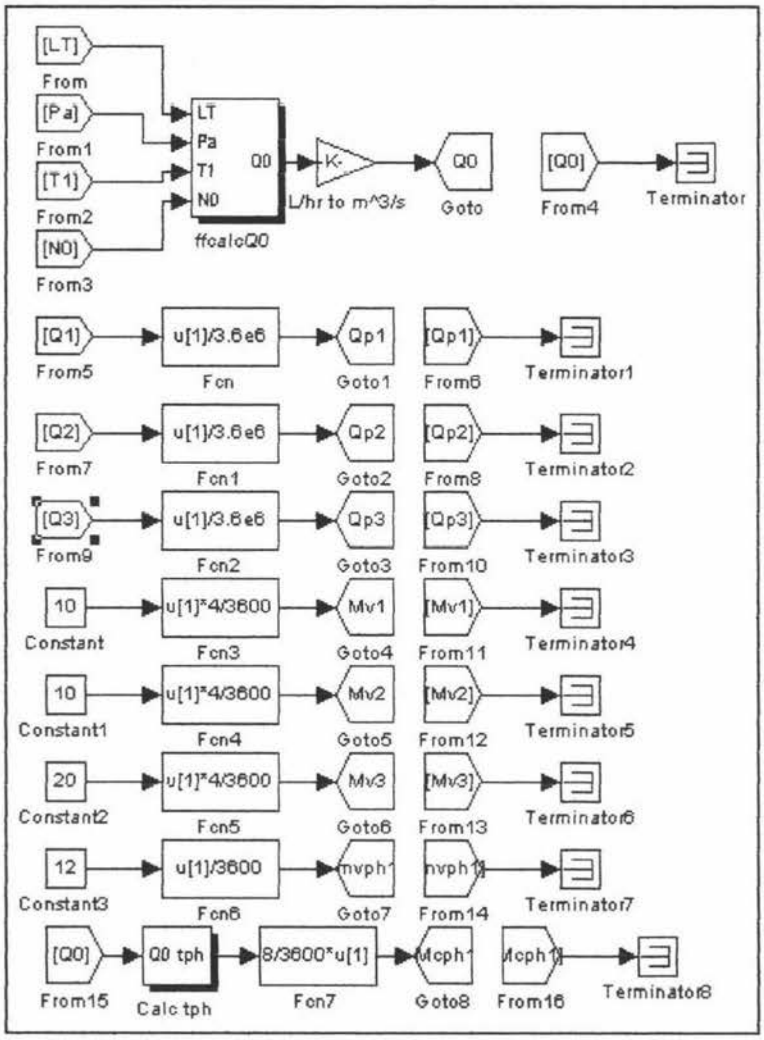

Figure 4-6 Sub-systems sub-model (under mask)

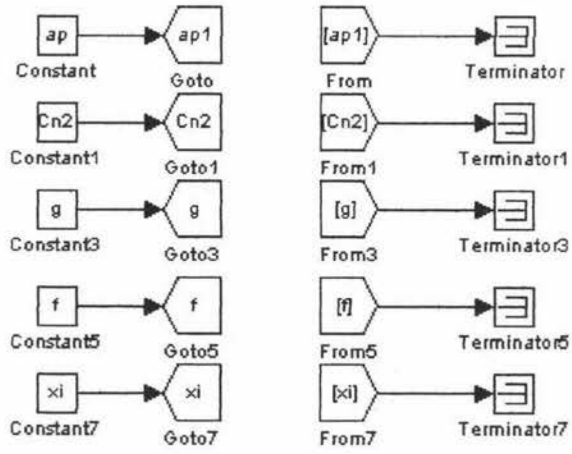

Figure 4-7 Constant sub-model (under mask)

- "Constant" sub-model contains all the system constant values in each Simulink sub-model. It is separated into six sub-blocks that are "effect 1", "effect 2", "effect 3", "preheater 1", "preheater 2" and "venturi condenser". Figure 4-7 shows an example sub-block under its block mask showing the ap1, Cn2, g, f and xi variables. Each "goto" block outputs constant values into the "from" block used in each Simulink sub-model with the same constant name.

4.1.3 Other changes made to the evaporator Simulink model

- In order to communicate with the control screen database in Fix32, the "ToFix" driver, "FromFix" driver and driver control panel [3] were added to the evaporator Simulink model. The "ToFix" driver allows the model to output simulation results to the control screens. The "FromFix" driver allows the model to receive system settings from control screens. The driver control panel allows enabling or disabling of the "ToFix" driver and the "FromFix" driver.

* In the existing m-file model, the unit of feed flowrate (Q_{in}) is changed from l/hr to m^3/s. The conversion value was wrong and would decrease the feed flowrate ten times. The value is changed to $3.6*10^6$.

4.2 SCADA Control System Modifications

The SCADA control system consists of two parts: the Fix32 database and the control screens. The Fix32 database consists of database blocks and chains. The database blocks include all the primary source of real-time process information for the real-time simulator. The control screens are graphic representation for the simulator model which display the simulation results and allow the simulator input parameters to be changed. In this section the discussion of SCADA modifications is separated into two parts, Fix32 database modifications and control screens modifications.

4.2.1 Fix32 database modifications

The simulator Fix32 database was developed using the Fix32 "Database builder" and included database blocks and chains. Inputs and output blocks were created and configured to match the variables being sent to and from the Simulink simulation. Three types of database blocks were used in building the simulator database. AI (analog input) blocks were used to stall all the variable values being sent from the Simulink model such as each effect temperature, liquid level in each effect and flowrate for each effect. Figure 4-8 shows an example AI (analog input) block for the effect 1 outlet flowrate. The variable names were putted into "Tag Name" field of these blocks to match Simulink variables, e.g. the tag name "EFF1FLOW" in the following figure was used to match Effect 1 outlet flowrate. The names contained in "Next Block" were used to connect with other Trend blocks like a chain and could pass the values of these tags into trend blocks.

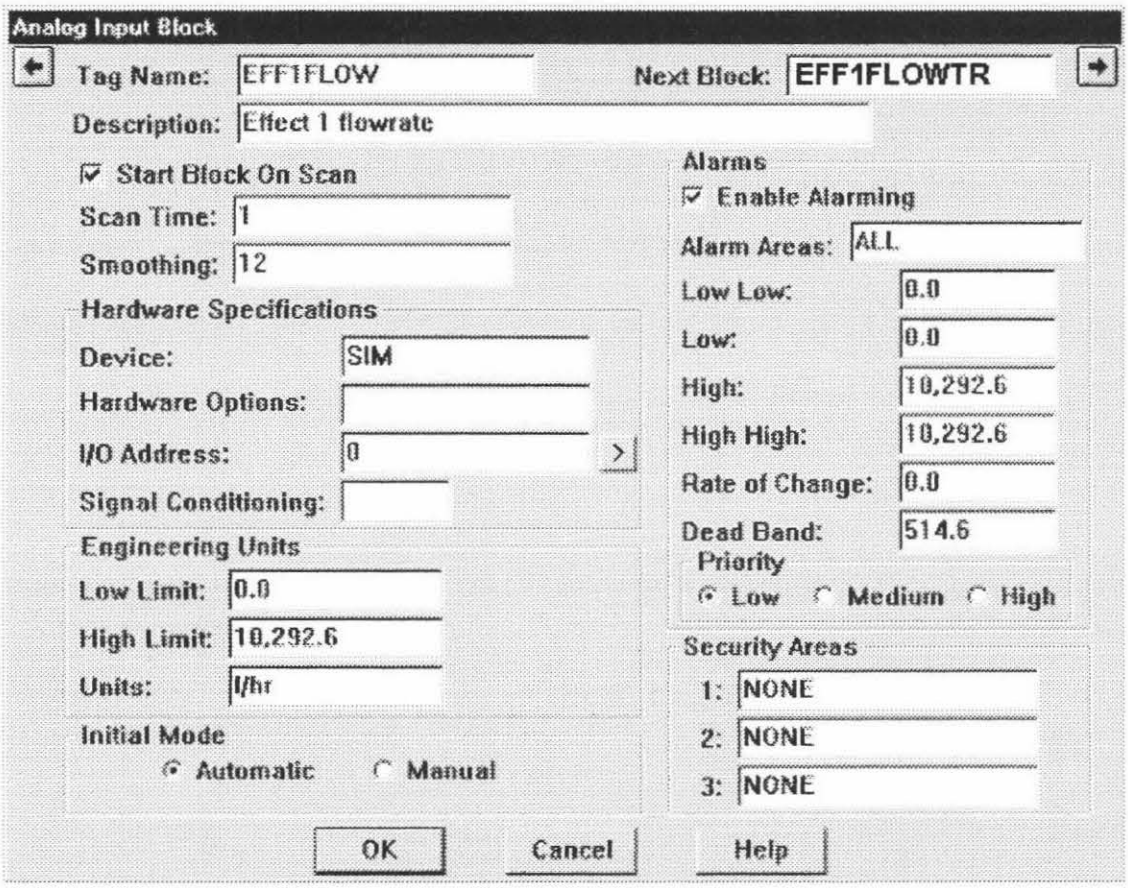

Figure 4-8 The effect 1 outlet flowrate

AO (analog output) blocks used to stall all the variable values being sent to the Simulink model such as pump speed for each effect, liquid infeed temperature and infeed flowrate. Figure 4-9 shows an example of AO block. The same as AI blocks, the names contained in the "Tag Name" field were used to match Simulink variables. The names contained in the "Next Block" field passed values to Trend blocks.

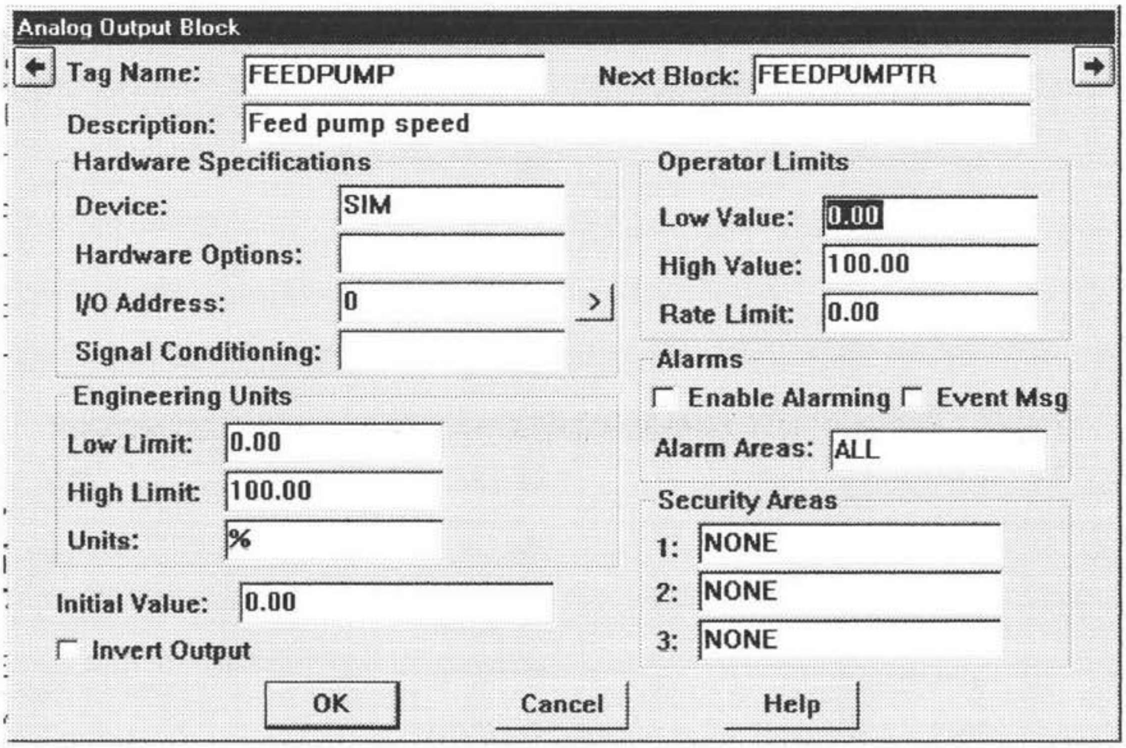

Figure 4-9 AO (analog output) Block for feed pump speed

TR (trend) blocks contain all the variables for trend pages. Figure 4-10 shows an example of a TR block. The names contained in the "Tag Name" field of these blocks were the trend block names and were used in "Next Block" field of each AI and AO block. The names contained in "Input Tag" field were the tag names of variable that need to be trended from each AI and AO block.

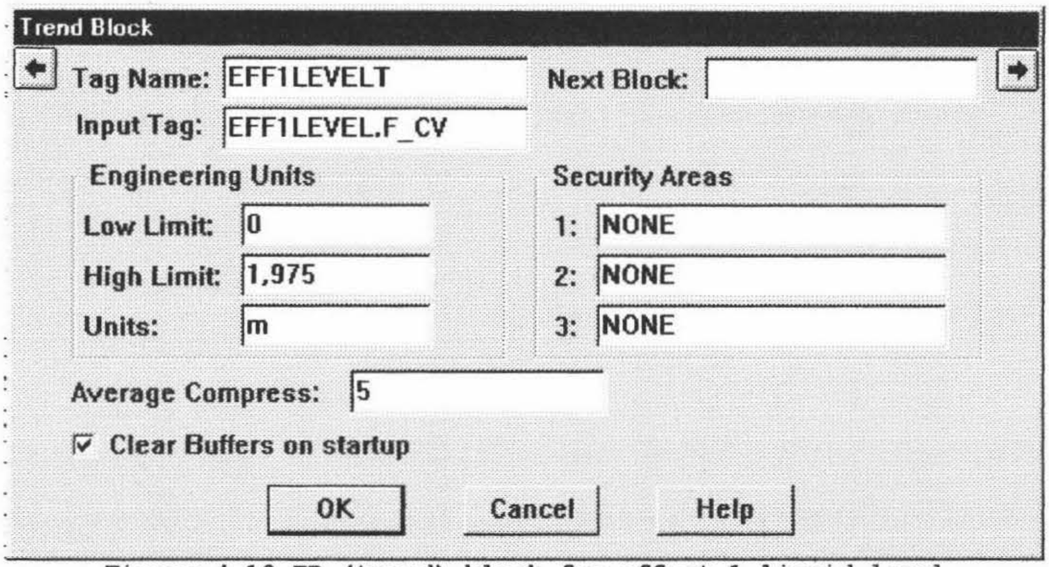

Figure 4-10 TR (trend) block for effect 1 liquid level

4.2.2 Control screens modifications

The control screens are designed for the use of the operators to change the input settings for the model and to display the simulation results. They are desired to match the real plant as closely as possible. For this reason they were redrawn from industrial screens. An example picture is shown in figure 4-11.

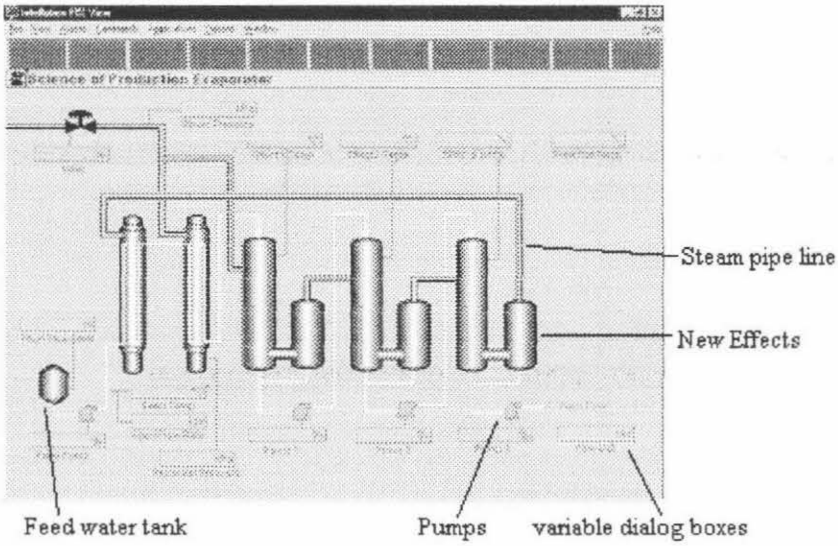

Figure 4-11 An example of picture Evapma_p.odf

The control screens include seven individual pages, e.g. "Evaporator A Overview", "Feed Tank", "Preheater", "Effect1", "Effect 2", "Effect 3", and "Condensor". In each individual page, new pictures of feed water tank, preheaters and effects were used to replace the existing industrial screens. New pictures of steam pipe lines; steam valve and pumps were also used to replace the existing industrial screens.

The variable dialog boxes are used to replace the entire data link in the control screen. They can be seen from the top and the bottom of the picture shown in figure 4-12. The variable dialog boxes for the pump speed and valve position display the values of the pump speed and valve position. They are also used to change the variable settings by double click the dialog boxes. Other variable dialog boxes are designed to display the simulation results. These are stored in the Fix32 database and are also designed as click buttons. Once they have been clicked the trend page will popup into the screen. The following figure shows an example of the trend page.

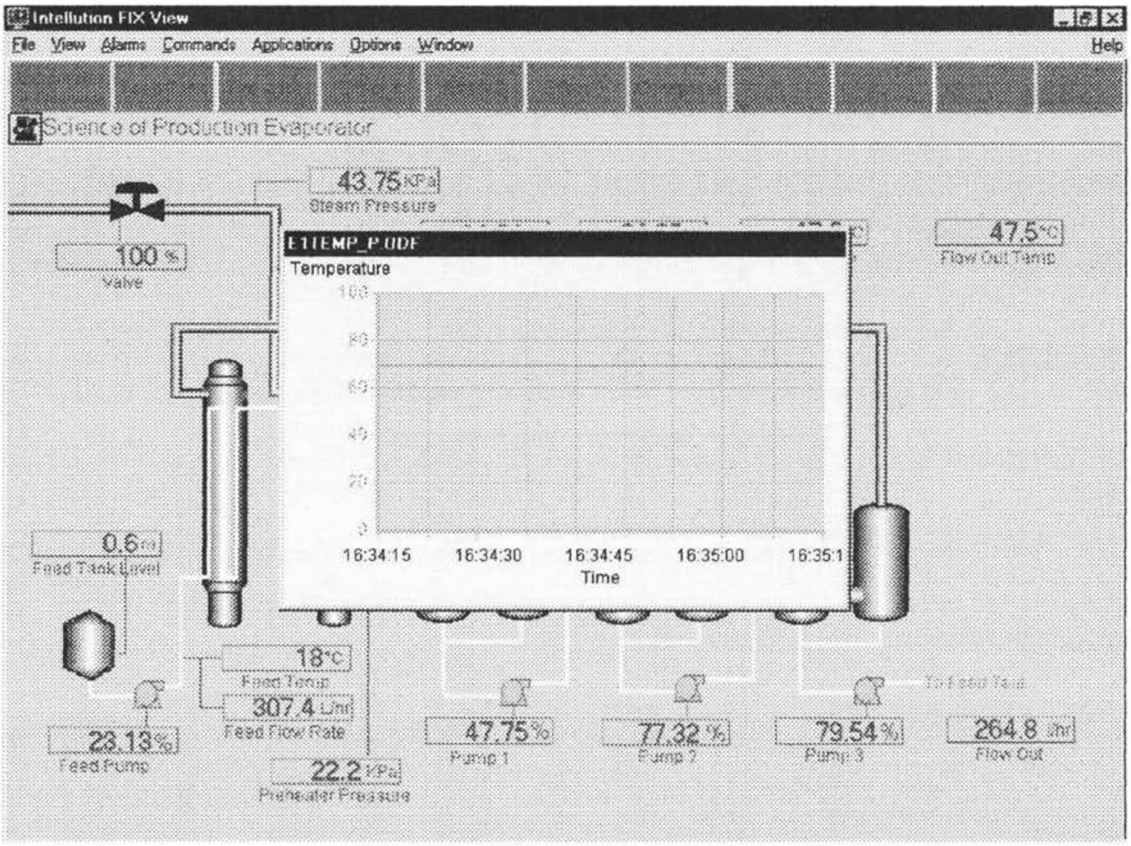

Figure 4-12 the example of trend page

5

Full Real-Time Simulator Description

OVERVIEW

This chapter provides an explanation, with the details, of the full real-time simulator. It includes the description of the Simulink block used to develop the Simulink model, the description of the full Simulink model and the description of the control screen.

5.1 Defining Simulink blocks in the Simulink model

The existing m-file model provided by Nigel Russell[4] is formed by some function files known as m-files. These m-files are programmed in Matlab language. To convert to a graphical representation Simulink model, the m-files must be converted into Simulink blocks.

In the existing m-file model, a discrete first order equation is used to represent the dynamic function of the outlet preheater temperature. A new transfer function was used in this project to replace the discrete first order equation. For this reason the discrete type of Simulink blocks are not used in this Simulink model. Thus only continuous blocks are used making simulation easier.

Like all the variables in the Simulink model, the symbols are used to represent all the constants and the initial condition parameters. For example, symbol 'ap' is used to represent the pump flow characteristic constant. The constant values were input directly into the masks by double clicking each Simulink block that was contained in the constant.mdl Simulink sub-model.

Each Simulink block used to build the Simulink model is discussed in Appendix 4.

5.2 Simulink model description

The Simulink model consisted of the effect sub-models, the preheater sub-model, the venturi condenser sub-model, the initial conditions sub-model and the I/O drivers. These sub-models contain all the differential equations and associated algebraic calculations required for each section of the evaporator. They are connected together and show the flow of information in the process. The evaporator effect sub-model is used as an example and is discussed later in this section. Other sub-models are shown in appendix 5.

There are a number of levels to the evaporator Simulink model *Evap.mdl*. The Simulink block diagrams in the figures on the following pages show the samples of the levels and how the sub-models are connected together.

- The top level (Figure 5-1) shows the main inputs and outputs of the model. It also contains the initial condition sub-model and the I/O drivers. Various inputs can be applied or controllers can be introduced in this level.

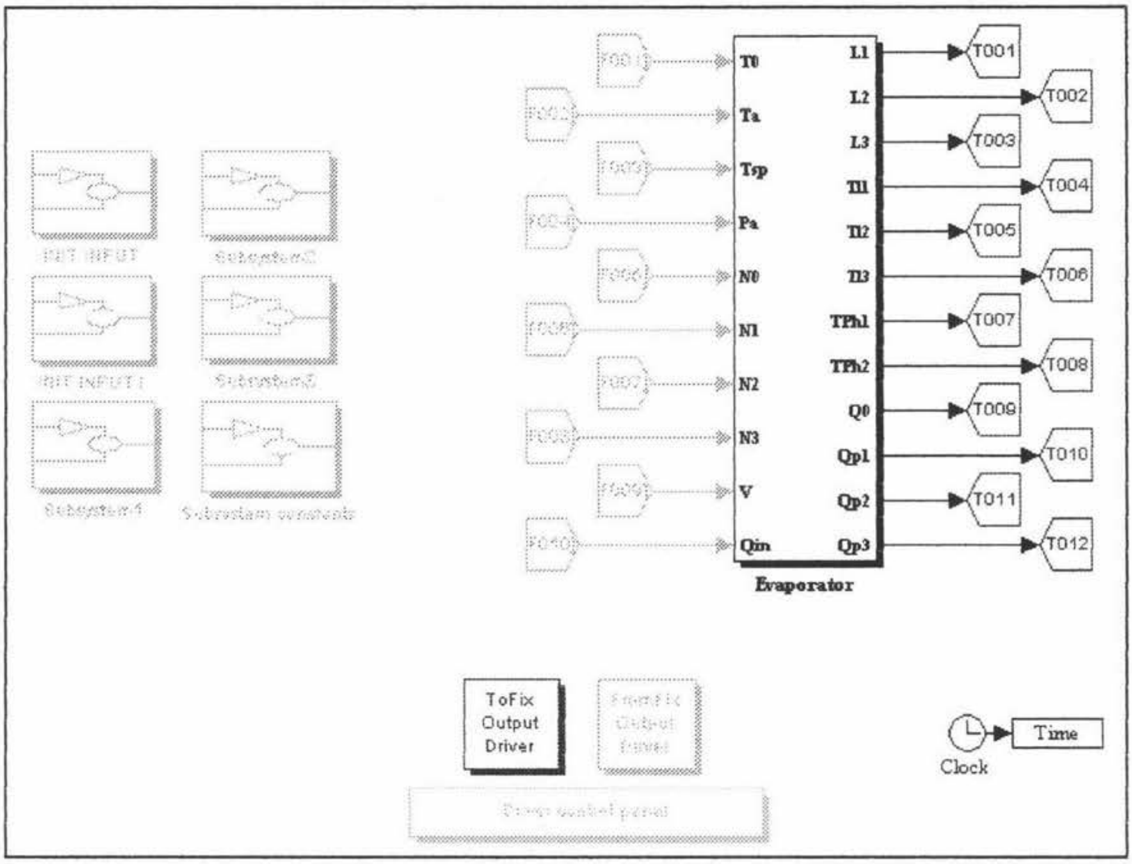

Figure 5-1 Top level of the *Evap.mdl* Simulink model

- The second level (Figure 5-2) shows the preheater, effects and venturi condenser sub-model linked together and the information paths between them. It is where the main structure of the model can be observed.

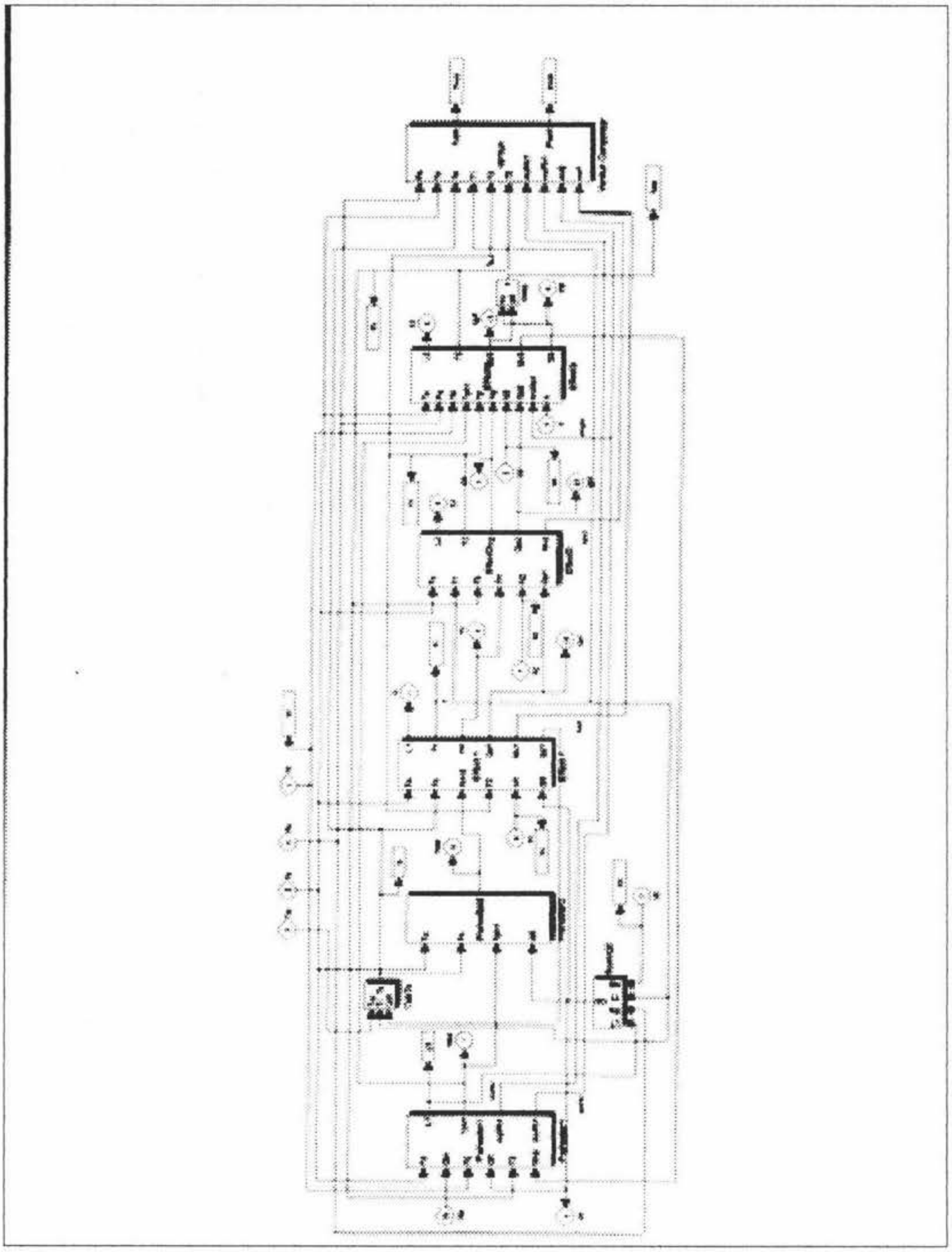

Figure 5-2 the second level of *Evap.mdl* Simulink model

* The third level is where the information is passed into the sub-model from the Simulink environment. An example of this is shown in figure 5-3 for the first effect sub-model.

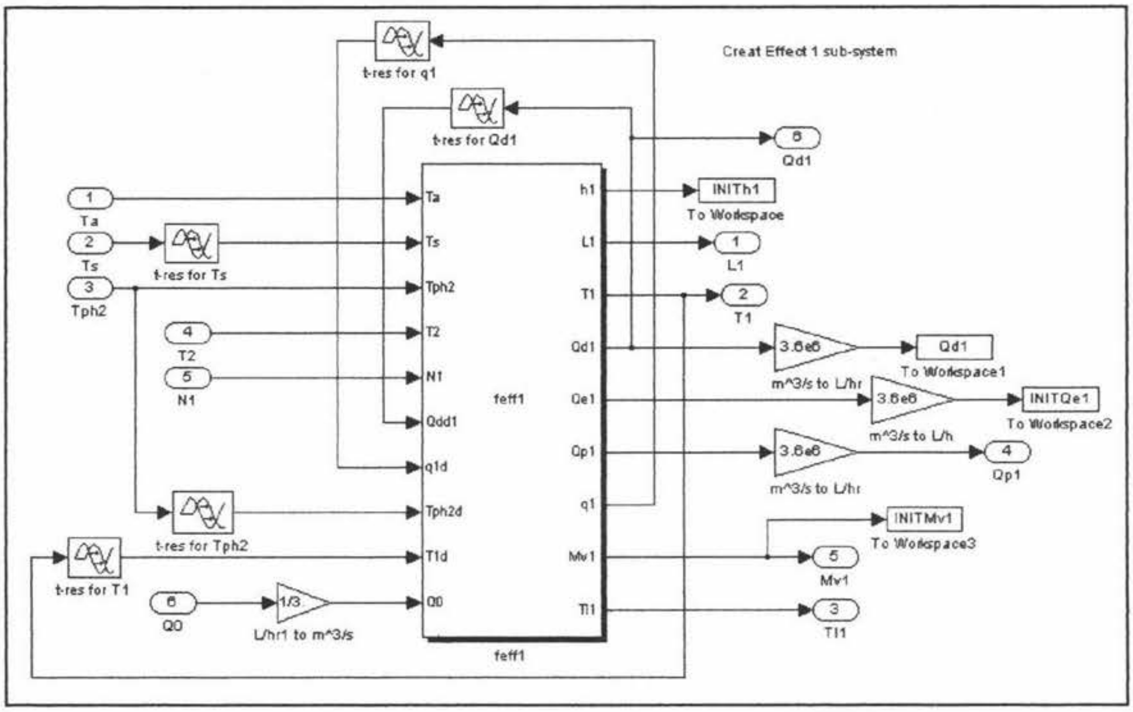

Figure 5-3 An example of the third level of the *Evap.mdl* Simulink model - *Effect 1*

* The lower level is where all the differential equations and associated algebraic calculations are contained. An example of this level is shown in figure 5-4 for the first effect.

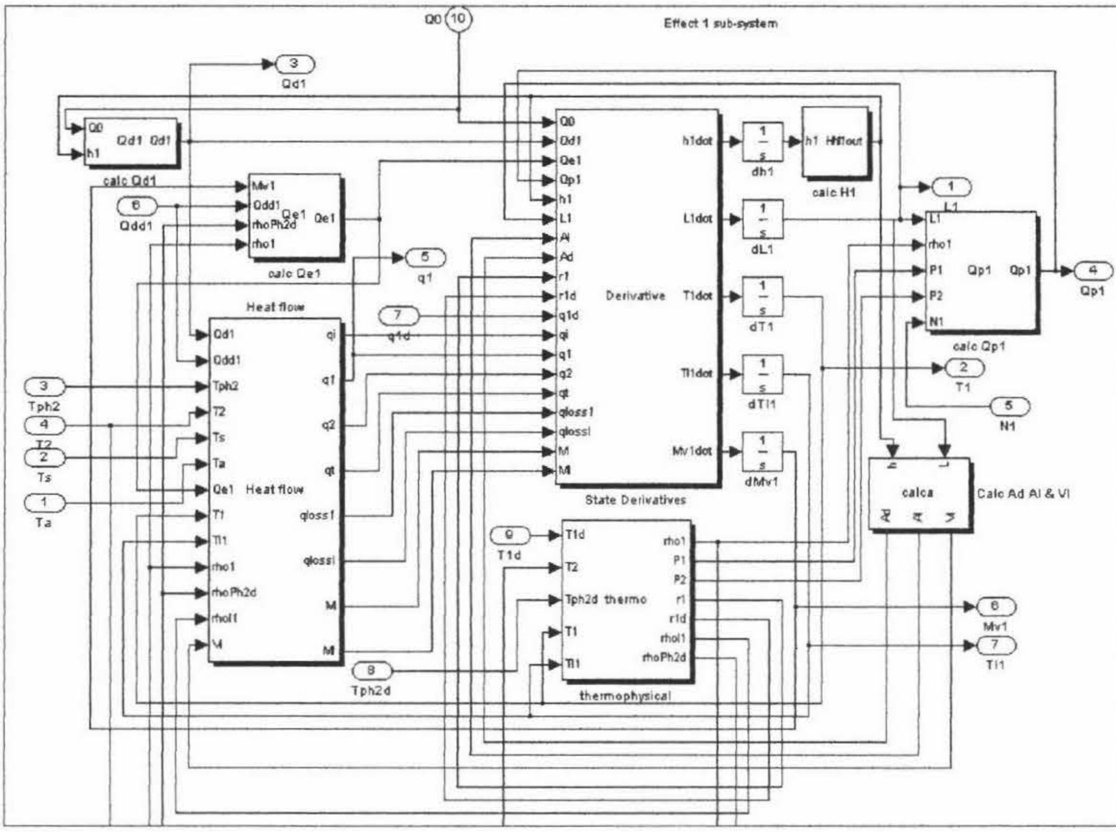

Figure 5-4 an example of the lower level of the *Evap.mdl* Simulink model - *Effect 1*

Before developing each Simulink sub-model, a number of Simulink model files are made to perform additional calculations within the Simulink models. These Simulink model files are used as Simulink blocks within each Simulink sub-model.

These Simulink blocks are converted from the sub-programs in the dynamic model. For example in these sub-programs, the calculations of cross-section area of distribution plate, level and volume of liquid in the Effect were the same for the Effect 1 and Effect 2, but were different for Effect 3. for this reason calca.m was separated into two Simulink block diagrams, calca.mdl and calcaEff3.mdl. The calca.mdl block was used in effect 1 and effect 2 sub-model and the calcaEff3.mdl block was used in effect 3 sub-model. The calctp.m was also separated into two Simulink block diagrams, which were calctp.mdl and calctpEff3.mdl. The calctp.mdl block was used to calculate the approximate transport between Effect 1&2 and between Effect 2&3 in effect 1 and effect 2 sub-models and calctpEff3.mdl was used to calculate the approx. transport delay between Effect 3 to output in effect 3 sub-model.

The Simulink block diagrams of these Simulink model files are shown in appendix 5. These files include:

- calca.mdl - This block includes the equations of calculation of the cross-sectional area on the distribution plate, area of liquid surface of the level at base of the effect and volume of liquid in the effect for effect 1 and 2.

- calcaEff3.mdl - This block includes the equations of calculation of the cross-sectional area on the distribution plate, area of liquid surface of the level at base of effect and volume of liquid in the effect level for effect 3.

- ffcalcq0.mdl - This block includes the equations of calculation of the feed flowrate of the evaporator (Q_0) based on current plant conditions. The convert.mdl Simulink block is used in this block to perform calculation of saturation pressure. The densities used to calculate the pressure are approximate densities.

- calctp.mdl - This block calculates the approximate transport delay between effect 1 and effect 2, between effect 2 and effect 3 for effect 1 and 2.

- calctpEff3.mdl - This block calculates the approximate transport delay from effect 3 to output for effect 3.
- calctph.mdl - This block includes the equation of calculation of the residence time for the liquid through the preheaters.
- convert.mdl - This block converts the temperature value into values of a related thermophysical property, such as saturation pressure, enthalpy or density. It also converts the pressure value into the value of temperature.
- calcTs.mdl - This block is used to estimate the external steam temperature (T_s). The external steam temperature is technically an input variable, however, it is calculated by the model as function of the steam controller setpoint. The PID controller in this block is used to adjust the steam valve position to regulate the steam pressure in the shell of the first effect.

Evaporator effect sub-model

In an industrial production evaporator, each effect is composed of a distribution plate sub-system, evaporation tube sub-system, product transport sub-system and evaporation tube energy sub-system. The Simulink effect sub-model includes all the differential equations and associated algebraic calculations that model these sub-systems. Some changes are also made to perform better simulation results.

The evaporator effect Simulink sub-model is composed of three sub-models, effect1 sub-model, effect 2 sub-models and effect 3 sub-model. Most of the equations used to model these three effects are the same with different input and output variables. This meant that these three sub-models have the same structures. Some differences were made while developing each effect sub-model and are discussed later in this section.

Effect 1 Simulink sub-model

Effect 1 Simulink sub-model contains three levels. The first level of the sub-model is shown in figure 5-5. This level of the sub-model is used in the second level of *evap.mdl* and shows all the inputs from the outside of the sub-model and outputs of the sub-model. There are six inputs and six outputs as can be seen from the figure.

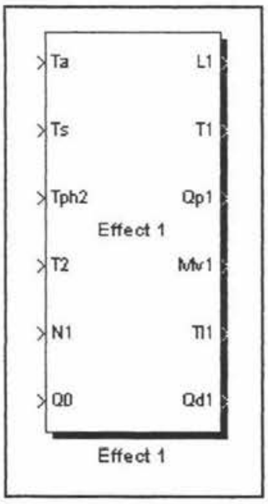

Figure 5-5 The first level of the effect 1 sub-model

In the effect 1 m-file (feff1.m) there are ten input variables and nine output variables that are used to model effect 1. These inputs and outputs are applied in the second level of the effect 1 sub-model, which are shown in figure 5-2. As can be seen from the figure the sub-model inputs Qdd1, q1d and T1d are connected with the sub-model outputs Qd1, q1 and T1 through the delay block. Other two inputs Ts and Tph2d are connected with the inputs of Ts and Tph2 through the delay blocks. All the initial conditions of these five inputs are defined in the delay block.

The main structure of the effect 1 sub-model is observed in the third level, which is shown in figure 5-4. All the differential equations and algebraic calculations are contained in this level and are separated into several masked sub-systems. Each sub-system provides different calculations. The state derivatives sub-system is used as a sample-masked sub-system and is shown in figure 5-6. Other masked sub-systems are shown in appendix 5.

- *Calc Qd1* includes the calculations of the product flowrate through the effect 1 distribution plate (Qd1).
- *Calc Qe1* includes the calculations of the product flowrate from the evaporation tube in the effect 1 (Qe1).
- *Calc Qp1* includes the calculations of the product flowrate out of the effect 1 (Qp1).
- *Calc Ad Al & Vl* includes the calculations of the area of liquid on the distribution plate (Ad), volume (Vl) and the surface area of liquid level at the base of the effect 1 (Al). The calca.mdl file is used to perform these calculations.
- *Calc h1* includes the calculations that used to clip the height of liquid above the distribution plate in the effect 1 (h1).

- *Heat flow* includes the calculation of the mass of liquid in the evaporation tube (M), the calculations of the heat flow in the evaporation tube (i.e. qi, q1, q2, qloss1) and the calculations of the heat flow in the base of the effect 1 (i.e. qt, qlossl, Ml).

- *State derivatives* include the calculations of the state derivatives. The integrator blocks are used outside of this sub-system to provide the outputs of the state variables. All the state variable initial conditions are defined in these integrator blocks.

- *Thermophysical* includes the calculations of the thermophysical properties. The convert.mdl files are used in here as Simulink blocks to convert the temperatures into densities, pressures and latent heats.

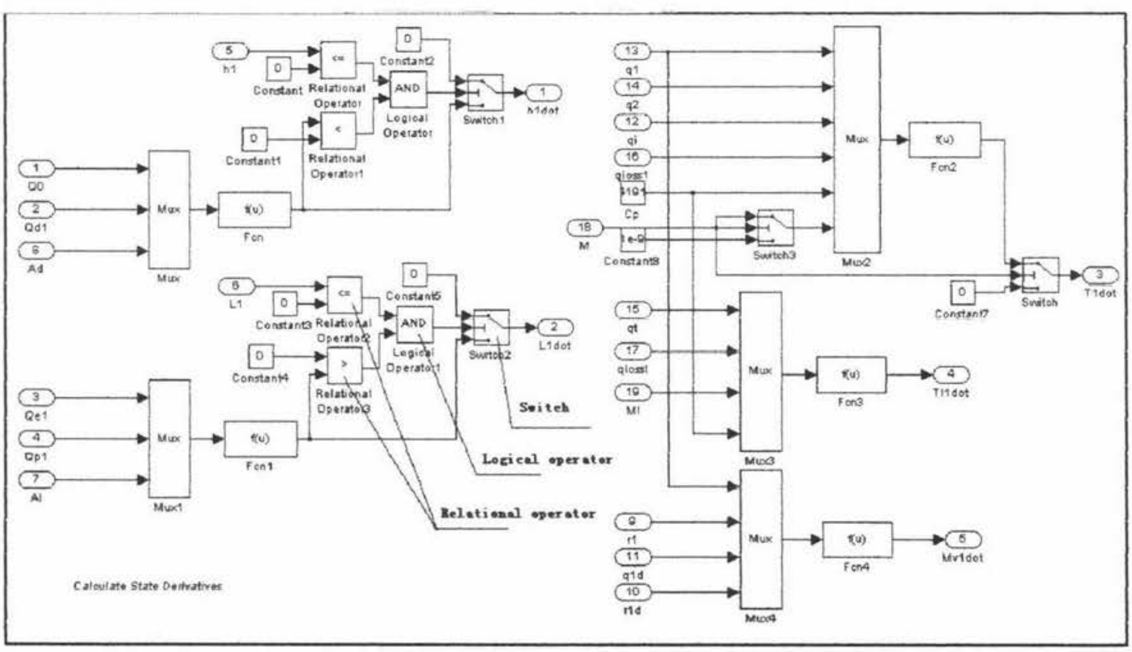

Figure 5-6 An example of the masked sub-system - *state derivatives*

During development of the evaporator Simulink model, the switch block was used with the logical operator block and relational operator block in the Simulink model to replace the 'if..else if..else..' commands that had been programmed in the Matlab m-file. An example of this replacement is shown in figure 5-6. If the input h1 is less than 0 and the output of the function block 'Fcn' is also less than 0. Then the switch block 'Switch 1' will pass the constant value 0 to the output port 'h1dot'. Otherwise, the switch block 'switch 1' will pass the output value of the function block 'Fcn' to the output port 'h1dot'.

Effect 2 Simulink sub-model

As discussed before, the three effect Simulink models have similar structures. The additional masked sub-system in the effect 2 sub-model is *calc tl1*, which is shown in figure 5-7. This masked sub-system includes the calculations of the temperature of product in the effect 1 balance tank. The heat loss from the input flow is considered in this sub-system. In the sub-system the input temperature of product in the effect 1 level (Tl1) minus the heat loss. The result of this calculation is output into the effect 2 sub-model and used as the temperature of product in the effect 1 level (Tl1).

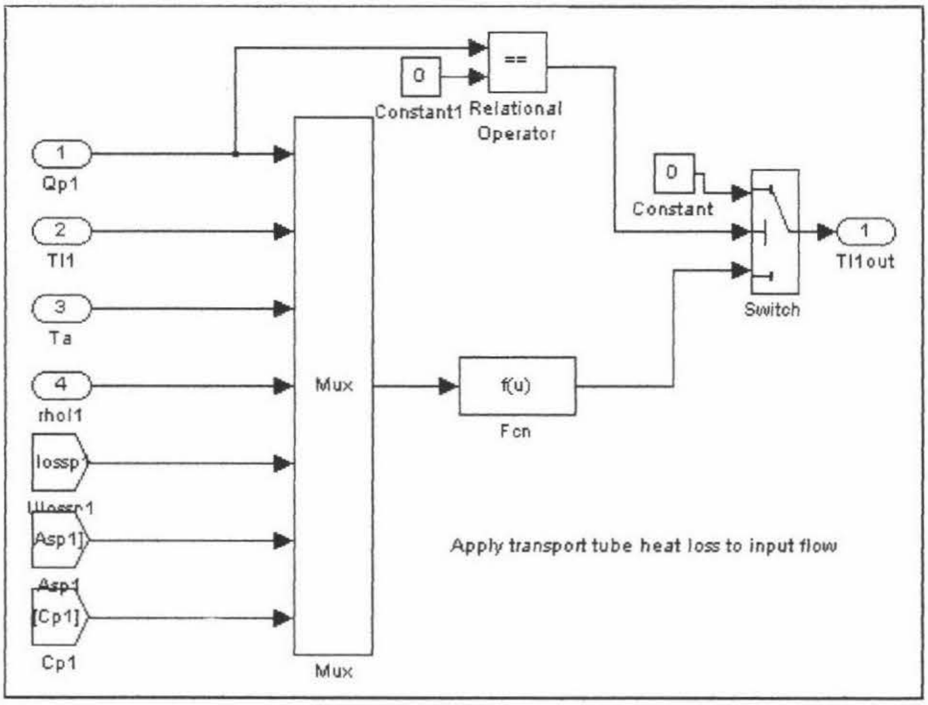

Figure 5-7 The additional masked sub-system - *calc Tl1*

Effect 3 Simulink sub-model

The effect 3 sub-model has a masked sub-system, *calc Tl2,* similar to that in the effect 2 sub-model.

The other differences made in the effect 3 sub-model are the heat lost to preheater 1 and the heat lost to the venturi condenser. They are included in the sub-model. These calculations are shown in the right side of figure 5-8.

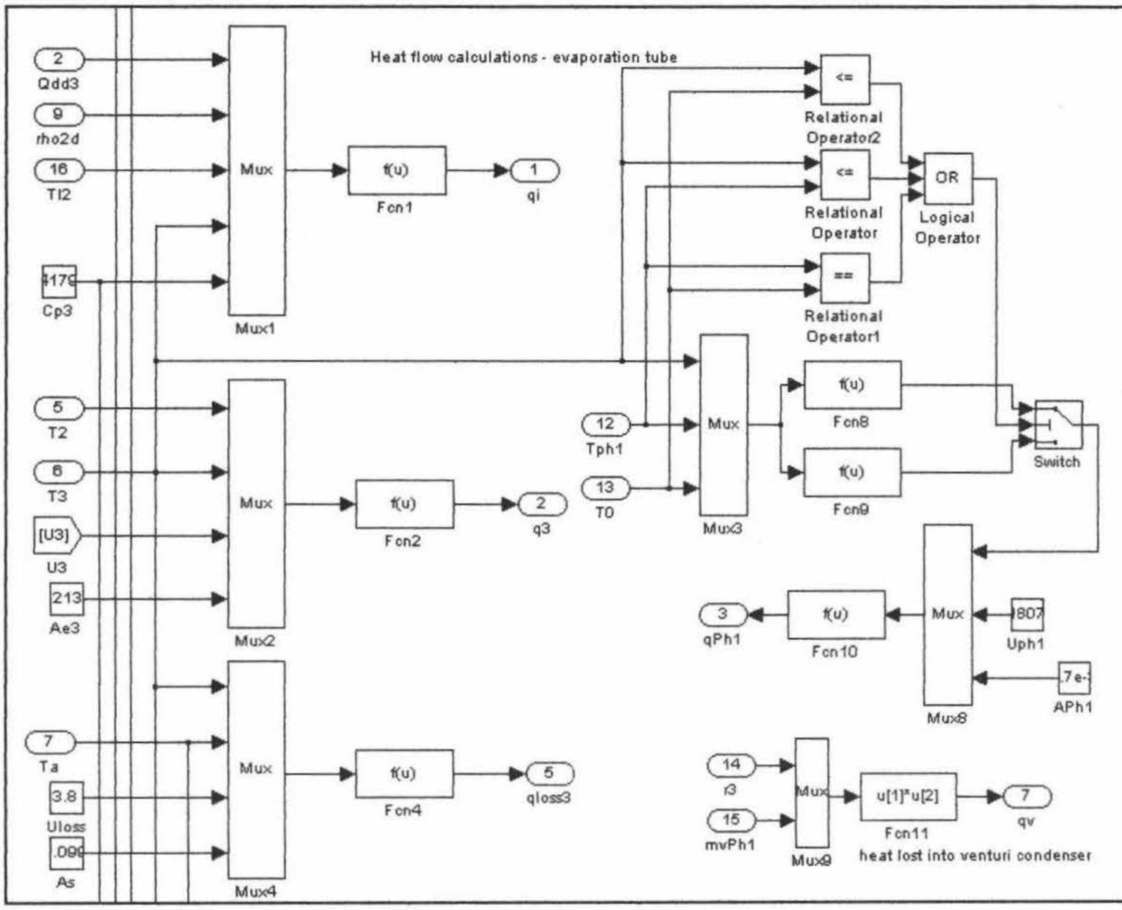

Figure 5-8 The calculations of heat loss into the preheater 1 and heat loss into the venturi condenser

5.3 Control System Description

The control system, as discussed before in chapter 4, consists of two parts: Fix32 database and control screens. Fix32 database contains the values of the system inputs and the simulation results. It connects with the Simulink model, outputs system inputs to the Simulink model through the FromFix driver and receives the simulation results from the Simulink model through the ToFix driver.

5.3.1 Fix32 database

Fix32 database consists of database blocks and chains. Database blocks are where the data of system parameters are stored. The chains are the processing loops that are constructed by connecting configurable database blocks.

There are two types of database blocks used to develop Fix32 database, primary blocks and secondary blocks. Primary blocks can receive data from the Driver Image Table and generate alarms based upon data. Secondary block manipulate data according to the instructions. It receives input from an upstream or primary block and performs a specific function with that input.

Analog Input (AI) blocks receive analog data from the ToFix driver in the Simulink model every time the blocks are scanned. They are primary blocks and store the values of the simulation results from Simulink model. Figure 4-8 shows an example Analog Input block (AI) that stores the value of the effect 1 output flowrate.

Analog Output (AO) blocks can send analog data to the FromFix driver in the Simulink model. These blocks are primary block and store the values of the simulation inputs that manually input from control screens. Figure 4-9 shows an example Analog Output block (AO) for the feed pump speed.

Trend blocks (TR) can collect real-time values from an upstream block and display these values as graph in Multi-pen chart. These blocks are secondary blocks. Figure 4-10 shows an example Trend block (TR) for the effect 1 level.

Chains are processing loops that constructed by connecting database blocks of control logic. In this project chains are used to provide data for Multi-pen chart.

The details of the Fix32 database are shown in appendix 6.

5.3.2 Control screens

Control screens are graphical display tools used for displaying process information of the real-time simulator. Operators can manipulate values of the system input variables directly from the control screens. They are designed to match the real plant or the control screens on the real plant as closely as possible. The control screens include seven pictures that are Evapma_p.odf, Ftank_p.odf, Prehea_p.odf, Eff1_p.odf, Eff2_p.odf, Eff3_p.odf and Condan_p.odf.

- Evapma_p.odf is an overview of the entire evaporator plant. It shows all the system information for feed tank, preheater, effect 1, effect 2 and effect3.

- Ftank_p.odf displays the information of the feed tank such as tank level, feed pump speed and input/output flowrate.

- Prehea_p.odf shows the information for the preheater such as preheater temperature, pressure and steam pressure.

- Eff1_p.odf, Eff2_p.odf and Eff3_p.odf show the information for the three effects such as feed flowrate, effect level, effect temperature and pump speed.

Figure 4-11 shows the main picture of the control screens (Evapma_p.odf). The tool bar on the top of the picture allows the operators to select different pictures. The variable dialog boxes display values of the variables for the simulator. They are also push buttons that allow the operators to view Multi-pen charts by clicking on them.

The details of the control screens are shown in appendix 6.

6
Results of testing Real-time Simulator

OVERVIEW

This chapter discusses the results of testing the Falling-Film Evaporator Simulator. The testing includes two parts: testing the real-time simulator Simulink model, and compiling the Simulink model and communicating with the SCADA system.

6.1 Testing the real-time simulator Simulink model

The aim of the model testing is to determine whether the real-time simulator model is an adequate representation of the existing m-file model. The m-file model was validated against the evaporator in earlier work[4]. Steady-state simulation initialization values need to be found based on the parameters used in the existing m-file model. Some of the model parameters are likely to be refining from the trials data of the existing m-file model in order to improve the real-time simulator model.

The parameters that most affected the calculations of the model steady-state initialization values were the heat transfer coefficients for the heating of the product (U)

and the heat losses to the surroundings (U_{loss}), and the flow characteristic constants for the pumps (ap), nozzles (C_N) and outlet valve (C_V). All other parameters were assumed to be fixed.

In the existing M-file model created by Russell[4], nine combinations of feed pump and steam pressure setpoints were used to determine the steady state trial data. From the steady-state trial data nine operating points of heat transfer coefficients were estimated by setting the model derivatives to zero. In order to represent the existing M-file model, mean values of the heat transfer coefficients from the nine operating points were used in the Simulink model to determine the steady-state initialization values.

In the existing M-file model, three sets of the flow pump, nozzle and outlet valve flow constants were optimized from the three trials data (one steady state trial and two random trials). Once again, the mean data from the three sets of the flow pump, nozzle and outlet valve flow constants were used in the Simulink model in order to predict the flowrates[4]. The following table summarizes the data used in the Simulink model.

Constant	Units	Mean
U_{Ph1}	$W/(m^2K)$	1935
U_{Ph2}	$W/(m^2K)$	1809
U_1	$W/(m^2K)$	3358
U_2	$W/(m^2K)$	3097
U_3	$W/(m^2K)$	1786
Ap_0	Pa/rpm^2	$3.7096*10^{-2}$
Ap_1	Pa/rpm^2	$2.1447*10^{-2}$
Ap_2	Pa/rpm^2	$1.9164*10^{-2}$
Ap_3	Pa/rpm^2	$2.9963*10^{-2}$

C_{N1}	$M^3(Pa^{1/2}s)$	$4.9057*10^{-7}$
C_{N2}	$M^3(Pa^{1/2}s)$	$5.4521*10^{-7}$
C_{N3}	$M^3(Pa^{1/2}s)$	$2.8898*10^{-7}$
C_V	$M^3(Pa^{1/2}s)$	$5.8987*10^{-7}$

Table 6-1: Data used on the Simulink model

Two Matlab functions (Linmod and Trim) were used to determine the steady-state values of state vectors used in the Simulink model. The "Linmod" function obtains linear models from the Simulink model and the "Trim" function can find steady-state parameters for the Simulink model for a given set of conditions.

As the model was not linear, once the steady-state initialization values were gained through the "Linmod" and "Trim" functions, some adjustment needed to be applied on these data by putting them into each subsystems as inputs and initialization values of state vectors (integrator block) and delay blocks. The outputs of each subsystem could than be adjusted into steady state by making small change of these steady-state initialization data.

There were total of 37 steady state initialization data that needed to be adjusted. These data included initial inputs for delay blocks and initial conditions for integrators.

The following figures show the "Effect 1" subsystem being adjusted. The steady-state initialization inputs data was input directly into the "Matlab command window" and saved as the subsystem input vector "U". By making small adjustment to the steady-state input data and initial values of the integrator blocks and delay blocks, the subsystem outputs were adjusted into steady-state.

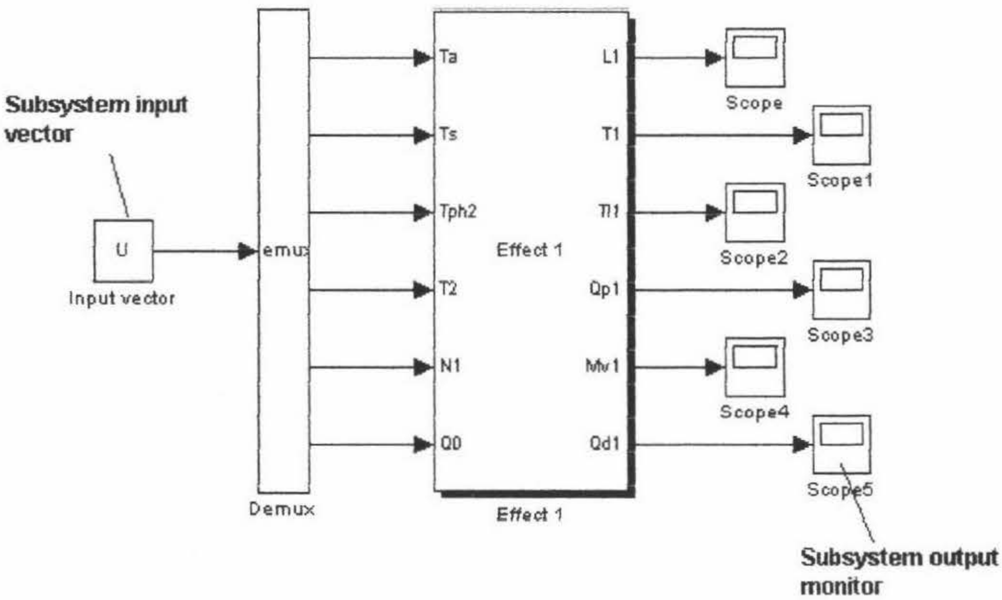

Figure 6-1: Testing Subsystem

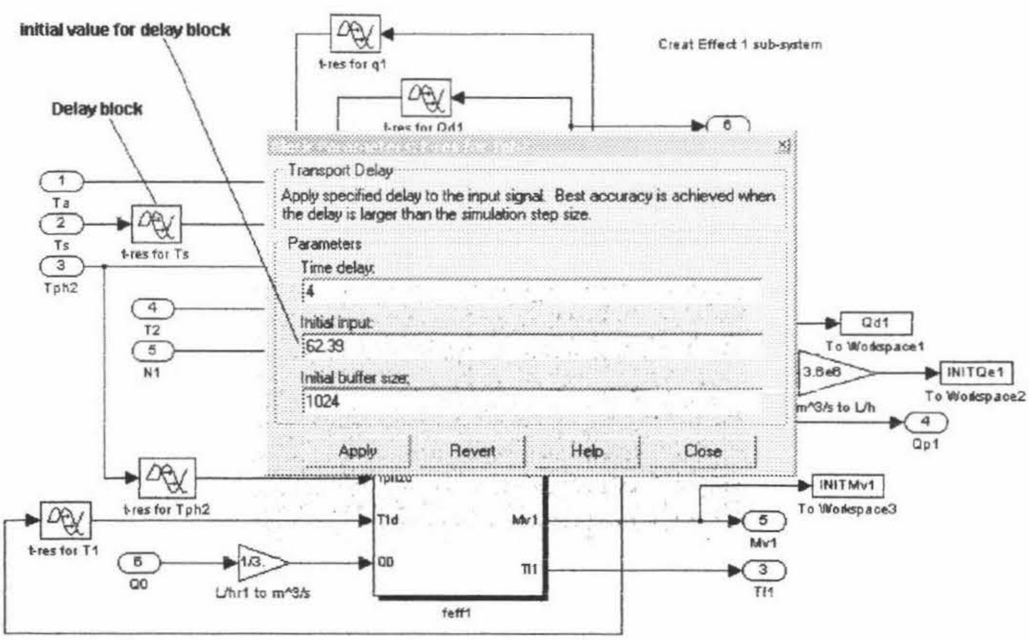

Figure 6-2: Testing Subsystem

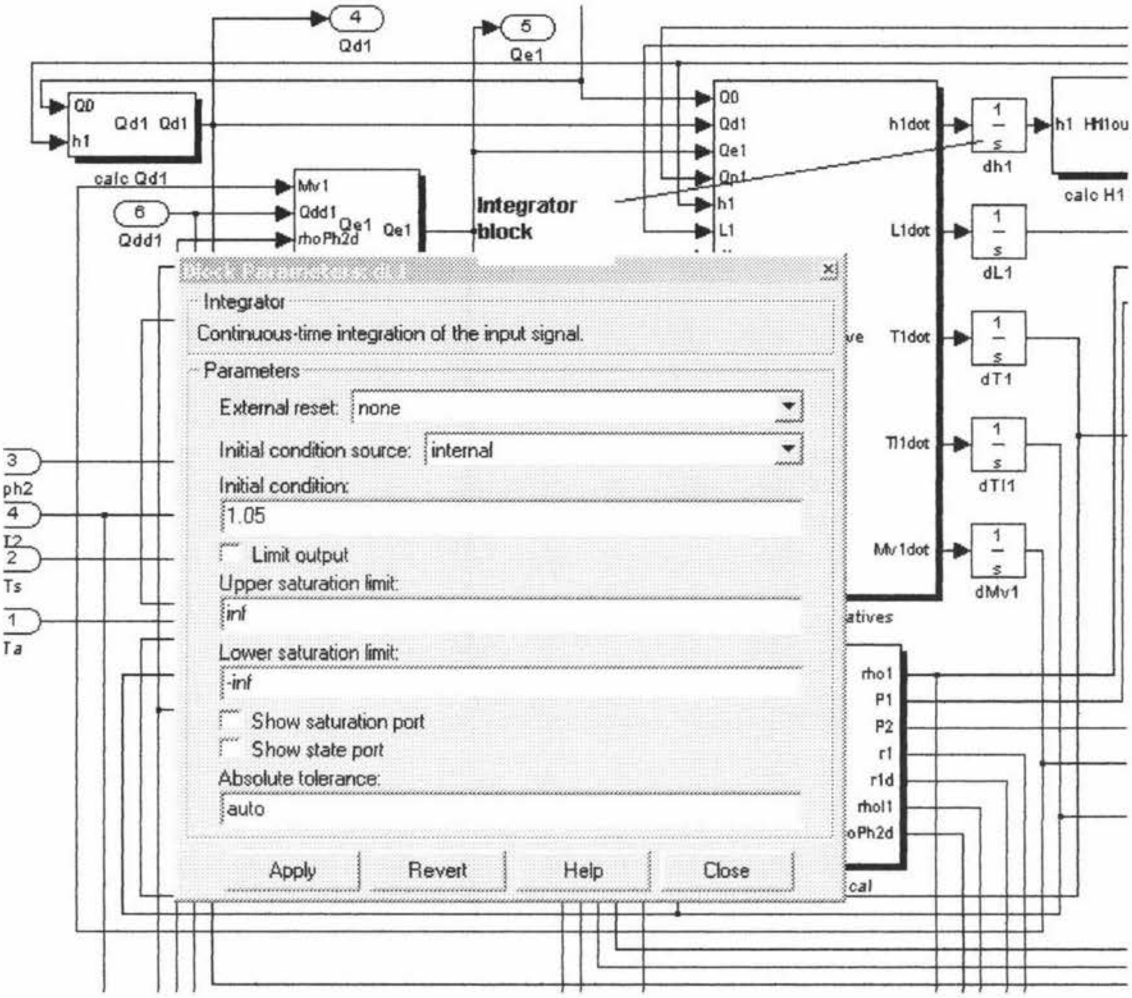

Figure 6-3: Testing Subsystem

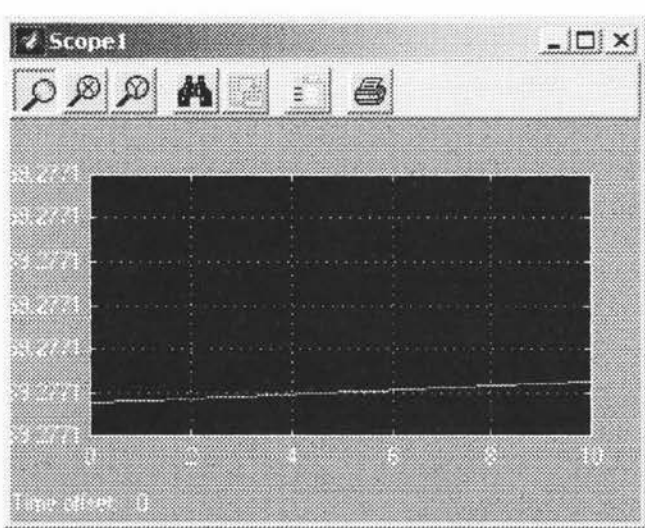

Figure 6-4: Testing Subsystem (Subsystem output T_{L1})

With the derivative terms of the ordinary differential equations from the existing m-file model set to zero, the steady-state values can be calculated and used to test the steady-state values from the Simulink model. The following table shows the steady-state values from the Simulink model and existing m-file model. This table determines that the Simulink model is an adequate representation of the existing m-file model.

Steady-state Data	Unit	Values from Simulink model	Values from existing m-file model
T_a	^oC	18	18
T_s	^oC	78.0491	78.0491
T_1	^oC	69.54	69.54
T_2	^oC	64.05	64.05
T_3	^oC	47.526	47.526
T_{L1}	^oC	69.2771	69.2770
T_{L2}	^oC	63.82159855	63.82159861
T_{L3}	^oC	47.3868	47.3867
T_{ph1}	^oC	46.32483013	46.32483013
T_{ph2}	^oC	62.39	62.39
Q_0	L/hr	307.4	307.4
Q_1	L/hr	298.3876	298.3978285
Q_2	L/hr	287.298	287.2980311
Q_3	L/hr	264.8323	264.8322
N_1	rpm	1520.22044	1520.2
N_2	rpm	2319.92705	2319.9
N_3	rpm	1878.412153	1878.4
Mv_3	Kg/s	0.0222	0.0222
Mv_{ph1}	Kg/s	0.00333	0.00333

Table 6-2: Steady-state values from Simulink model & existing m-file model

6.2 Compiling the Simulink model and communicating with SCADA system

Before communicating to the SCADA control system and running in real-time, the Simulink model must be converted into C code through the Real-Time Workshop and then be compiled into a standalone application through Microsoft Visual C. After the compilation this standalone application could communicate with SCADA control screens through the "EDA Link".

The test of the control screens includes system input values should be correctly sent to the Simulink model from the control screens and the results of the simulation should be correctly read from the Simulink model. There were seven input values could be input into the control screens and ten output values to be read from the Simulink model. The input and output values are shown in the following table. In the table, the values in "Control Screen" column were the values displayed on the control screens and the values in "Simulink Model" were the values used to test the Simulink model. This table demonstrates that the control screens communicated correctly with the Simulink model.

Input Values	Control Screen	Simulink Model
T0	18C	18
Ts	78.04C	78.0491
N0	23.13%	23.13
N1	47.75%	47.75
N2	77.32%	77.32
N3	79.54%	79.54

V	100%	100
Output Values	Control Screens	Simulink Model
L1	1.05m	1.05
L2	1.05m	1.05
L3	1.05m	1.05
Tph1	46.32C	46.32483013
Tph2	62.39	62.39
T1	69.54	69.54
T2	64.05	64.05
T3	47.5	47.526
Q0	307.4L/hr	307.4
Q3	264.8L/hr	264.8322

The following figures show the values on the control screens and trend pages.

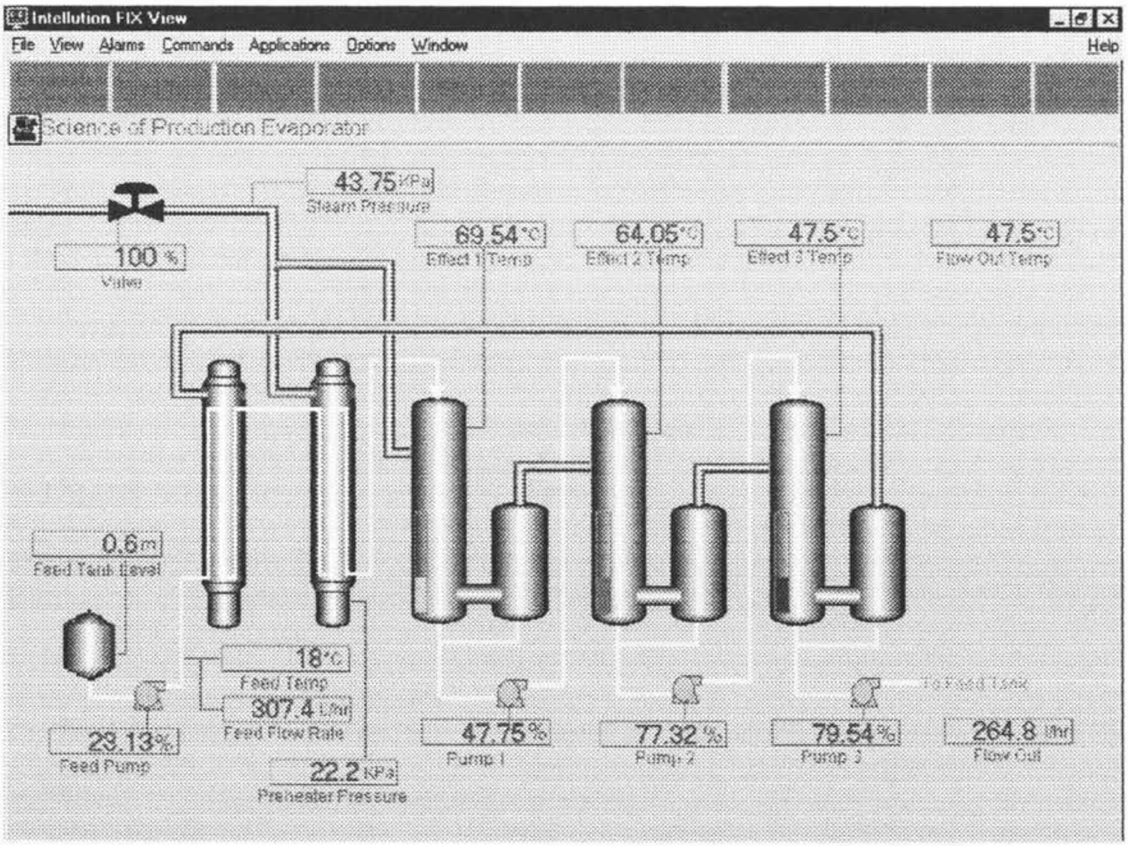

Figure 6-5: SCADA Control Screen (Overview Page)

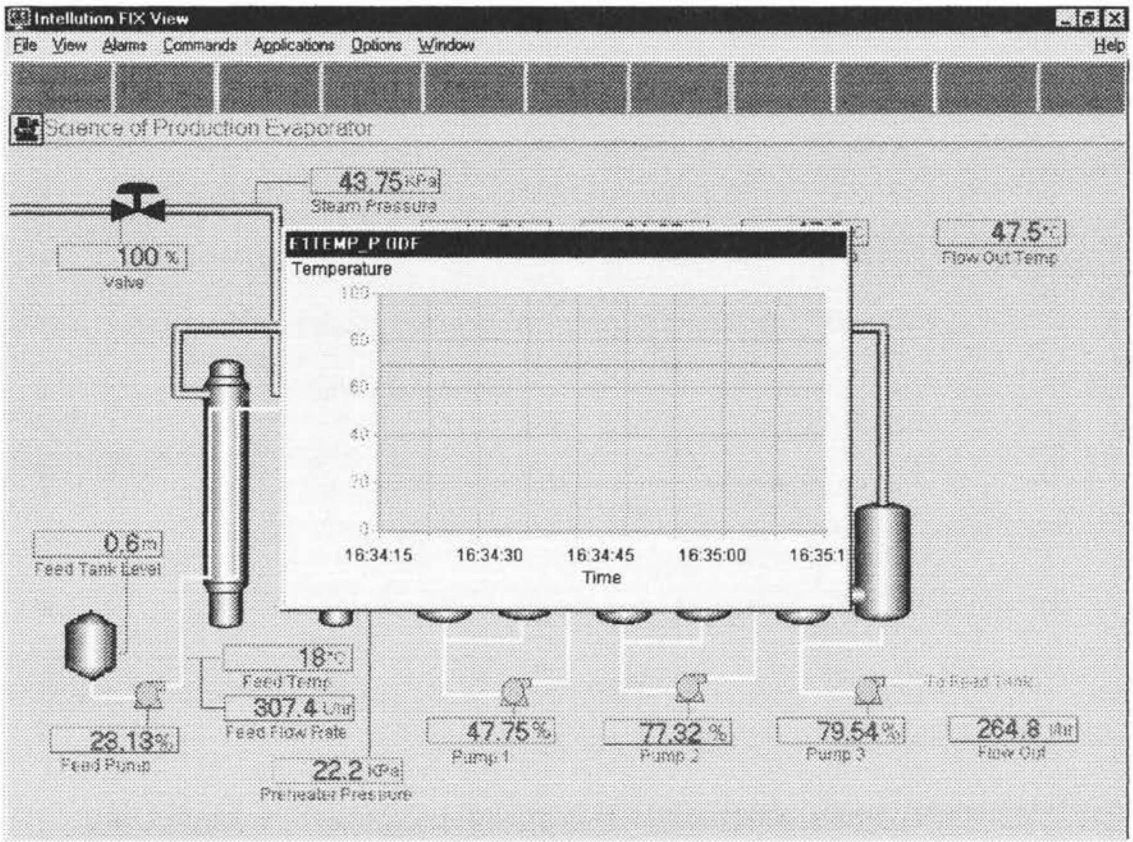

Figure 6-6: SCADA Control Screen (Trend page for Effect 1 temperature)

6.3 Conclusions

The parameters that have been chosen during this testing were the mean values of the trail data. During the test, the simulink model could correctly represent the existing m-file model and the control screens could correctly communicate with the Simulink model. This means the development of Real-Time Fulling-film Evaporator Simulator was successful.

Currently the real-time simulator runs in steady-state during the simulation. The values for the input variables such as infeed temperature, pump speed can be changed from the control screen but may make the system unstable. For the future development, the PID controllers can be put into the model for the steam pressure and the pump speed to keep the real-time simulator stable.

7

Conclusions and Recommendations

The development of a real-time falling-film evaporator simulator followed from specification through design, implementation and testing. The design of the simulator was based around the structure of the existing Matlab M-file model. The implementation consisted of converting the existing M-file model into a Simulink model, modifying some of the differential equations to make the model more accurately and compiling the model into a real-time application. Testing was also carried out to ensure that the specifications were met. The final simulator was an executable application that ran with a Fix32 control system in real-time and can be used for operator training.

Some recommendations for further work include:

- General model improvements in order to match it more closely to the responses of the real plant. This could include such things as improving the estimation of the steam temperature. Improving this part of the model would greatly improve the temperature estimates.
- Currently the real-time simulator runs in steady state during the simulation. The values for the input variables such as infeed temperature, pump speed can be changed from the control screen but may make the system

unstable. For the future development, the PID controllers can be put into the model for the steam pressure and the pump speeds to keep the real-time simulator stable.

- Currently an operator can not reset the real-time simulator. Ideally, there should be a "reset simulation" button on the Fix32 control screen pages to perform this function. This can be done by improving the communication driver to reset the model under its control.

8
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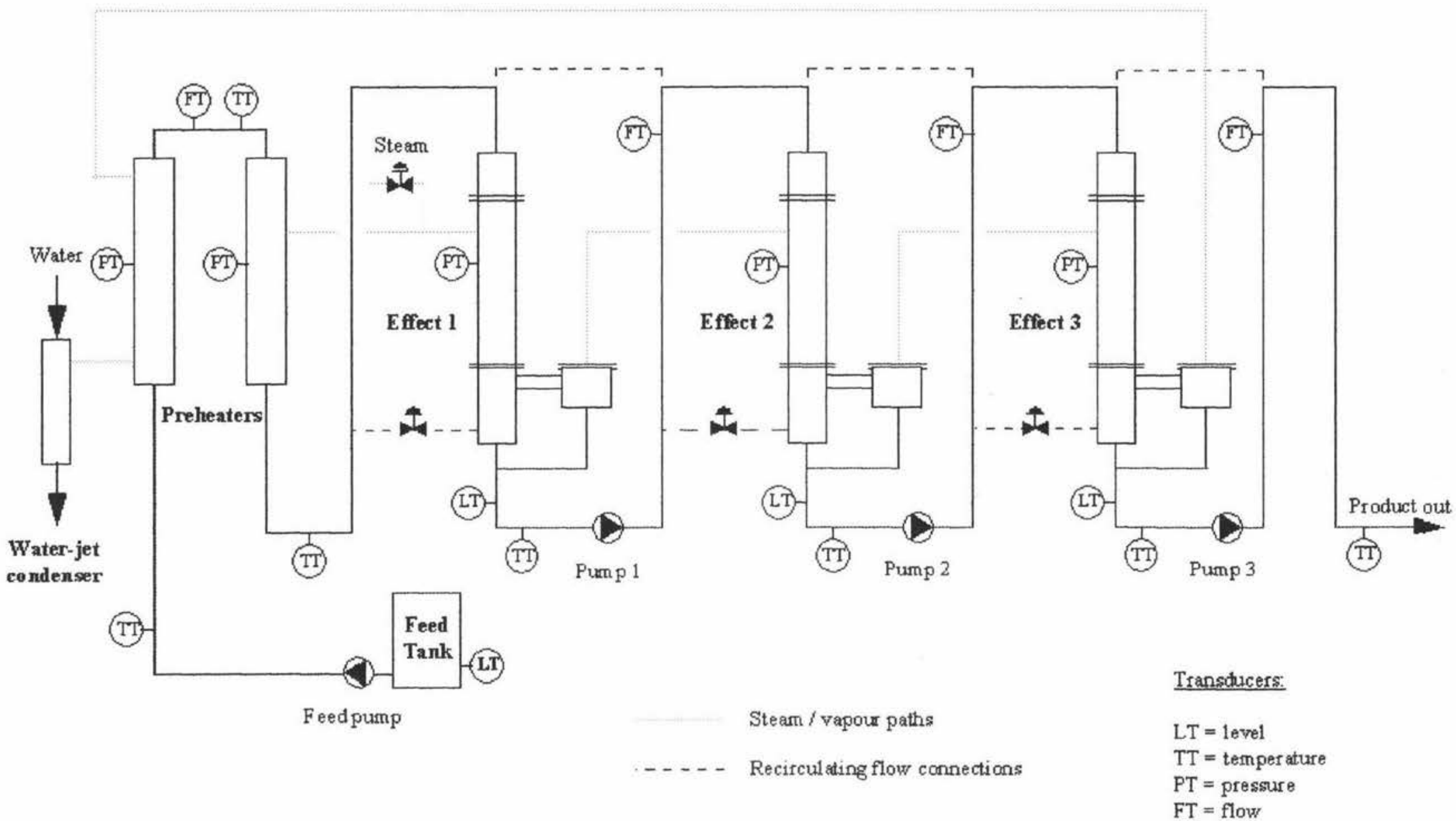
Appendix



Schematic of the Production Technology falling-film evaporator

Appendix 2

Glossary of Analytical Model Symbols

Symbol	Description	Unit
a_P	Pump flow characteristic constant	Pa/rpm^2
A_c	Area of orifice for the condensate flows	m^2
A_d	Area of liquid surface on the distribution plate	m^2
A_e	Heat transfer area of evaporation tube	m^2
A_h	Area of holes in the distribution plate	m^2
A_l	Area of liquid surface of the level at base of effect	m^2
A_p	Cross-sectional area of the standard pipework	m^2
A_{ph}	Heat transfer area in the preheater	m^2
A_s	Surface area of the evaporation tube sub-system	m^2
A_{sl}	Surface area of the level sub-system	m^2
A_{sp}	Surface area of the pipework between effects	m^2
A_{sph}	Surface area of preheater	m^2
A_{sv}	Surface area of venturi condenser	m^2
A_T	Cross-sectional area of the feed tank	m^2
A_t	Cross-sectional area of diffuser throat in the condenser	m^2
A_v	Cross-sectional area of projection cone throat in the condenser	m^2
c_j	Specific heat capacity of condenser water jet	J/(kgK)
c_p	Specific heat capacity of liquid in the effect	J/(kgK)
c_{ph}	Specific heat capacity of liquid in the preheaters	J/(kgK)
C_N	Flow characteristic constant for the distribution nozzle	$m^3/(Pa^{½}s)$
C_V	Flow characteristic constant for the manual outlet valve	$m^3/(Pa^{½}s)$
C_{vc}	Flow characteristic constant for the condensate streams	$kg/(Pa^{½}s)$
d	Internal diameter of standard pipework	m
d_p	Internal diameter of pipework in the preheaters	m
D	External diameter of standard pipework	m
D_p	External diameter of pipework in the preheaters	m
f	Fanning friction factor	-
g	Gravitational acceleration constant	m/s^2
h_c	Height of the condenser discharge point	m
h_N	Height of the distribution nozzle	m

Symbol	Description	Unit
k_d	Derivative constant for steam PID controller	-
k_i	Integral constant for steam PID controller	-
k_p	Proportional constant for steam PID controller	-
K_c	Friction constant for condensate flow from effect shells	-
K_f	Constant for the pressure drop due to friction through the condenser	-
K_h	Friction constant for flow through distribution plate	-
l_e	Equivalent length of pipework between effects (considering fixtures and fittings)	m
l_f	Equivalent length of pipework in feed stream (considering fixtures and fittings)	m
l_p	Equivalent length of pipework in the preheaters (considering fixtures and fittings)	m
L	Height of the liquid level at the base of the effect	m
L_d	Height of liquid above the distribution plate	m
L_T	Height of liquid in feed tank	m
m_c	Mass flow of total condensate entering the condenser	kg/s
m_{ci}	Mass flow of condensate from the shell of effect *i*	kg/s
m_{cphi}	Mass flow of condensate from the shell of preheater *i*	kg/s
m_j	Mass flow of the jet in the venturi condenser	kg/s
m_v	Mass flow of vapour entering the condenser	kg/s
m_{vent}	Mass flow of liquid exiting the venturi condenser	kg/s
m_{vph1}	Mass flow of vapour from preheater 1	kg/s
M	Mass of liquid product in the evaporation tube	kg
M_{cph1}	Mass of condensate produced in the first preheater shell per residence time	kg
M_l	Mass of liquid product in the effect level	kg
M_v	Mass of vapour produced in the evaporation tube per residence time	kg
N	Effect pump speed	rpm
N_0	Feed pump speed	rpm
P_a	Ambient pressure	Pa
P_e	Pressure in the evaporation tube	Pa
P_f	Pressure in the evaporation tube of the downstream effect	Pa
P_v	Pressure in the shell of the effect	Pa
P_{vent}	Suction pressure produced by the venturi condenser	Pa
q_c	Heat supplied by the condensate stream into the condenser	W
q_i	Heat supplied from the product stream into the effect	W
q_{loss}	Heat loss to the surroundings from the evaporation tube system	W

Symbol	Description	Unit
q_{lossl}	Heat loss to the surroundings from the level system	W
q_{lossp}	Heat loss to the surroundings from the pipe between the effects	W
q_{lossv}	Heat loss to the surroundings from the venturi condenser	W
q_{phi}	Heat transfer in preheater *i*	W
q_{shell}	Heat flow into the evaporation tube from shell	W
q_t	Heat supplied by product flow into effect level	W
q_{tube}	Heat flow into the evaporation tube of the downstream effect	W
q_v	Heat supplied by the vapour stream into the condenser	W
Q_d	Product flowrate through the distribution plate	m^3/s
Q_e	Product flowrate from the evaporation tube	m^3/s
Q_i	Product flowrate into an effect	m^3/s
Q_{in}	Product flowrate into the feed tank	m^3/s
Q_p	Product flowrate out of the effect	m^3/s
Q_0	Feed flowrate	m^3/s
r_{Phl}	Latent heat of vaporization	KJ/Kg
r_{Phld}	Latent heat of vaporization with time delay	KJ/Kg
r_l	enthalpy of vaporisation	J/Kg
r_{ld}	enthalpy of vaporisation with time delay	J/Kg
t	Time	s
t_s	Sampling time for the discrete first order equation for the preheaters	s
T_0	Temperature of product leaving the feed tank	°C
T_a	Ambient temperature	°C
T_c	Temperature of the condensate entering the condenser	°C
T_e	Temperature of product in the evaporation tube	°C
T_p	Temperature of product leaving the effect	°C
T_{in}	Temperature of product into feed tank	°C
T_l	Temperature of product in the effect level	°C
T_s	Temperature of the external steam supply	°C
T_{shell}	Temperature of the vapour in the shell of the effect	°C
T_{tube}	Temperature of the product in the downstream evaporation tube	°C
T_{vent}	Temperature of the exit stream from the venturi condenser	°C
$\overline{T}_{ph}$	Steady-state temperature of the product exiting a preheater	°C
T_{phi}	Log-mean temperature difference in preheater *i*	°C
t_c	Time constant for the steam valve system	s
$t_{c(ph)}$	Time constant for the first order preheater systems	s
t_e	Residence time through the evaporation tube	s

Symbol	Description	Unit
t_f	Product transport delay between feed tank and first effect	s
U_e	Heat transfer coefficient for the evaporation tube	W/(m^{2}K)
U_{loss}	Heat transfer coefficient for heat loss to surroundings from tubes	W/(m^{2}K)
U_{lossl}	Heat transfer coefficient for heat loss to surroundings from liquid level	W/(m^{2}K)
U_{lossp}	Heat transfer coefficient for heat loss to surroundings from pipework	W/(m^{2}K)
U_{lossph}	Heat transfer coefficient for heat loss to surroundings from preheater	W/(m^{2}K)
U_{lossv}	Heat transfer coefficient for heat loss to surroundings from the condenser	W/(m^{2}K)
U_{ph}	Heat transfer coefficient for heat transfer in the preheater	W/(m^{2}K)
v_e	Fluid velocity into the liquid level	m/s
v_p	Fluid velocity at the discharge of the effect	m/s
v_T	Fluid velocity at the feed tank	m/s
v_0	Fluid velocity entering effect 1	m/s
V_l	Volume of liquid in the effect level	m^3
V_f	Volume of the pipework in feed system	m^3
V_p	Volume of the pipework between the effects	m^3
w_d	Product concentration through the distribution plate	kg/kg
w_e	Product concentration out of the evaporation tube	kg/kg
w_i	Product concentration in to the effect	kg/kg
w_{in}	Product concentration into the feed tank	kg/kg
w_l	Product concentration out of the effect level	kg/kg
w_p	Product concentration out of the effect	kg/kg
w_T	Product concentration out of the feed tank	kg/kg
w_0	Product concentration into the first effect	kg/kg
Xi	The constant used in m-files	-
λ_ε	Latent heat of vaporisation of product in evaporation tube	J/kg
λ_{phi}	Latent heat of condensation of vapour in shell of preheater i	J/kg
ρ_{phi}	Density of product in preheater *i*	kg/m^3
$\overline{\rho}$	Estimate of product density in the product transport system	kg/m^3
$\overline{\rho}_f$	Estimate of product density in the feed system	kg/m^3
η_{ph}	A function of the system time constant	

Appendix 3

1. Distribution plate sub-system

This sub-system models the flow of solution through the distribution plate and into the evaporation tube. The distribution plate is considered as a mixed tank with perforations that allow the liquid distribute into the evaporation tube.

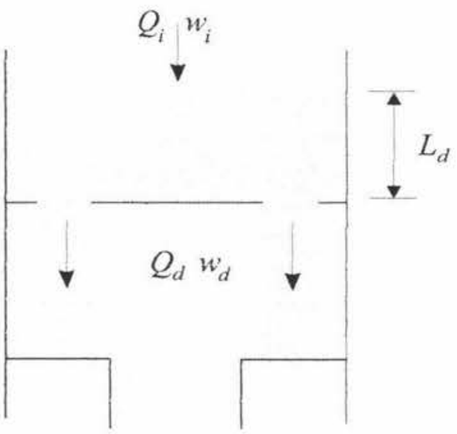


Figure 3-1: Distribution plate sub-system.

The flow through the distribution plate, Q_d, can be determined using the following equation.

$$Q_d(t) = A_h\sqrt{\frac{2gL_d(t)}{K_h}} \tag{3.1}$$

Where L_d is the height of liquid above the plate, A_h is the area of the holes in the plate, g is the gravitational acceleration constant and K_h is a friction factor dependent on the dimensions of the holes.

The height of liquid above the plate is a state variable and is given by the following differential equation.

$$\frac{dL_d(t)}{dt} = \frac{Q_i(t) - Q_d(t)}{A_d} \tag{3.2}$$

Where Q_i is the flow into the distribution plate system of the effect and A_d is the area of the liquid surface

2. *Evaporation tube sub-system*

This sub-system models the mass flow of the liquid out of the evaporation tube which is obtained by performing a mass balance over the evaporation tube sub-system and the mass of vapour produced in the evaporation tube.

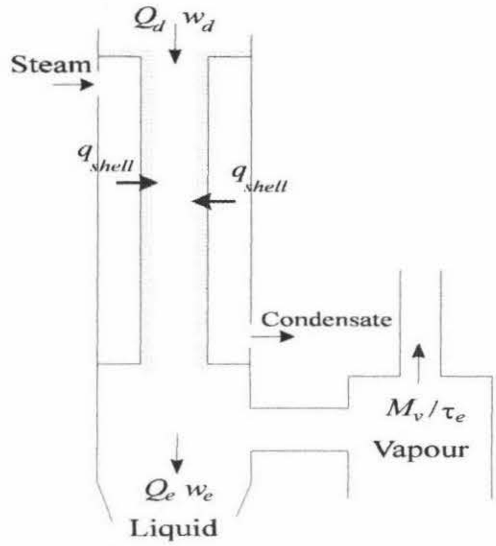


Figure 3-2: Evaporation tube sub-system.

Before modeling the evaporation tube sub-system two assumptions are made:

- The heat flow across the tube is considered to be uniform.
- The fall velocity of the liquid film is assumed to be constant.

Since the residence time is assumed constant the mass of liquid out of the tube at time *t* is equal to the mass flow into the tube at $t - \tau_e$ minus the amount of product vaporized during the residence time.

$$Q_e(t) = \frac{\rho_d(t-\tau_e)}{\rho_e(t)} Q_d(t-\tau_e) - \frac{1}{\rho_e(t)\tau_e} M_v(t). \tag{3.3}$$

M_v is the total mass of vapour produced in the evaporation tube during the previous τ_e seconds and is estimated by

$$\frac{dM_v(t)}{dt} = \frac{q_{shell}(t)}{\lambda_e(t)} - \frac{q_{shell}(t-\tau_e)}{\lambda_e(t-\tau_e)}. \tag{3.4}$$

3. *Product transport sub-system*

This sub-system models the flow of product from one effect to the next. It involves the reservoir of liquid concentrate, the pipe work connecting the effects and the distribution nozzle in the downstream effect. The temperature changes that occur through the product transport system are also modeled.

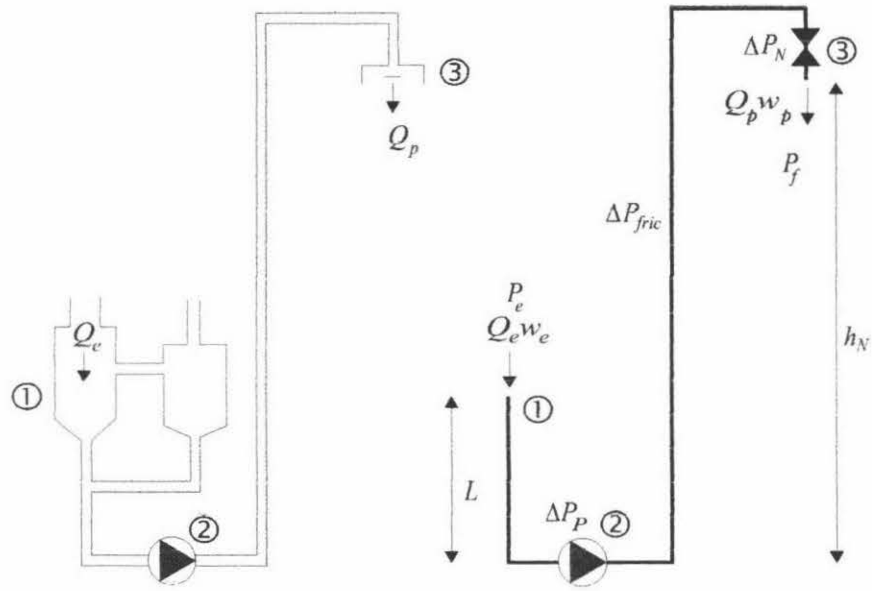


Figure 3-3: Product transport sub-system.

Product Level and flowrate

For this model a differential equation with the height of the concentrate level, *L*, as the state variable was used;

$$\frac{dL(t)}{dt} = \frac{Q_e(t) - Q_p(t)}{A_l} \tag{3.5}$$

Where Q_p is the flowrate out of the effect and A_l is the area of the level surface.

A_l is a function of *L* since the geometry of the pipe work changes over the operating range of the level.

To calculate Q_p an energy balance between points ¬ and ® in Figure 3-3 is required. Finally get Q_p:

$$Q_p(t) = \sqrt{\frac{P_e(t) + \rho_e(t)gL(t) + a_P N(t)^2 - P_f(t) - \rho_p(t)gh_N}{\frac{32 f l_e \bar{\rho}(t)}{\pi^2 d^5} + \frac{1}{C_N{}^2} + \frac{1}{2}\left(\frac{\rho_e(t)}{A_l^2} - \frac{\rho_p(t)}{A_p{}^2}\right)}}. \qquad (3.6)$$

Concentration

An approach to assuming plug flow conditions from point ¬ to point ® is to assume perfect mixing in the reservoir at the base of the effect and plug flow only in the pipe from the pump to the next effect (point - to ®). Then

$$w_p(t) = w_l(t - \tau_p) \qquad (3.7)$$

Where τ_p is the time delay between the pump and the next effect and w_l, the concentration of the liquid out of the reservoir, is determined using

$$\frac{dw_l(t)}{dt} = \frac{\rho_e(t)Q_e(t)w_e(t) - \rho_l(t)Q_p(t)w_l(t)}{\rho_l(t)A_l L(t)} \qquad (3.8)$$

Where ρ_l is the density of the flowrate out of the level.

Temperature

An energy equation is defined for the liquid level at the base of the effect. A transducer is located in this region on the pilot-plant to measure the temperature of the product. It is necessary to have as part of the

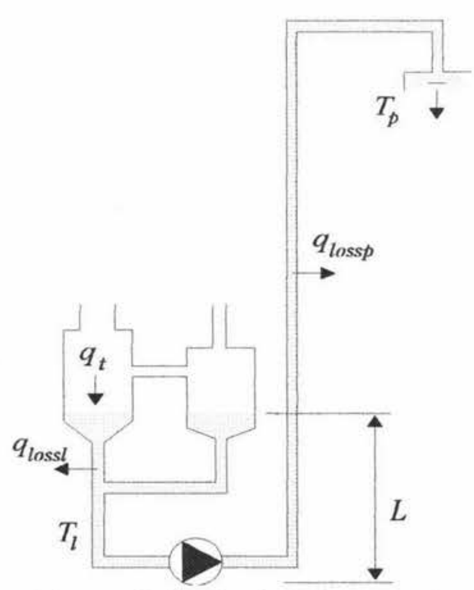


Figure 3-4: Product transport heat flows.

model a calculation of the product temperature at this point for comparison with the measured temperature.

The change in temperature of the product in the level is given by

$$\frac{dT_l(t)}{dt} = \frac{q_t(t) - q_{lossl}(t)}{M_l(t)c_p} \tag{3.9}$$

Where M_l is the mass of liquid in the level and is given by

$$M_l(t) = \rho_l(t)V_l, \tag{3.10}$$

and c_p is the specific heat capacity of the product in the level and V_l is the volume of liquid that is a function of the liquid height.

The two heat flows are calculated by

$$q_t(t) = Q_e(t)\rho_e(t)c_p(T_e(t) - T_l(t)) \tag{3.11}$$

and

$$q_{lossl}(t) = U_{lossl}A_{sl}(T_l(t) - T_a(t) \tag{3.12}$$

Where A_{sl} is the surface area of the level sub-system and U_{lossl} is the heat transfer coefficient for the convective heat loss.

The temperature of the product flowing into the next effect can then be estimated by applying the transport delay, τ_p to T_l in a similar manner to calculating the output concentration. If an estimate of heat loss is included then the output temperature of the effect is

$$T_p(t) = T_l(t - \tau_p) - \frac{U_{lossp}A_{sp}(T_l(t) - T_a(t))}{\overline{\rho}(t)Q_p(t)c_p} \tag{3.13}$$

Where A_{sp} is the surface area of the pipework, U_{lossp} is the heat transfer coefficient for the convective heat loss and the density is estimated using $\bar{\rho}$.

4. Evaporation tube energy sub-system

This sub-system models the heat transfer in the evaporation tube sub-system. This includes the heat received from the heat steam, heat lost to the surrounding and heat lost to the downstream effect from the condensation of the vapour.

Each effect is formed by these sub-systems. In addition the effects are related to the following sub-systems.

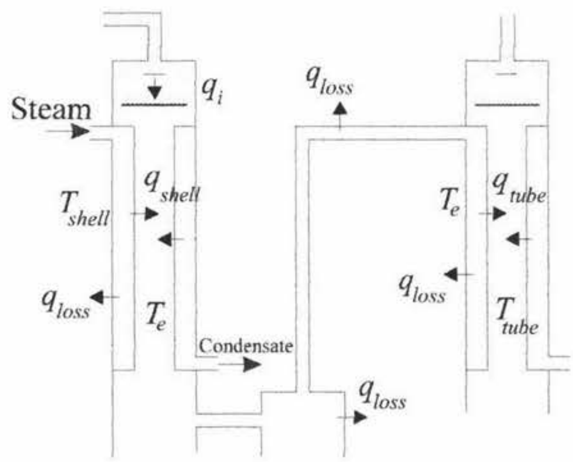


Figure 3-5: Evaporation tube energy sub-system.

Figure 3-5 illustrates the energy sub-system relating to the evaporation tube. The system is characterised by four heat flows, the combination of which determine the change in temperature of the product through the evaporation tube. It is assumed that the temperature is the same over the length of the tube at any one time.

The energy balance defining this system is;

$$\frac{dT_e(t)}{dt} = \frac{q_{shell}(t) + q_i(t) - q_{tube}(t) - q_{loss}(t)}{M(t)c_p} \tag{3.14}$$

Where T_e is the product temperature in the tube, M is the mass of liquid in the evaporation tube, and c_p is the specific heat capacity of the product.

The energy flow from the heating vapour is given by

$$q_{shell}(t) = U_e A_e (T_{shell}(t) - T_e(t)) \tag{3.15}$$

Where T_{shell} is the temperature of the vapour in the shell. A_e is the heat transfer area of the evaporation tube, and U_e is the overall heat transfer coefficient for the heat transfer from the bulk of one stream to the bulk of the other.

Similarly for the next effect downstream

$$q_{tube}(t) = U_e A_e (T_e(t) - T_{tube}(t)) \tag{3.16}$$

Where U_e and A_e are the heat transfer area and heat transfer coefficient of the downstream effect and T_{tube} is the temperature of the product in the tube.

The heat from the input stream is represented by a term

$$q_i(t) = \rho_d(t) Q_d(t) c_p (T_i(t) - T_e(t)), \tag{3.17}$$

Where T_i is the temperature of the incoming product stream.

The heat loss to the surroundings is given by

$$q_{loss}(t) = U_{loss} A_s (T_e(t) - T_a(t)) \tag{3.18}$$

Where T_a is the ambient temperature,

A_s is the surface area of the sub-system, and

U_{loss} is the overall heat transfer coefficient for the convective heat transfer.

5. *Feed sub-system*

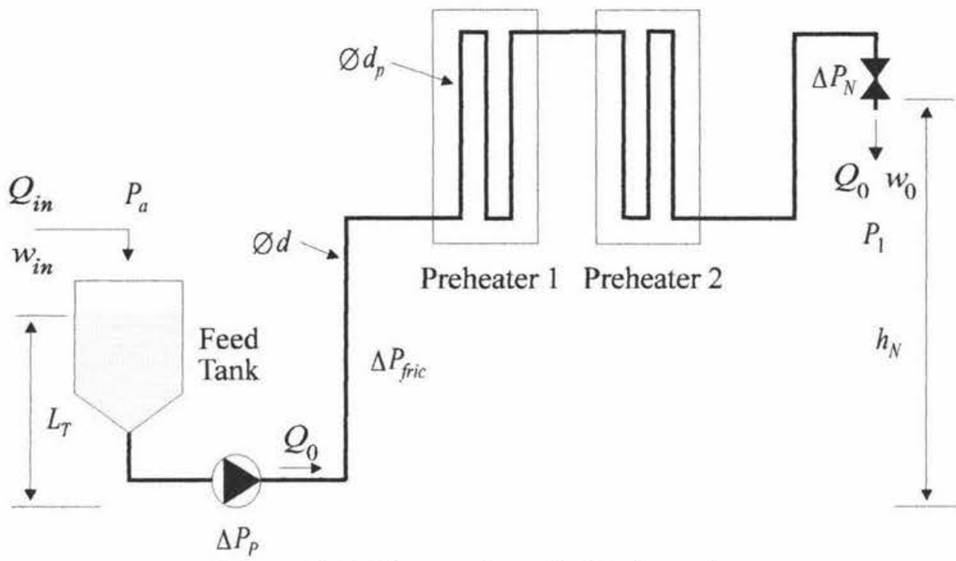


Figure 3-6: Evaporator feed sub-system

This sub-system models the flowrate of the liquid, which is pumped from the feed tank into the first effect through the preheater tubes. The feed flow sub-system consists of the feed tank, feed pump and the pipe work from the tank to the first effect via the two preheaters (Figure 3-6).

The state variable of this sub-system is the liquid level in the feed tank, L_T

$$\frac{dL_T(t)}{dt} = \frac{Q_{in} - Q_0(t)}{A_T} \tag{3.19}$$

Where A_T is the tank cross-sectional area, Q_0 is the feed flowrate into the evaporator and Q_{in} is the input flow into the feed tank that is assumed to be constant.

The feed flowrate Q_0 is

$$Q_0(t) = \sqrt{\frac{P_a(t) + \rho_T(t) g L_T(t) + a_{P0} N_0(t)^2 - P_1(t) - \rho_{ph2}(t) g h_N}{\frac{32 f \rho_f(t)}{\pi^2}\left(\frac{l_p}{d_p{}^5} + \frac{l_f}{d^5}\right) + \frac{1}{C_N{}^2}}} \tag{3.20}$$

The feed tank temperature can be considered as a state variable and if perfect mixing and negligible heat losses are assumed then;

$$\frac{dT_0(t)}{dt} = \frac{\rho_{in}(t)Q_{in}(t)(T_{in}(t) - T_0(t))}{\rho_T(t)A_T L_T(t)}. \tag{3.21}$$

6. *Preheater sub-system*

This sub-system models the temperature of the liquid out of each preheater. It includes the heat transfer in the preheaters. Russell used a discrete first order differential equation to represent the existing m-file model. This differential equation is not very suitable for the sub-system.

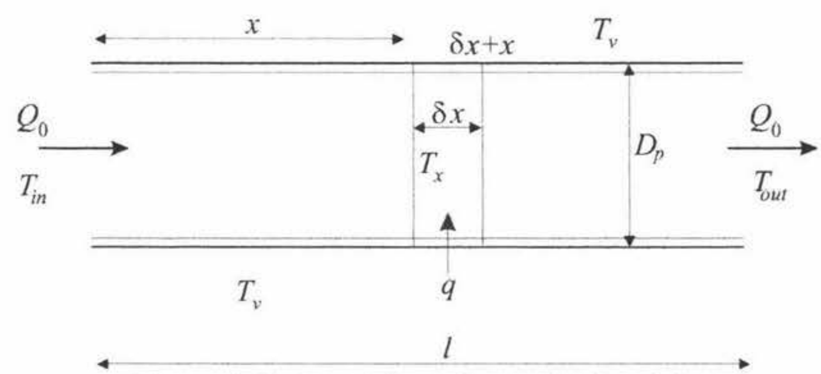


Figure 3-7: A section of a preheater tube

The equations used for preheater 1 and preheater 2 temperatures are discussed in chapter 3.

The heat loss; $q_{lossph} = U_{lossph} A_{sph} (T_v - T_a)$,

7. *Venturi condenser sub-system*

The sub-system models the suction pressure produced by the venturi condenser and the rise in cooling water temperature due to the condensate and vapour exhaust stream.

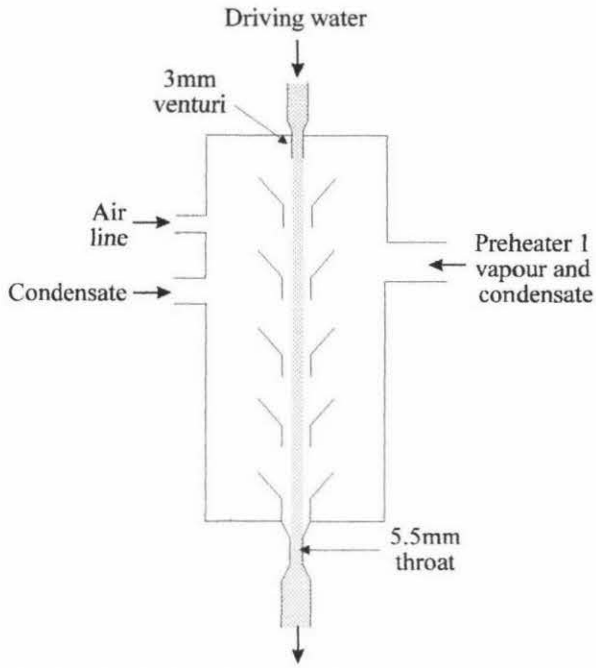


Figure 0-1: Venturi condenser

Entrainment rates

The residence time of the product through the preheater can be estimated by dividing the preheater tube volume by the feed flowrate;

$$\tau_{ph} = \frac{V_{ph}}{Q_0(t)} \quad \text{for } Q_0(t) > 0. \tag{3.22}$$

The mass flow of condensate from the first preheater can then be estimated as follows;

$$m_{cph1}(t) = \frac{M_{cph1}(t)}{\tau_{ph}}. \tag{3.23}$$

The vapour mass flowrate is then estimated by subtracting the condensate flow from the third effect vapour that entered the preheater τ_{ph} seconds before.

$$m_{vph1}(t) = \frac{M_{v3}(t - \tau_{ph})}{\tau_e} - m_{cph1}(t) \tag{3.24}$$

The temperature of the vapour and condensate mixture flowing from the first preheater is assumed to be equal to the temperature of the third effect, T_{e3}.

Condenser temperature

The temperature of the entrained condensate into the venturi can be calculated based on the relative temperatures and flowrates of each stream.

$$T_c(t) = \frac{[m_{cph2}(t) + m_{c1}(t)]T_s(t) + m_{c2}(t)T_{e1}(t) + m_{c3}(t)T_{e2}(t) + m_{cph1}(t)T_{e3}(t)}{m_{cph2}(t) + m_{c1}(t) + m_{c2}(t) + m_{c3}(t) + m_{cph1}(t)} \quad (3.25)$$

where T_{ei} is the temperature of effect i and is assumed to be the temperature of the condensate from the shell of effect i+1; T_s is the steam supply temperature and the temperature of the condensate from the second preheater and first effect shells.

The temperature of the driving fluid exiting the venturi, T_{vent}, can be calculated considering the heat flows in and out of the venturi system;

$$T_{vent} = T_j + \frac{q_c + q_v - q_{lossv}}{m_j c_j} \quad (3.26)$$

where T_j is the temperature of the in-flowing venturi driving water,

q_c is the heat supplied by the condensate,

q_v is the heat supplied by the vapour

q_{lossv} is the heat lost to the surroundings, and

c_j is the specific heat capacity of the water jet.

Suction pressure

$$P_{vent} = \beta(P_a - \rho_j g h_c) - \frac{m_j^2}{\rho_j \alpha A_v^2} + \frac{(K_f + \beta) m_{vent}^2}{2\rho_j \beta^2 A_v^2} + \frac{R+1}{(1-\alpha)A_v^2}\left(\frac{m_c^2(\alpha + R)}{\rho_c(1-\alpha)} - \frac{m_v^2}{\rho_v R}\right). \quad ...(3.27)$$

Equation (3.27) represents the suction pressure generated by the jet condenser. This is theoretically assumed to be the minimum achievable pressure inside the condenser vessel.

8. External steam input sub-system

The sub-system models the temperature of the external steam input. The influence of the evaporation in the first effect can be considered as a disturbance (ΔT_s) to this system. The disturbance on the steam temperature can be estimated by considering the change in the heat given up in the first effect per unit mass flow of liquid.

$$\Delta T_s = \frac{1}{c_{p1}} \frac{d}{dt}\left(\frac{q_{e1}}{m_{e1}}\right) = \frac{U_{e1} A_{e1}}{c_{p1}} \frac{d}{dt}\left(\frac{T_s - T_{e1}}{Q_{d1}\rho_{d1}}\right) \quad (3.28)$$

Appendix 4

Each Simulink block used to build the Simulink model is discussed in the following:

Constant blocks are used to define the constant parameters that are used in each differential equation or each algebraic calculation within the Simulink model. These blocks can output either scalar or vector values depending on the length of the constant value parameter. The *constant blocks* are used as the input of the *"goto" blocks* in the *"constant.mdl"* sub-model.

To workspace blocks are used to write the system input or output variable values into the specified matrix in the workspace. Then other variables in the Simulink model, such as initial conditions, can read these values from the workspace. In these blocks four parameters i.e. variable name, maximum number of rows, decimation and sample time must be defined. Note the variable name in the parameter section must be the same as the variable name in the Simulink model.

In the linear type of Simulink block, there are four blocks used in the Simulink model. They are gain block, sum block, integrator block and transfer function block.

Gain blocks can generate the output by multiplying the input by the constants that are specified in the block parameter section. These blocks are mainly used to change the flowrate units that input to or output from the Simulink model. For example, the unit of the feed flowrate into the first effect can be changed from L/hr to m^3/s by multiplying with the gain of 1/3.6e6. The unit of the flowrate output from the first effect can be changed from m^3/s to L/hr by multiplying with the gain of 3.6e6.

Sum blocks are used to perform the calculations of plus or minus between the input signals. The number of inputs in this block must be greater than 1.

Integrator blocks are mainly used to integrate the state derivatives in the effect sub-models and preheater sub-models. In these blocks the initial condition source can be defined either internal or external. Using the external initial condition source the initial condition can be defined as an input to the block. In this Simulink model most of the initial condition source are selected as internal. This allows the initial conditions to be defined in the block parameter section. The symbols are written into the initial condition section to represent all the initial conditions and the values of the initial conditions are written into a Microsoft Access Table file. This file must be loaded into the workspace before starting the simulation by using the load command in the Matlab command window.

Transfer function blocks are mainly used in the preheater sub-model to implement the transfer function for the outlet temperature of the preheater.

In the nonlinear type of Simulink block a number of blocks are used in the Simulink model such as minmax, product, logical operator, relational operator, transport delay, variable transport delay, fcn and switch.

Minmax blocks can output minimum or maximum input value by select min or max function in the parameter section of the block. These blocks are used in the venturi condenser sub-model. When the min function is selected, the block compares the value of the mass flow of total condensate entering the condenser (m_c) and the value of the mass of vapour produced in the evaporation tube per residence time (m_v). The block outputs the minimum value of these two variables and used it as the value of the mass flow of total condensate entering the condenser. When the max function is selected, the block compares the value of the saturation pressure of venturi water and the value of the suction pressure produced by the venturi condenser. The block outputs the maximum value of these two variables and used it as the value of the suction pressure produced by the venturi condenser.

Product blocks are used to provide multiply or divide calculation in the preheater sub-model.

Logical operator blocks are used to perform AND or OR logical operations by select the operator in the parameter section. The output is 1 if TRUE and 0 if FALSE.

Relational operator blocks are used to perform the relational operations that are specified by the operator in the parameter section of the block. The output is 1 if TRUE and 0 if FALSE.

Switch blocks are used to select one of the block inputs to the block output. The switch block has two inputs and a control input. If the value of the control input is greater than the value of the threshold that is defined in the parameter section, the block outputs the first input, otherwise, the block outputs the second input.

Note: The switch blocks are used with the logical operator blocks and relational operator blocks to perform the' if..else if..' operations in the Simulink model. These operations are used to replace the 'if..else if..' commands that were used in the Matlab m-files.

Delay blocks and *variable delay blocks* are used to perform the time delay operations. The difference between these two blocks is that in the delay block the delay time is specified in the block parameter section and in the variable delay block the delay time is one of the block inputs. The value of the maximum delay that is specified in the variable delay block parameter section defines the largest value the time delay input can have. Both of these two blocks allow the symbol of the initial conditions to be defined in the block parameter section.

Fcn blocks are used to perform the associated algebraic calculation equations in the Simulink model.

In the connections type of Simulink block, five blocks are used in the Simulink block. These blocks are in, out, mux, from and goto.

In blocks and *out blocks* are used to provide the input and output ports in the Simulink model.

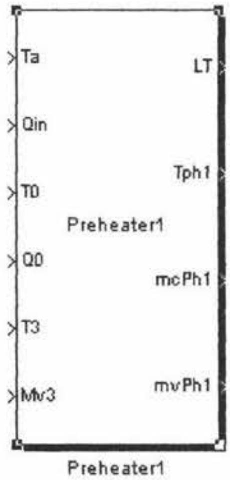
Mux blocks are used to combine the system variables and constants into one vector. The block outputs are used as the inputs of the fcn blocks in the Simulink model.

From blocks and *goto blocks* are used to pass the system constant values into each Simulink sub-model. They are also used to read data from the FIX control screen and write the simulator outputs to the FIX control screen.

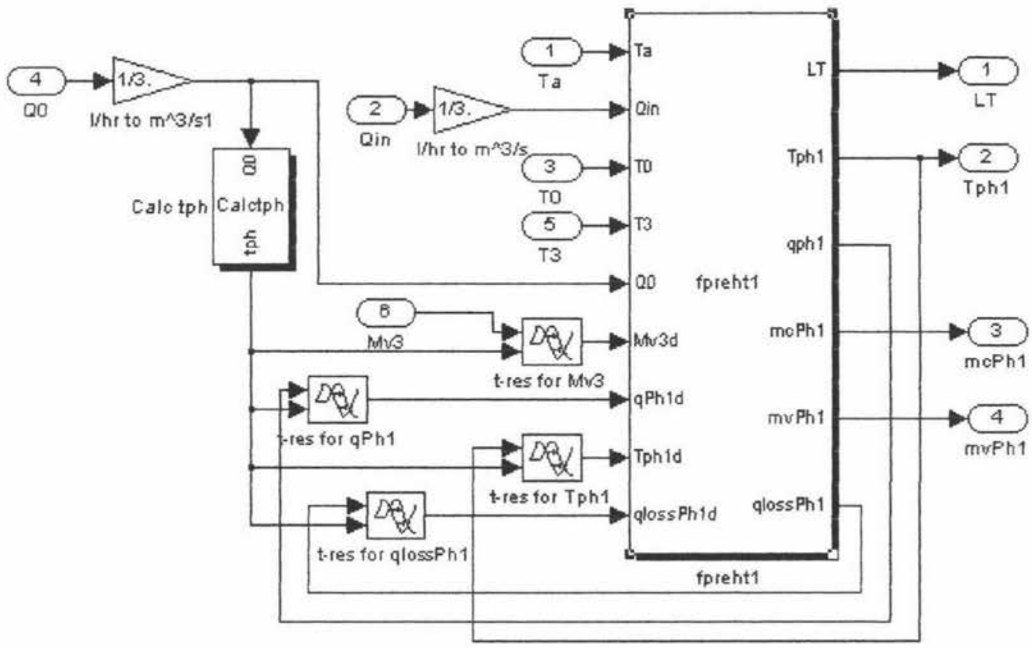
Appendix 5

The Simulink model consisted of the effect sub-models, the preheater sub-model, the venturi condenser sub-model, the initial conditions sub-model and the I/O drivers. These sub-models contain all the differential equations and associated algebraic calculations required for each section of the evaporator. They are connected together and show the flow of information in the process.

1. Preheater Sub-System

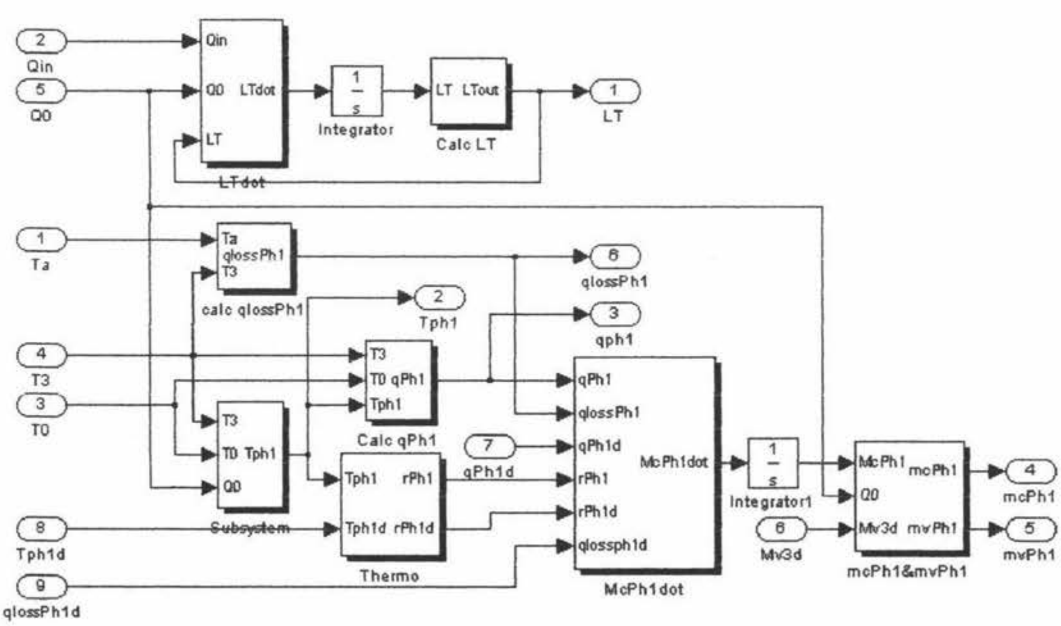


First Level of Preheater 1 Sub-system: *Preheater1.mdl*



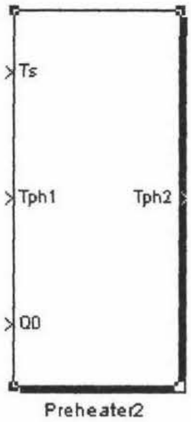
second level of the Preheater1 sub-model

Second Level of Preheater 1 Sub-system

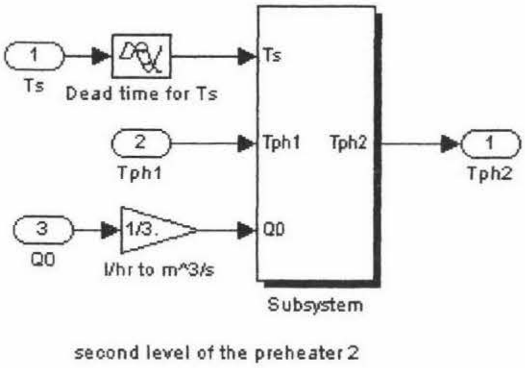


Preheater 1 sub-model defines the temperature of liquid out of the first preheater, the mass of condensate produced in the first preheater, mass flow of vapour from preheater 1, height of liquid in the feed tank, heat transfer in the preheater 1 and heat loss to the surrounding in the preheater 1.

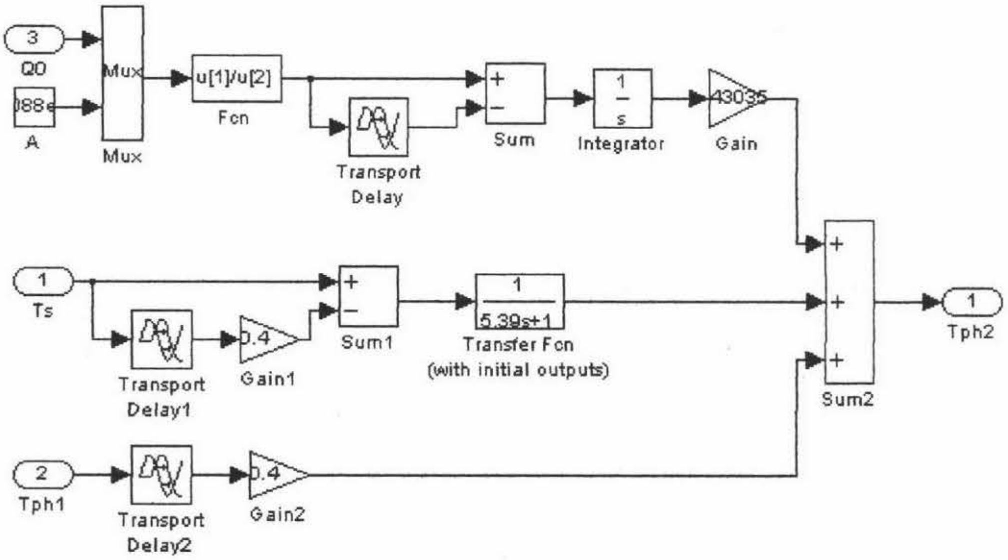
Third Level of Preheater 1 Sub-system



First Level of Preheater 2 Sub-system: *Preheater2.mdl*

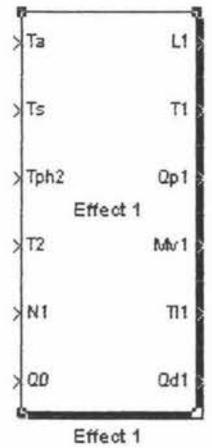


Second Level of Preheater 2 Sub-system

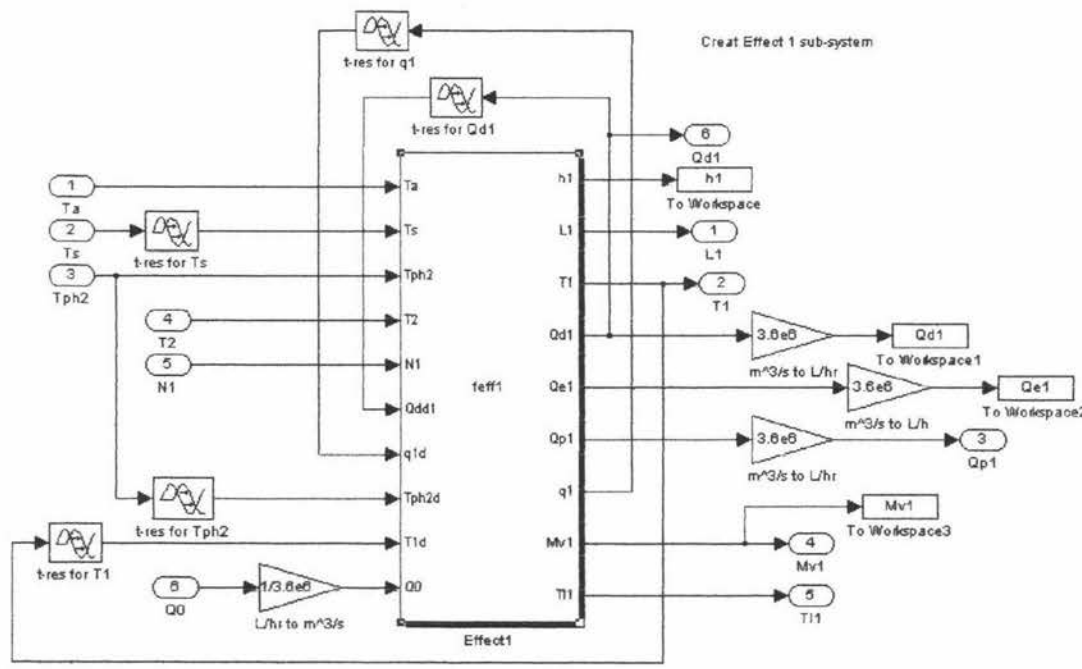


Third Level of Preheater 2 Sub-system

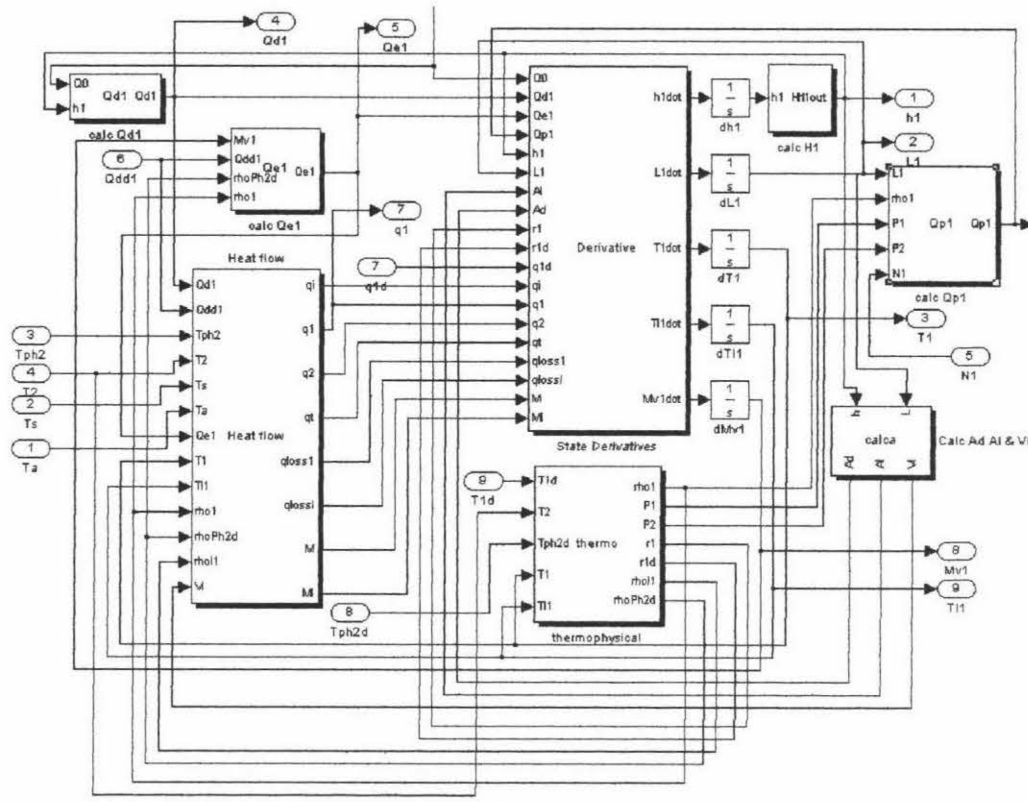
2. Effect Sub-systems



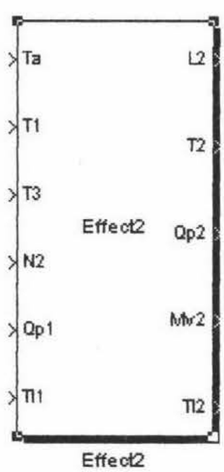
First Level of Effect 1 Sub-system



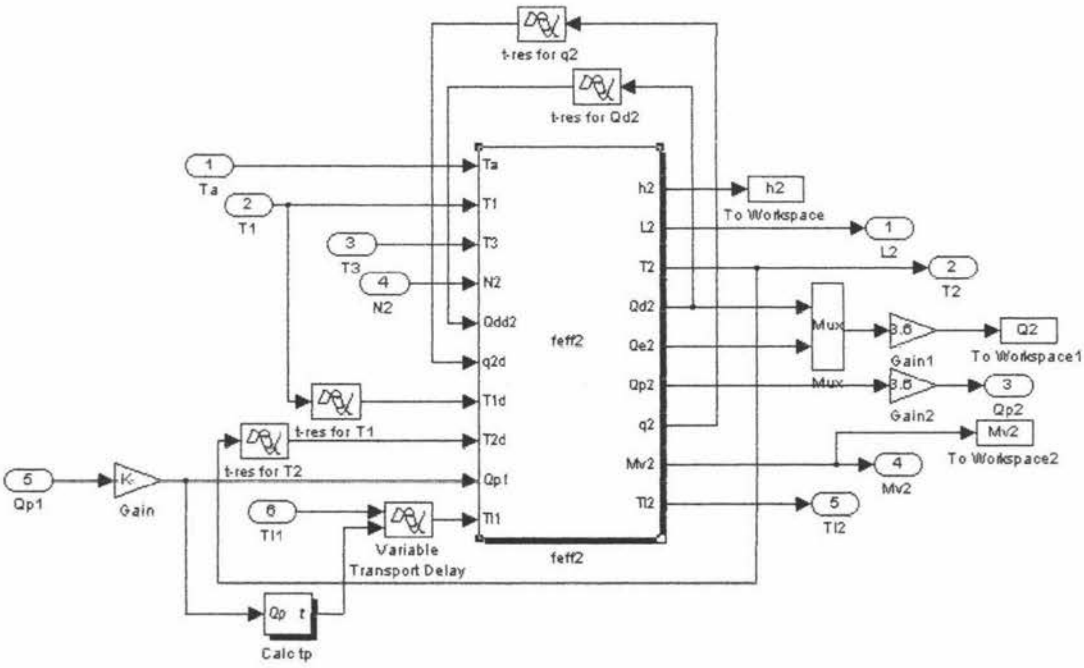
Second Level of Effect 1 Sub-system



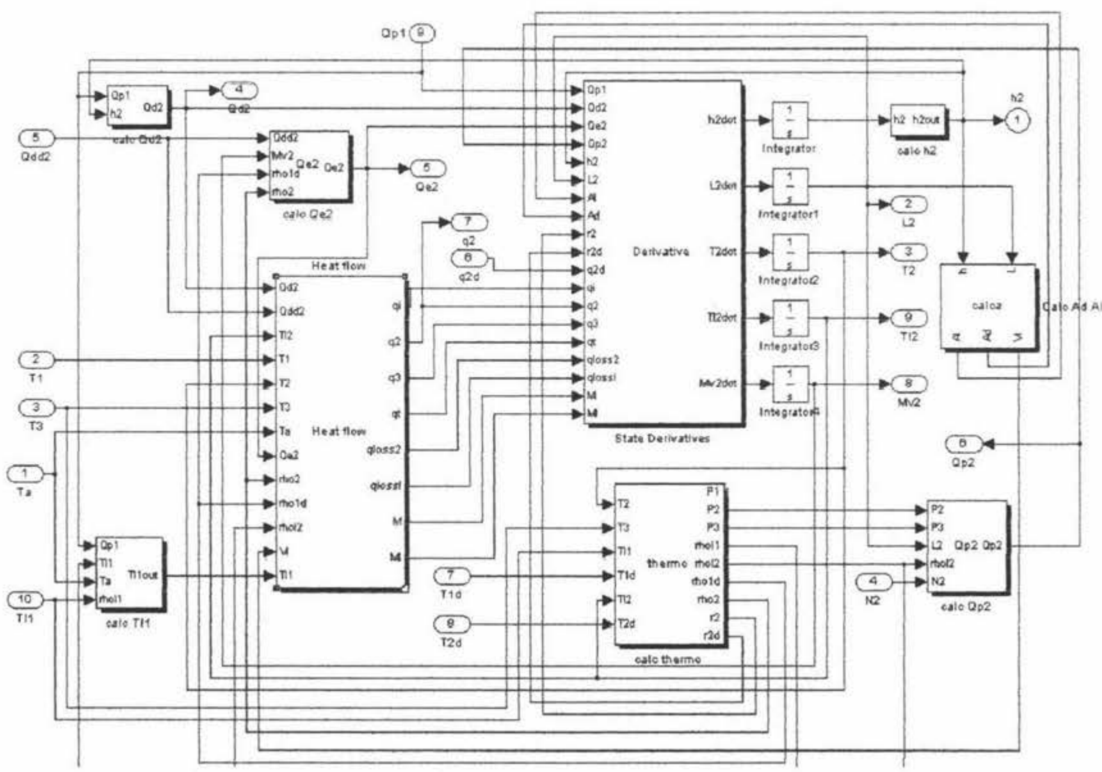
Third Level of Effect 1 Sub-system



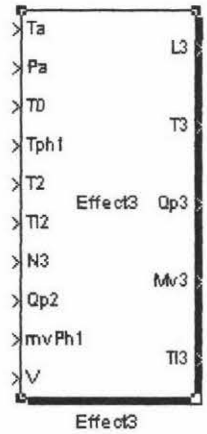
First Level of Effect 2 Sub-system



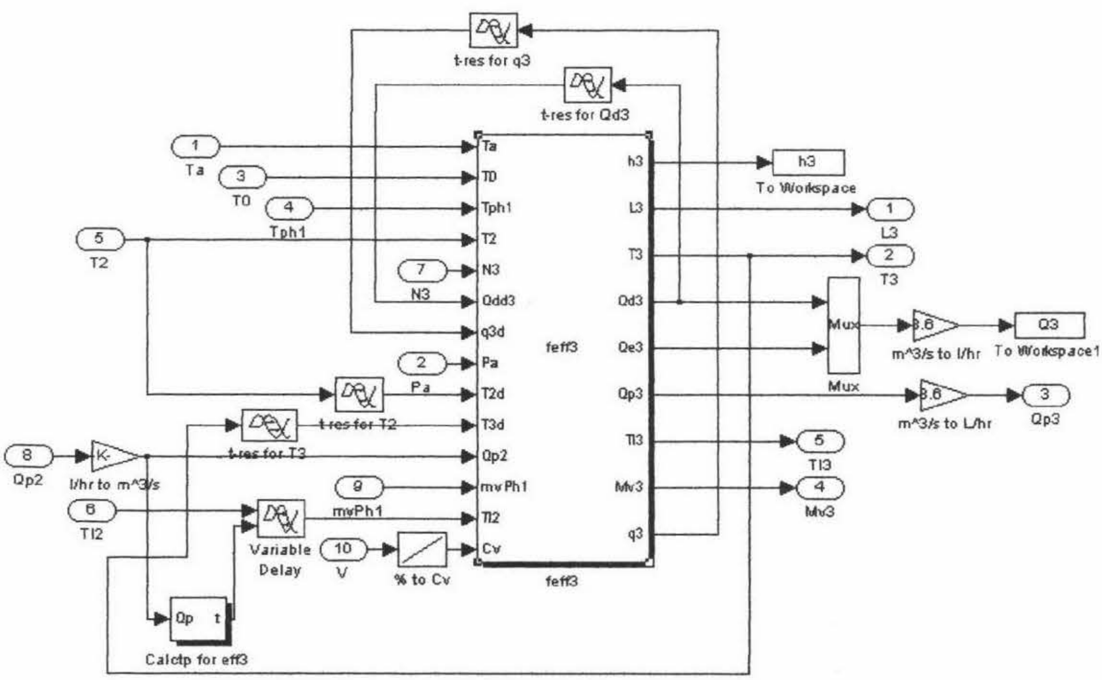
Second Level of Effect 2 Sub-system



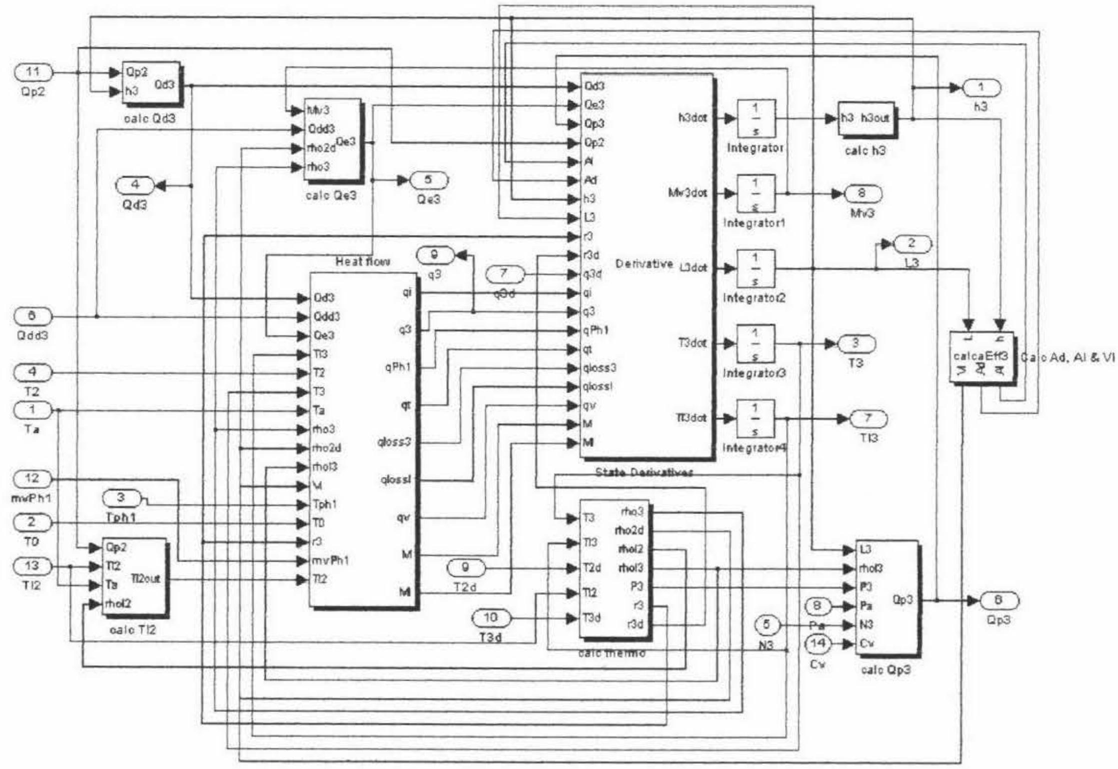
Third Level of Effect 2 Sub-system



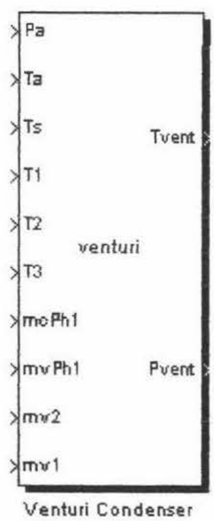
First Level of Effect 3 Sub-system



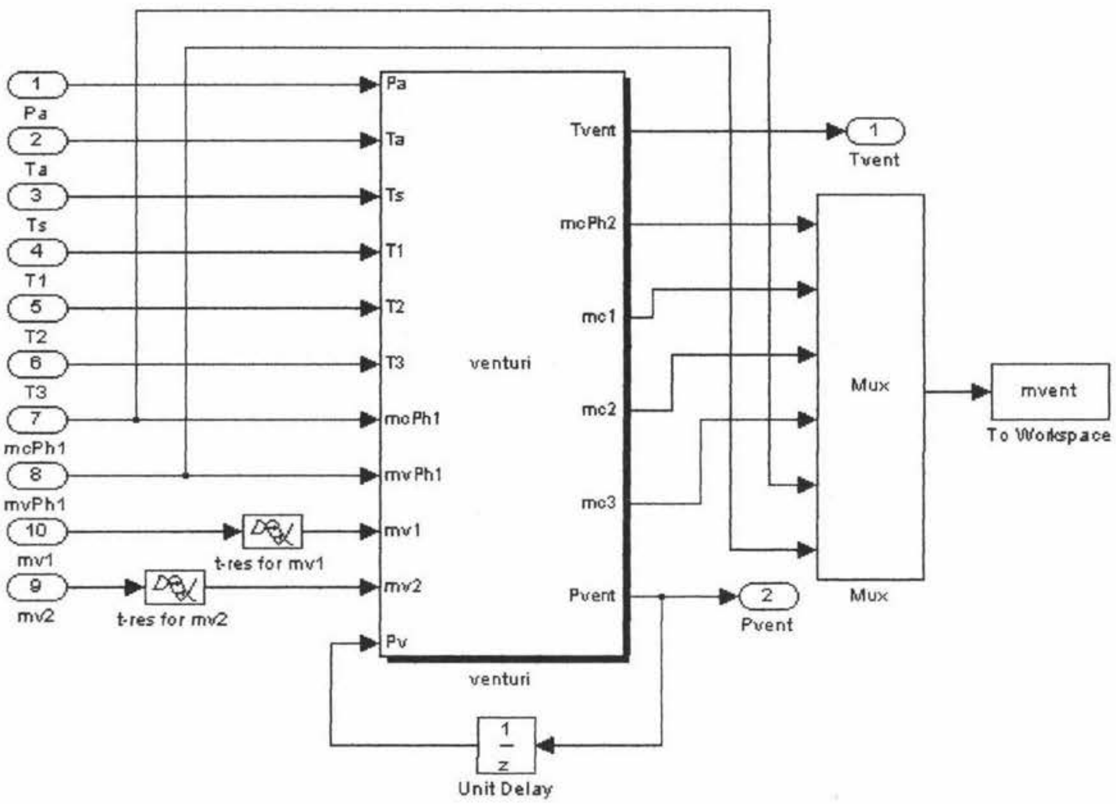
Second Level of Effect 3 Sub-system



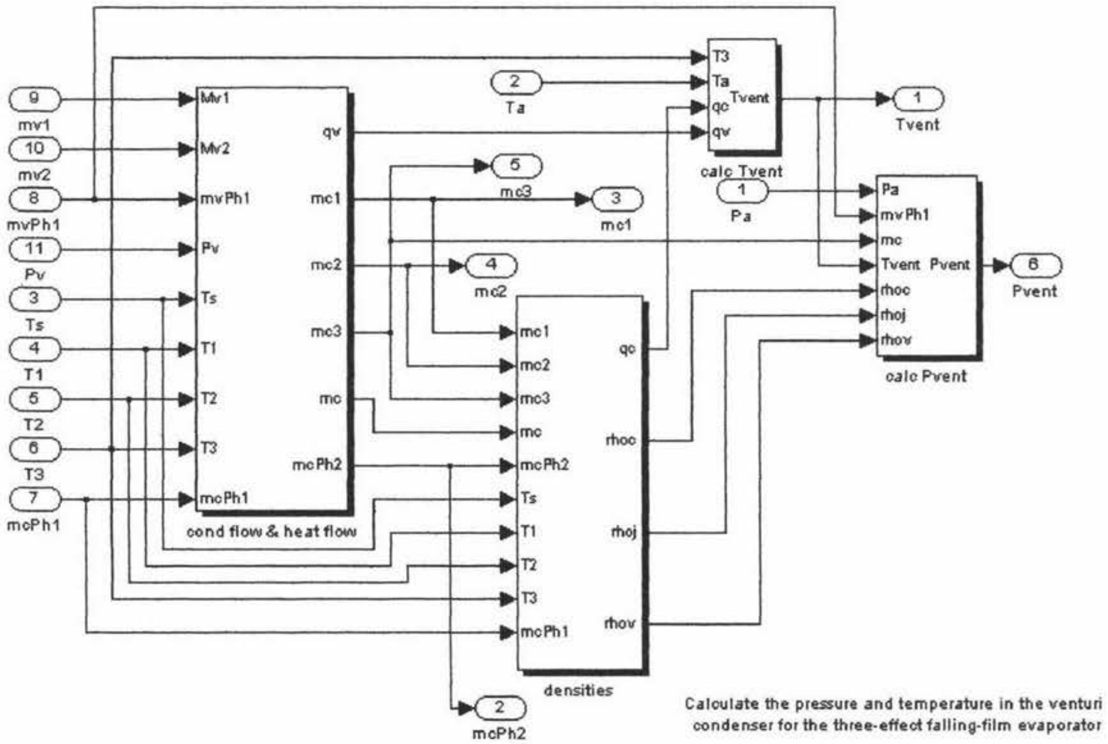
Third Level of Effect 3 Sub-system



First Level of Venturi Condenser Sub-system

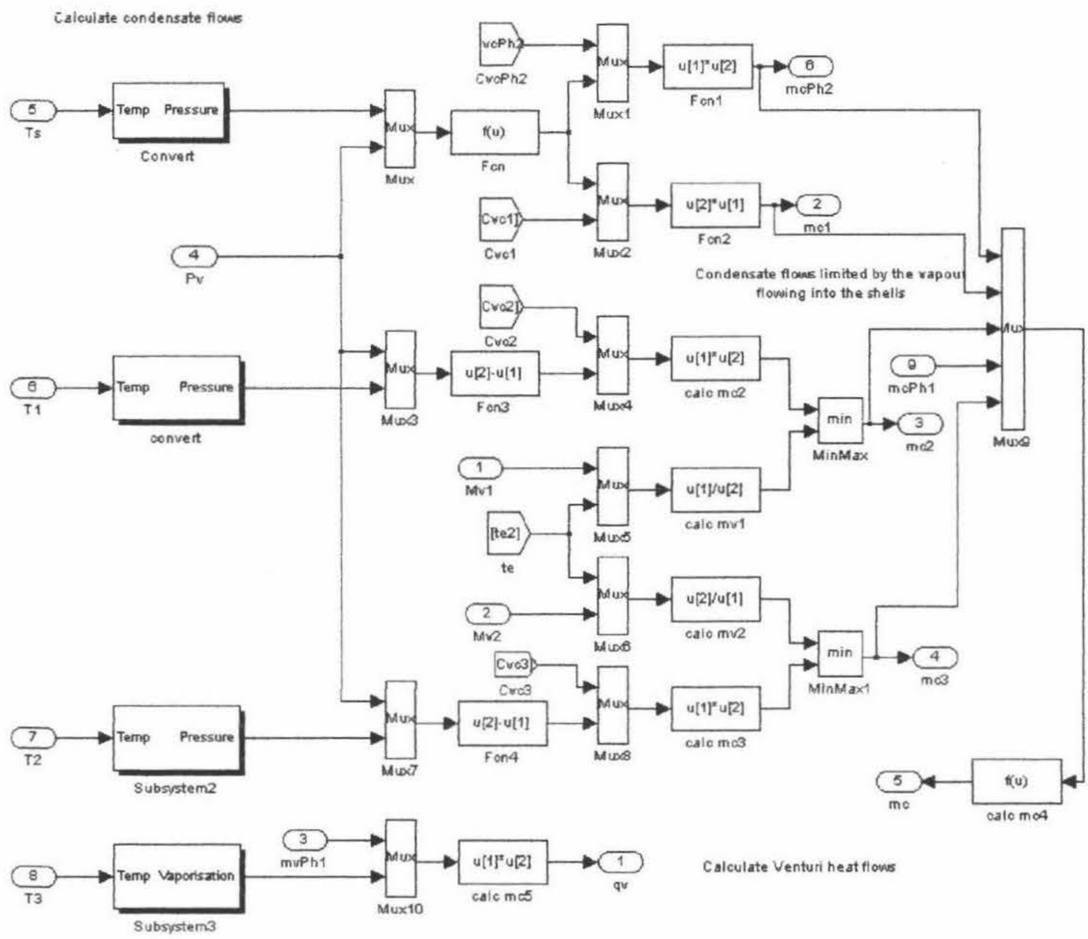


Second Level of Venturi Condenser Sub-system

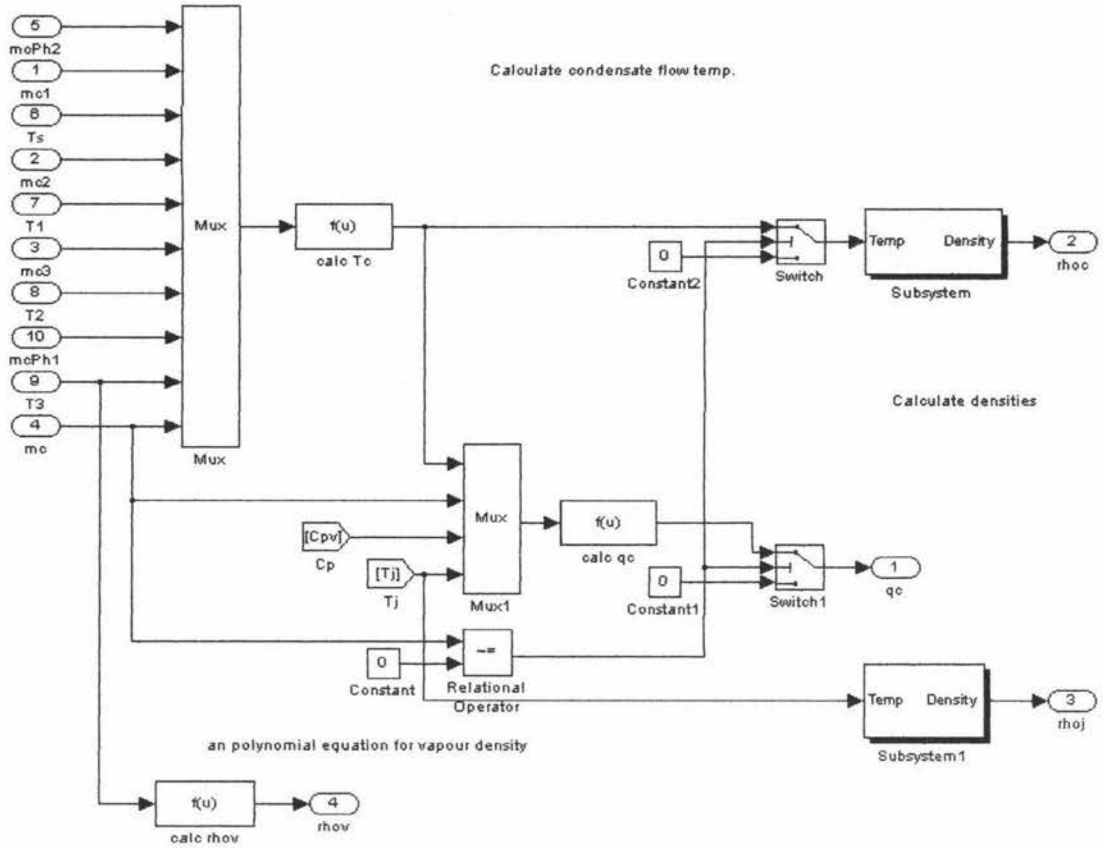


Third Level of Venturi Condenser Sub-system

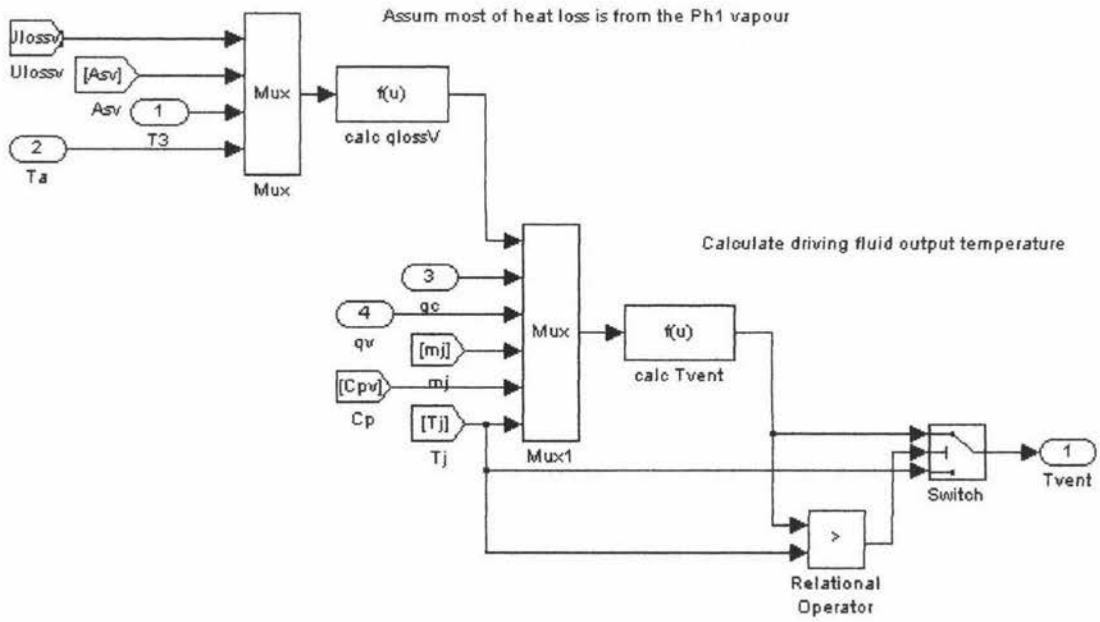
Sub-blocks contained in the third level of Venturi Condenser:



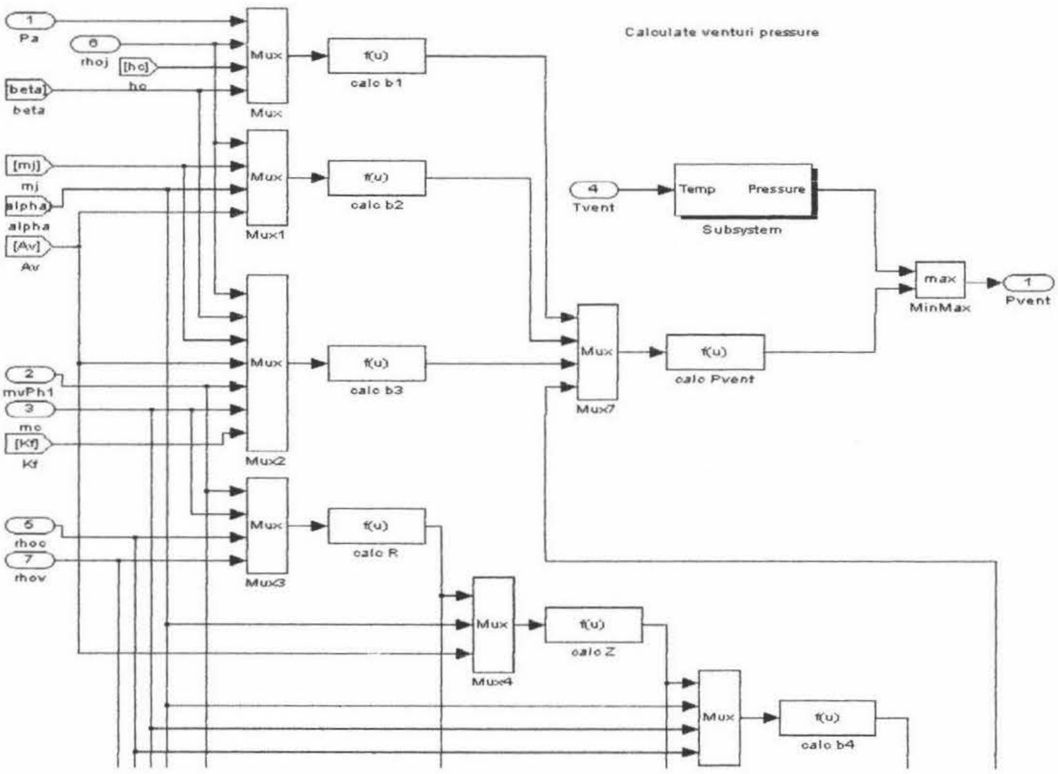
Condensate Flow & Heat Flow Sub-block



Densities Sub-block

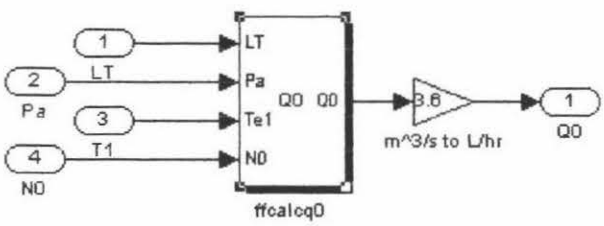


calc Tvent Sub-block

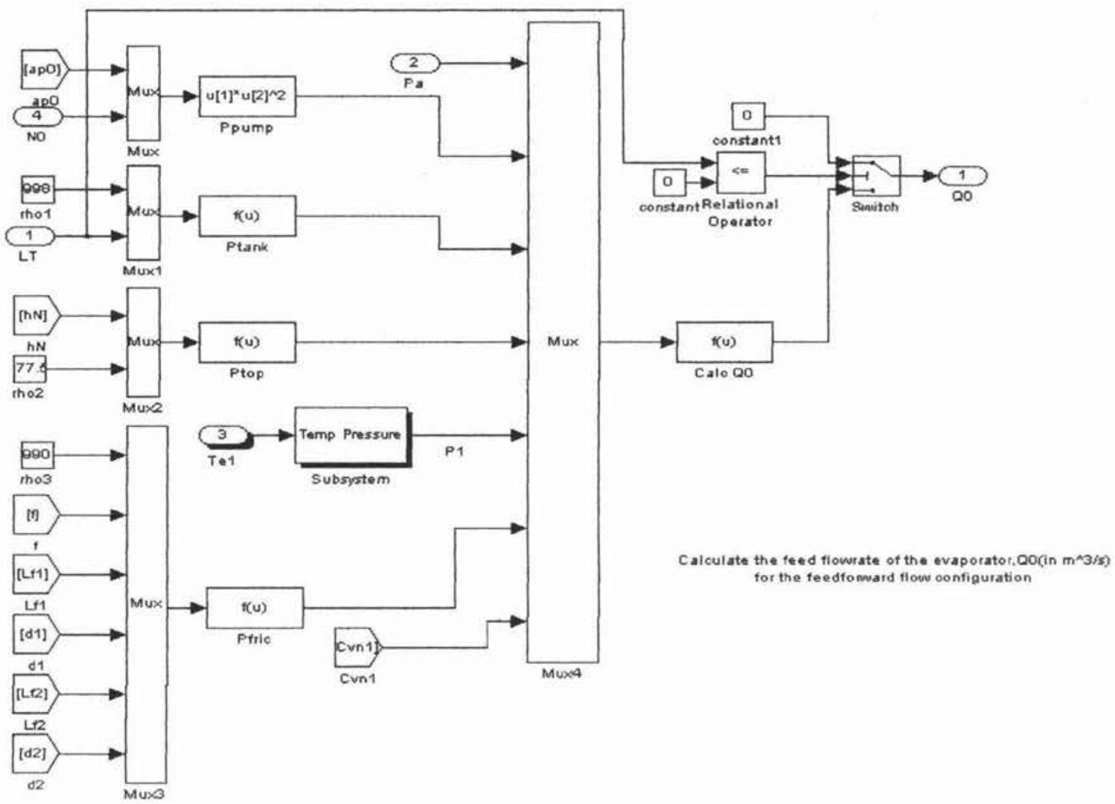


calc Pvent Sub-block

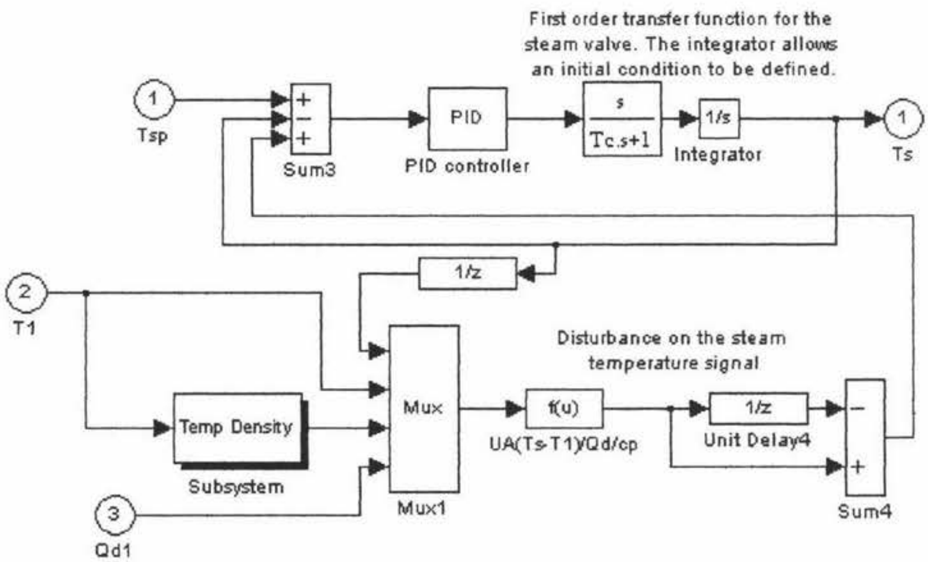
Other Sub-blocks used in Simulink model:



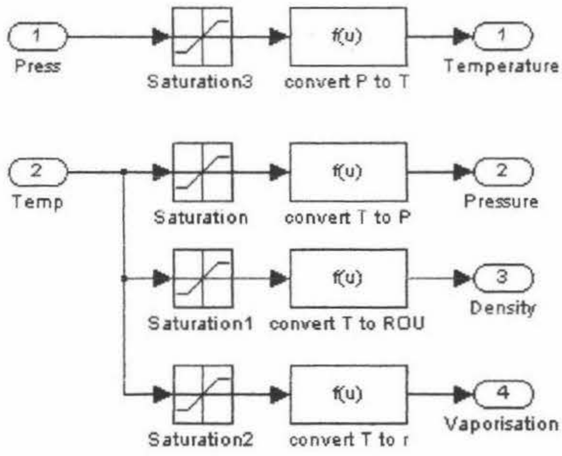
ffcalcq0.mdl



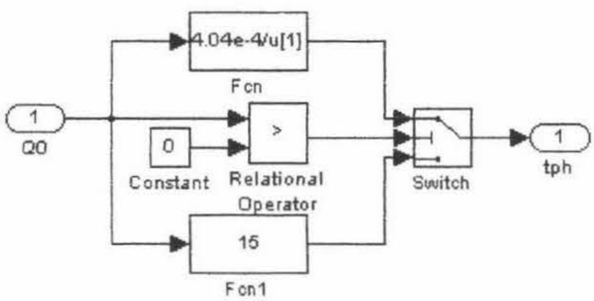
ffcalcq0.mdl



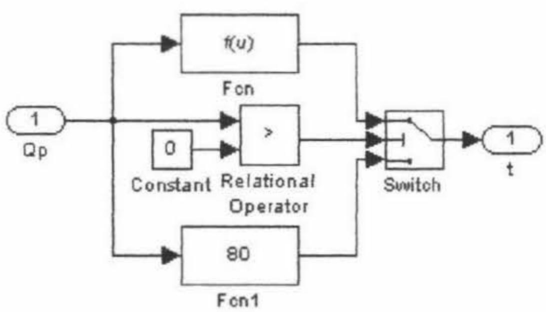
CalcTs.mdl



Convert.mdl



Calct$_{ph}$.mdl



Calct.mdl

Appendix 6

1. FIX32 SCADA system database

There are two types of database blocks used to develop Fix32 database, primary blocks and secondary blocks. Primary blocks can receive data from the Driver Image Table and generate alarms based upon data (such as AI and AO blocks). Secondary blocks manipulate data according to the instructions. It receives input from an upstream or primary block and performs a specific function with that input (such as TR block).

AI (analog input) blocks contain input parameters for the SCADA system; these parameters are the outputs of the Simulink model. AI blocks were constructed for the following parameters.

- **EFF1FLOW** - Effect 1 outlet flowrate.
- **EFF1LEVEL** - Effect 1 liquid level.
- **EFF1PRESS** - Effect 1 shell pressure.
- **EFF1TEMP** - Effect 1 shell temperature.
- **EFF2FLOW** - Effect 2 outlet flowrate.
- **EFF2LEVEL** - Effect 2 liquid level.
- **EFF2PRESS** - Effect 2 shell pressure.
- **EFF2TEMP** - Effect 2 shell temperature.

* **EFF3FLOW** - Effect 3 outlet flowrate.
* **EFF3LEVEL** - Effect 3 liquid level.
* **EFF3PRESS** - Effect 3 shell pressure.
* **EFF3TEMP** - Effect 3 shell temperature.
* **FEEDFLOW** - Effect 1 in feed flowrate.
* **FEEDLEVEL** - Feed tank level.
* **PREHT1PRES** - Preheater 1 pressure.
* **PREHT1TEMP** - Preheater 1 temperature.
* **PREHT2PRES** - Preheater 2 pressure.
* **PREHT2TEMP** - Preheater 2 temperature.
* **STEAMPRESS** - External steam pressure.

AO (analog output) blocks contain output parameters for the SCADA system; these parameters are the inputs of the Simulink model. AO blocks were constructed for the following parameters.

* **FEEDPUMP** - Feed tank outlet pump speed.
* **STMVALVE** - External steam valve position.
* **EFF1PUMP** - Effect 1 outlet pump speed.
* **EFF2PUMP** - Effect 2 outlet pump speed.
* **EFF3PUMP** - Effect 3 outlet pump speed.

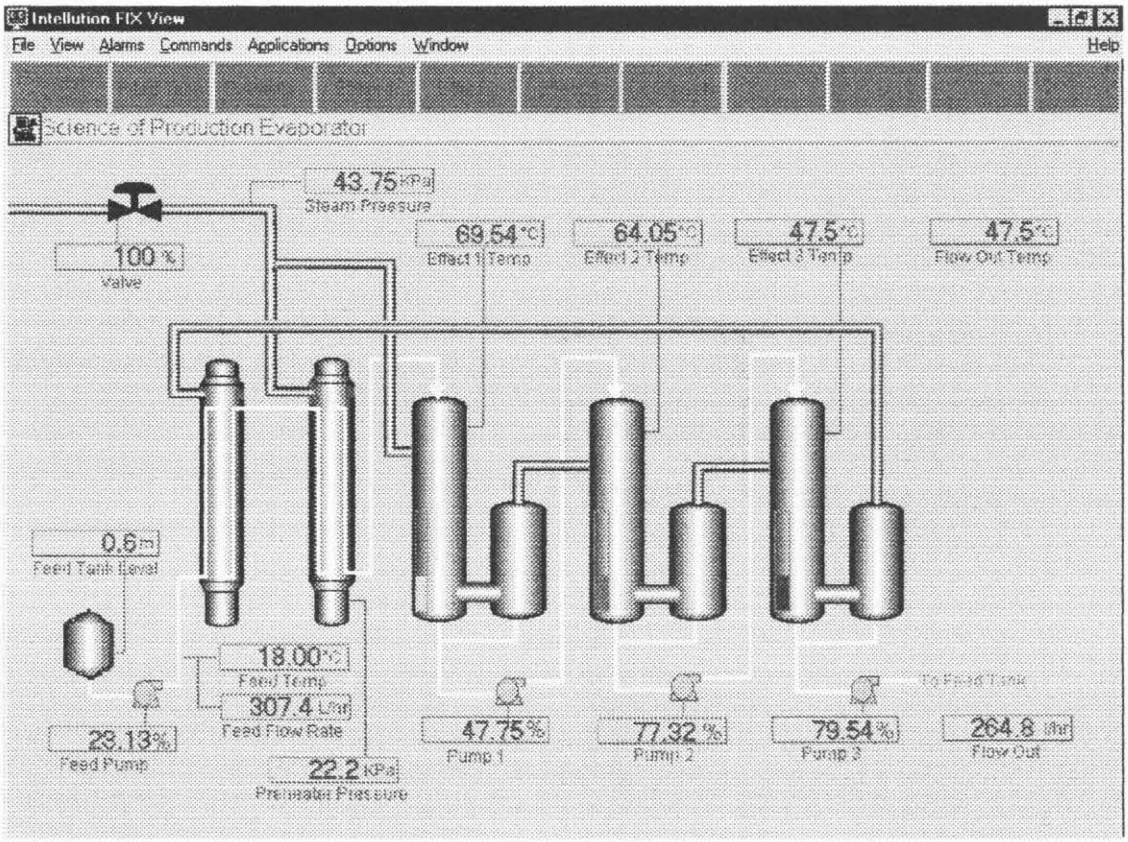
- **FEEDTEMP** - Temperature of the product leaving the feed tank.
- **AMBTEMP** - Ambient temperature.
- **INFLOW** - Product flowrate into the feed tank.
- **STMINTEMP** - Temperature of the external steam supply.
- **AMBPRESS** - Ambient pressure.

All the parameters used in AI and AO blocks are used in TR (Trend) blocks too. AI and AO blocks connect with TR blocks structured for SCADA system chains.

2. FIX32 SCADA system control screens

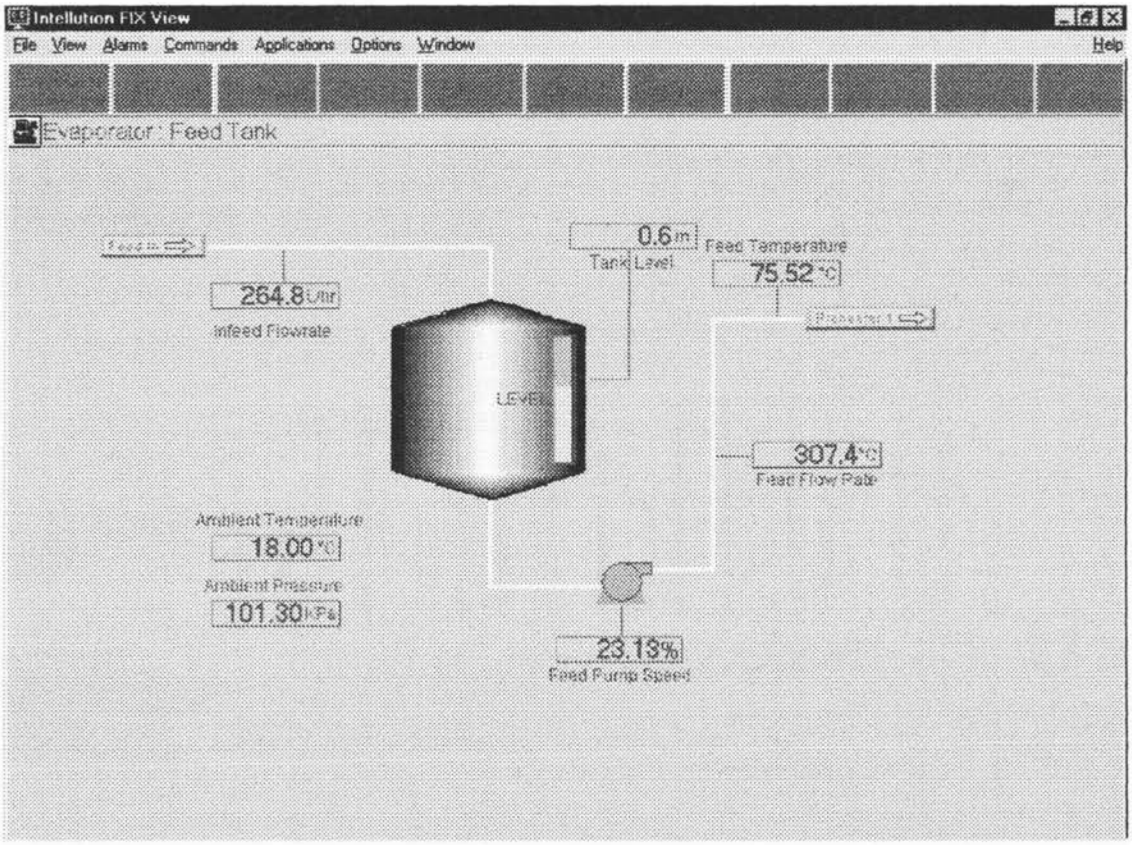
Control screens are graphical display tools used for displaying process information of the real-time simulator. Users can manipulate values of the system input variables directly from the control screens. The control screens include seven pictures that are Evapma_p.odf, Ftank_p.odf, Prehea_p.odf, Eff1_p.odf, Eff2_p.odf, Eff3_p.odf and Condan_p.odf.

- **Evapma_p.odf** is an overview of the entire evaporator plant. It shows all the system information for feed tank, preheater, effect 1, effect 2 and effect3.



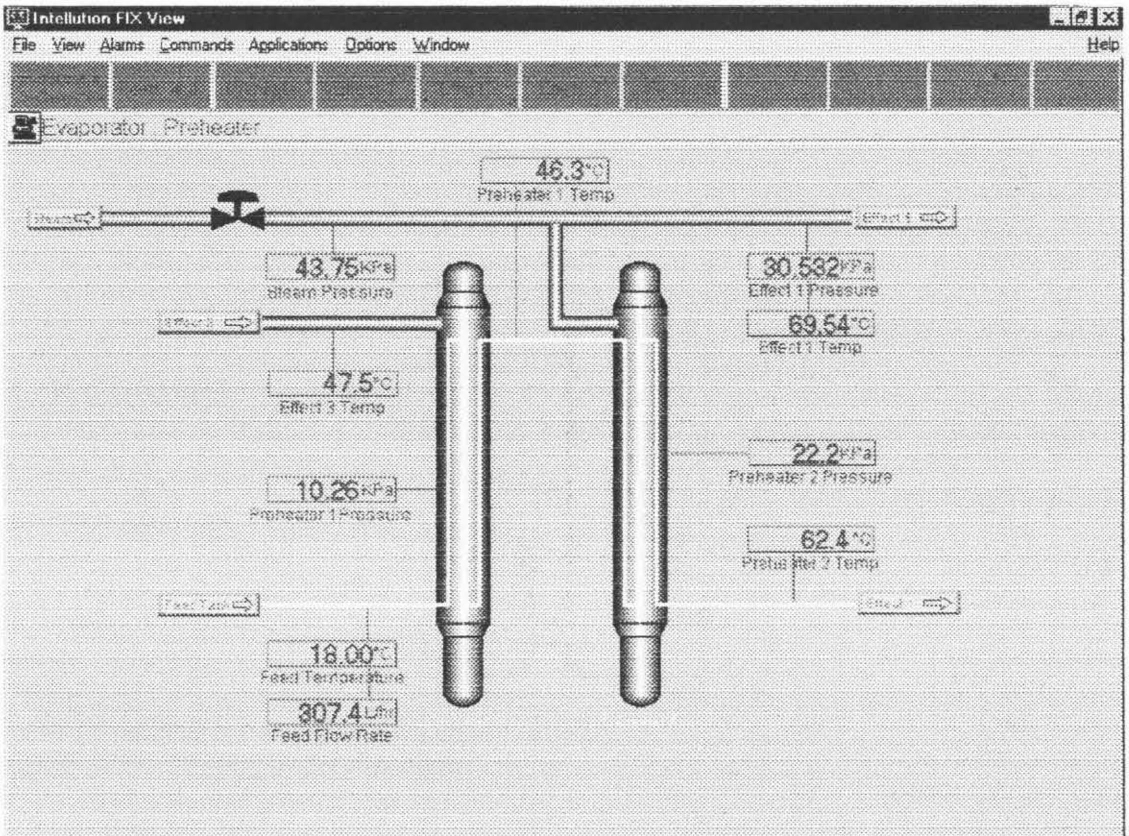
Evapma_p.odf

- **Ftank_p.odf** displays the information of the feed tank such as tank level, feed pump speed and input/outputflowrate.



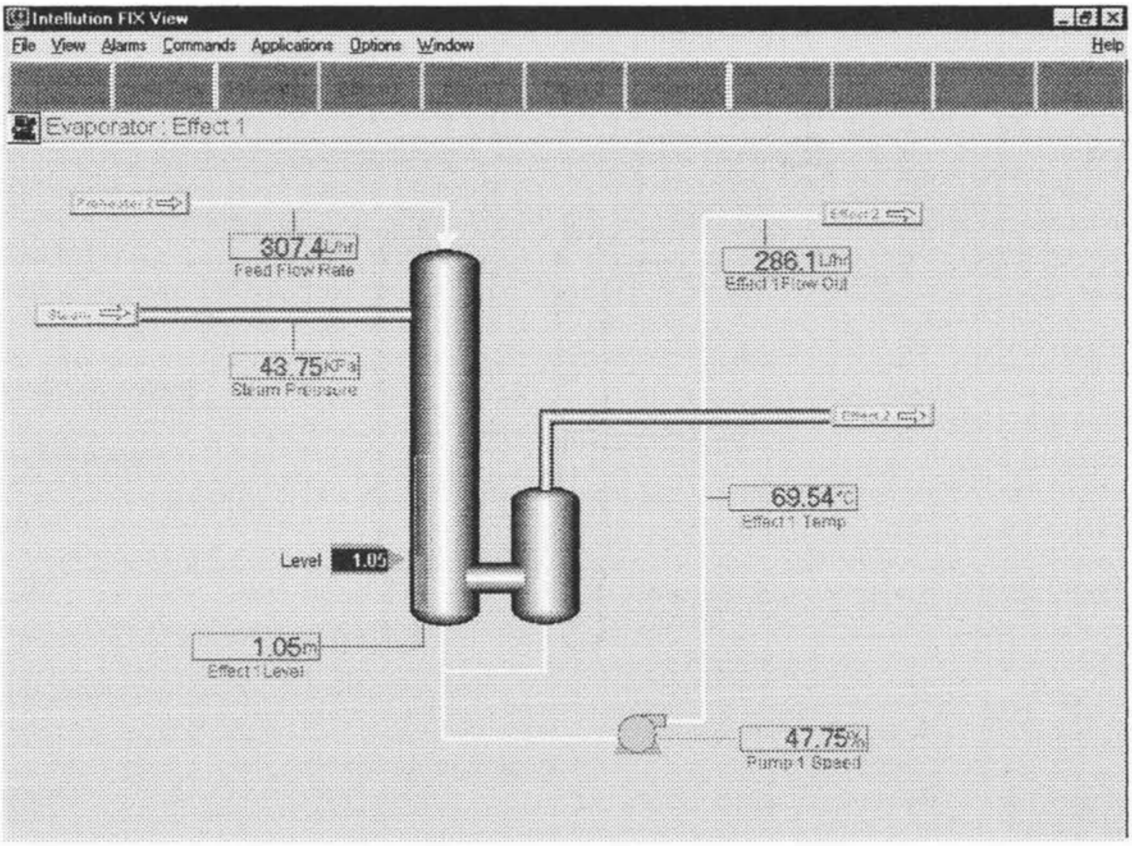
Ftank_p.odf

* **Prehea_p.odf** shows the information for the preheater such as preheater temperature, pressure and steam pressure.

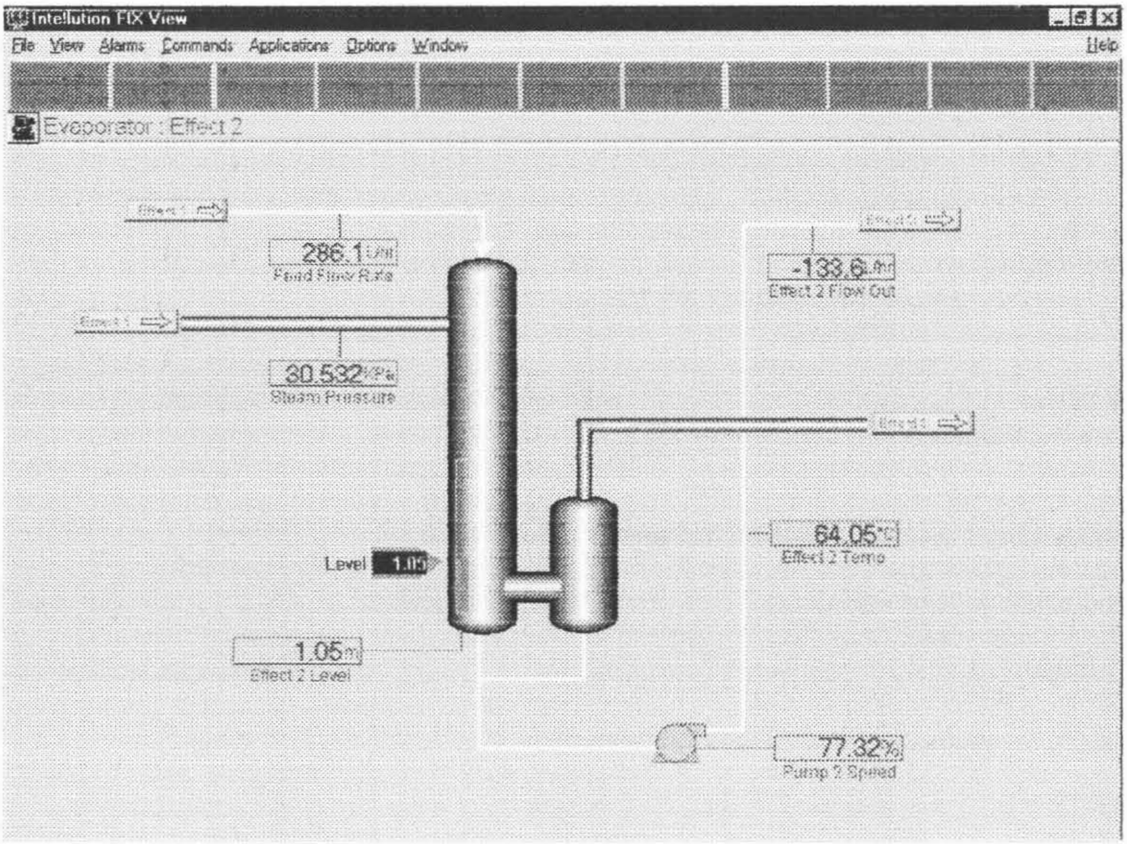


Prehea_p.odf

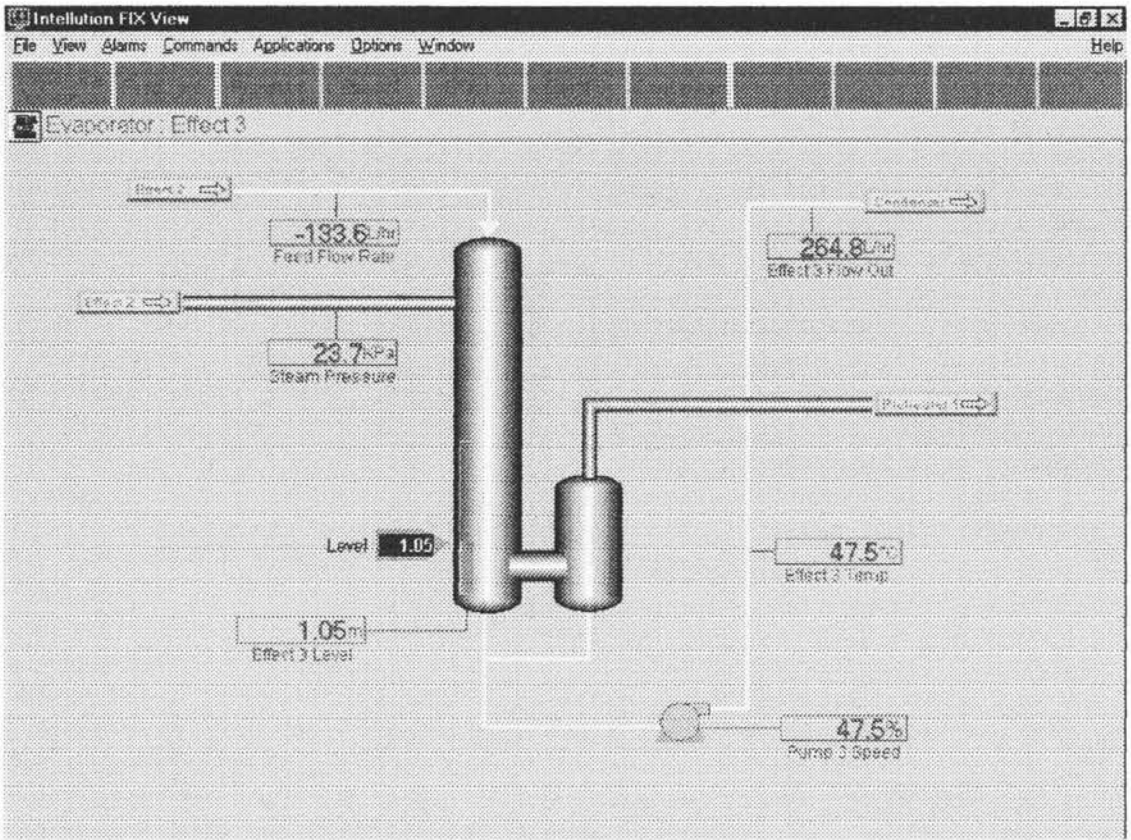
* **Eff1_p.odf**, **Eff2_p.odf** and **Eff3_p.odf** show the information for the three effects such as feed flowrate, effect level, effect temperature and pump speed.



Eff1_p.odf


Intellution FIX View
File View Alarms Commands Applications Options Window
Help
Evaporator : Effect 2
286.1
Feed Flow Rate
-133.6
Effect 2 Flow Out
30.532KPa
Steam Pressure
Level
64.05°C
Effect 2 Temp
1.05m
Effect 2 Level
77.32%
Pump 2 Speed

Eff2_p.odf


Intellution FIX View
File View Alarms Commands Applications Options Window Help
Evaporator : Effect 3
-133.6 L/hr
Feed Flow Rate
264.8 L/hr
Effect 3 Flow Out
23.7 kPa
Steam Pressure
Level 1.05
47.5
1.05 m
Effect 3 Level
47.5%
Pump 3 Speed

Eff3_p.odf

Appendix 7

Constants used in Simulink Model

Effect 1 Sub-model			
Parameter	**Value**	**Parameter**	**Value**
Ah	2.36e-6	Cp	4191
te	4	U1	2787
Ae1	0.3313	U2	2794
Ae2	0.3313	Uloss	4.8
As	1.059	Uloss1	4.8
As1	0.363	Le	10.5
d	0.0218	f	0.009
hN	4.82	ap	2.1919e-2
Cn2	5.7684e-7		
Effect 2 Sub-model			
Parameter	**Value**	**Parameter**	**Value**
Ah	2.36e-4	te	4
Cp2	4185	U2	2794
Ae2	0.3313	U3	1841
Ae3	0.2137	Uloss	4.5
As	1.059	Uloss1	4.5
As1	0.363	Ulossp1	4.8
Asp1	0.55	Cp1	4191
hN	4.82	Le	10.5
d	0.0218	f	0.009
ap	2.3149e-2	Cn3	2.5118e-7
Effect 3 Sub-model			
Parameter	**Value**	**Parameter**	**Value**
Ah	2.36e-4	te	4
Cp3	4179	U3	1841
Ae3	0.2137	Uloss	3.8
As	1.099	Uloss1	3.8
As1	0.379	Uph1	1807
Aph1	0.227419892	Ulossp2	4.5
Asp2	0.55	Cp2	4185
Le	21.8	d	0.218
f	0.009	hV	1.0

ap	2.9533e-2		
Preheater 1 Sub-model			
Parameter	**Value**	**Parameter**	**value**
Uloss1	3.8	Asph	0.65
Uph1	1807	Aph	0.198769
te	4	Cp	4179
L	5.7	Atank	0.159
dT	1	a	9.8e-3
d	11.1e-3		
Venturi Condenser			
Parameter	**Value**	**Parameter**	**Value**
Ulossv	4.8	Asv	0.105
Cp	4180	mj	0.3
Tj	20	Cvcph2	1.92e-5
Cvc1	2.16e-5	Cvc2	2.72e-5
Cvc3	3.3e-5	te	4
hc	1.8	dj	3
kf	0.3	Av	3.73e-4
a	1.96e-5	α	0.01894
β	0.0525		

Initial Conditions for Simulink Sub-model

Preheater 1 Sub-model			
State Variable	**Value**	**State Variable**	**Value**
Mv3	0.0222	qPh1	7715.86
Tph1	46.3248	T3	47.5266
T0	18	LT	0.6
Preheater 2 Sub-model			
State Variable	**Value**	**State Variable**	**Value**
Ts	78.0491	Tph1	46.3248
Effect 1 Sub-model			
State Variable	**Value**	**State Variable**	**Value**
q1	7856.7017	Qd1	8.5389e-5
Tph2	62.39	T1	69.54
Ts	78.04906537	h1	6.6724e-3
L1	1.05	T11	69.2770735
Mv1	0.0111	T13	47.38681844
Mv3	0.0222		

Effect 2 Sub-model			
State Variable	**Value**	**State Variable**	**Value**
q2	5081.8306	Qd2	8.2885e-5
T1	69.54	T2	64.05
T11	69.2770735	h2	6.2869e-3
L2	1.05	T2	64.05
T12	63.8216	Mv2	0.0111
Effect 3 Sub-model			
State Variable	**Value**	**State Variable**	**Value**
q3	6500.89355	Qd3	0.00079805
T2	64.05	T3	47.52601683
T12	63.82159855	h3	0.005828
L3	1.05		

Appendix 8

Fulling-film Evaporator Simulink Sub-model Steady-state Testing.

1. Preheater 1 Sub-model Testing

Figure 7-1 shows how the preheater 1 sub-model was tested. Parameter "U" in constant block is the input vector that manually input into "Matlab Command Window" and saved as MAT-file. "U" contains all the sub-model's inputs: Ta, Qin, T0, Q0, T3, Mv3. The outputs of the sub-model (LT, Tph1, mcPh1 and mvPh1) are adjusted into steady state by adjusting the state vectors of the sub-model. The other figures show the steady state values of the sub-model outputs.

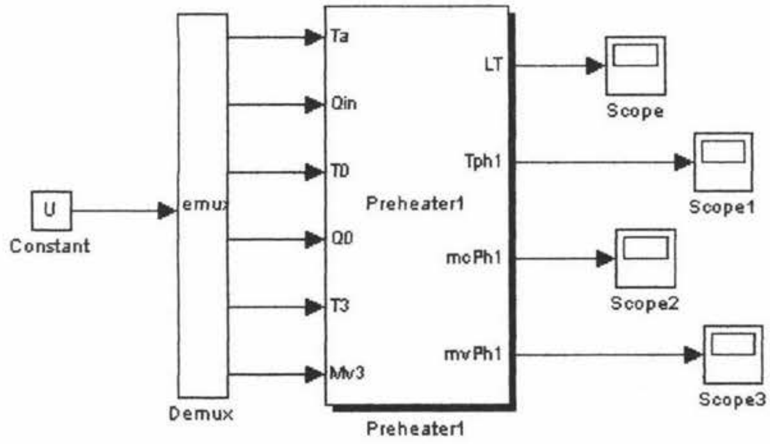


Figure 7-1: Preheater 1 sub-model testing

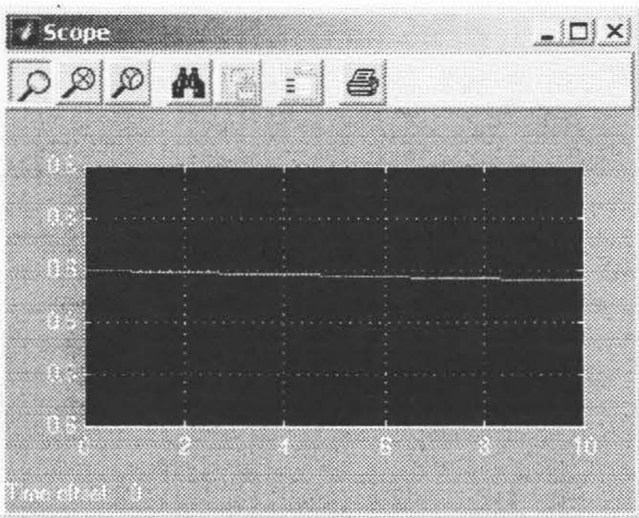


Figure 7-2: Perheater 1 Sub-model output LT

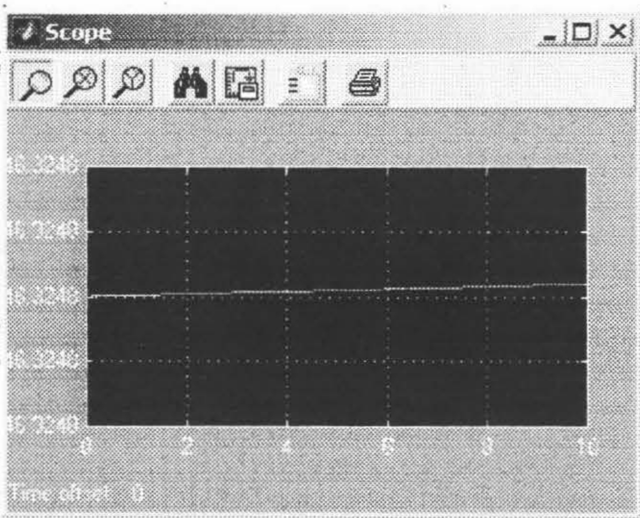


Figure 7-3: Preheater 1 Sub-model output Tph1

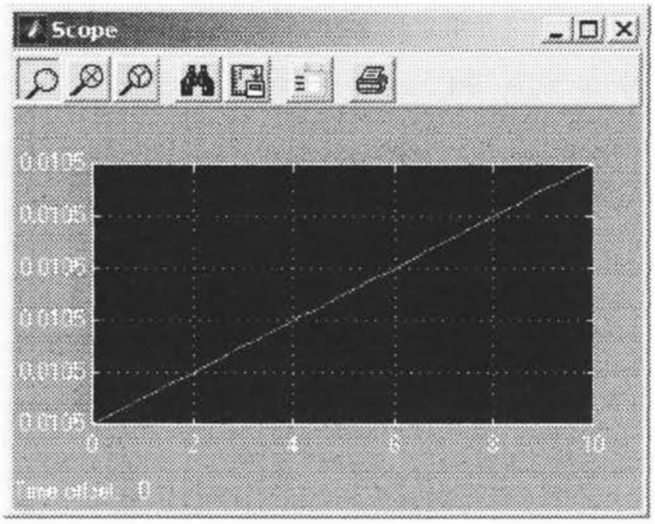


Figure 7-4: Preheater 1 Sub-model output mcPh1

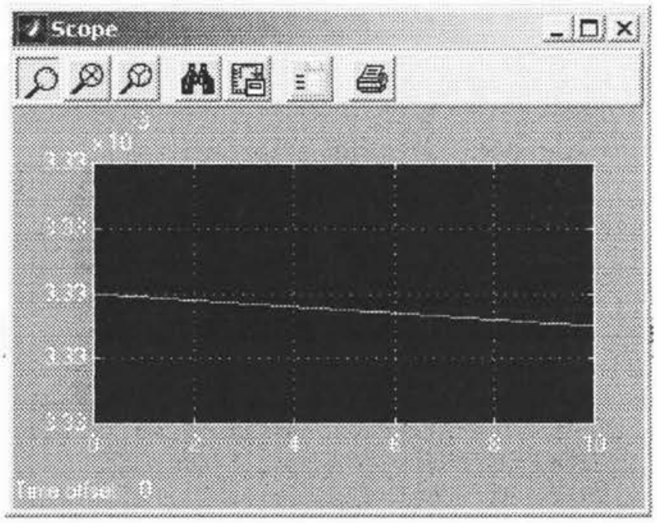


Figure 7-5: Preheater 1 Sub-model output mvPh1

2. Preheater 2 Sub-model Testing

Figure 7-6 shows how the preheater 2 sub-model been tested. Parameter "U" in constant block is the input vector that manually input into "Matlab Command Window" and saved as MAT-file. "U" contains all the sub-model's inputs: Ts, Tph1, Q0. The output of the sub-model Tph2 are adjusted into steady state by adjusting the state vectors of the sub-model. The other figure shows the steady state value of the sub-model output.

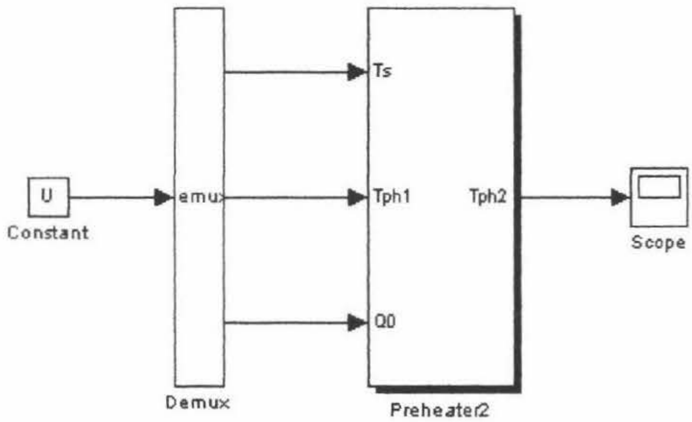


Figure 7-6: Preheater 2 Sub-model Testing

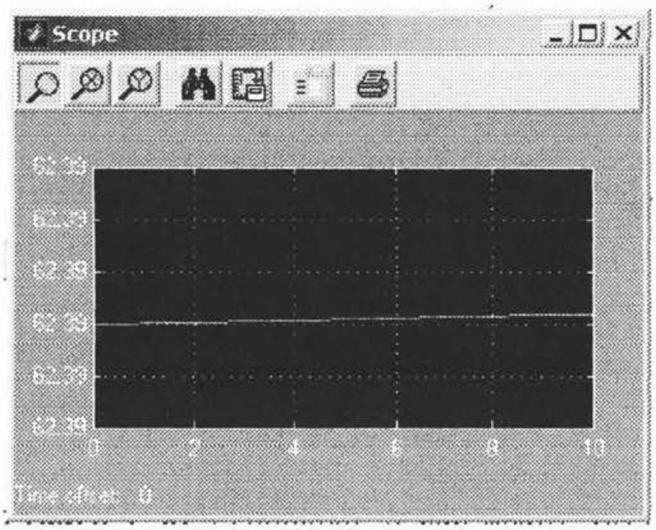


Figure 7-7: Preheater 2 Sub-model output Tph2

3. Effect 1 Sub-model Testing

Figure 7-8 shows how the Effect 1 sub-model has been tested. Parameter "U" in constant block is the input vector that manually input into "Matlab Command Window" and saved as a MAT-file. "U" contains all the sub-model's inputs: Ta, Ts, Tph2, T2, N1, Q0. The outputs of the sub-model (L1, T1, Tl1, Qp1, Mv1, Qd1) are adjusted into steady state by adjusting the state vectors of the sub-model. The other figures show the steady state value of the sub-model outputs.

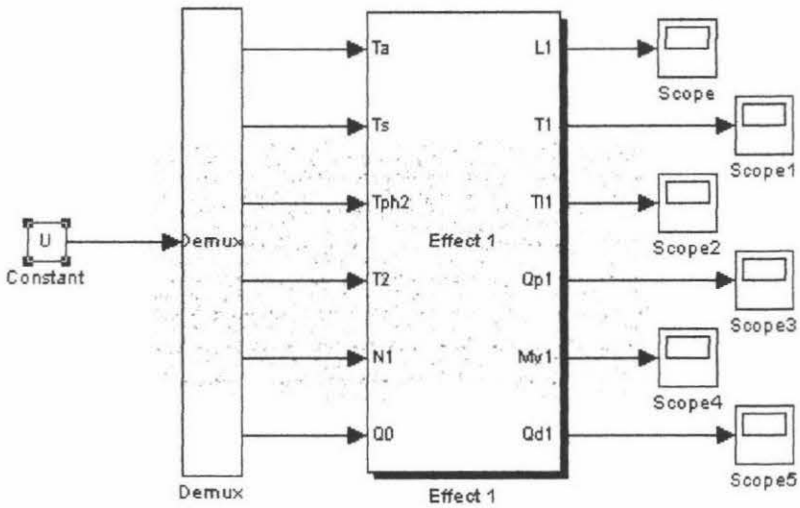


Figure 7-8: Effect 1 Sub-model Testing

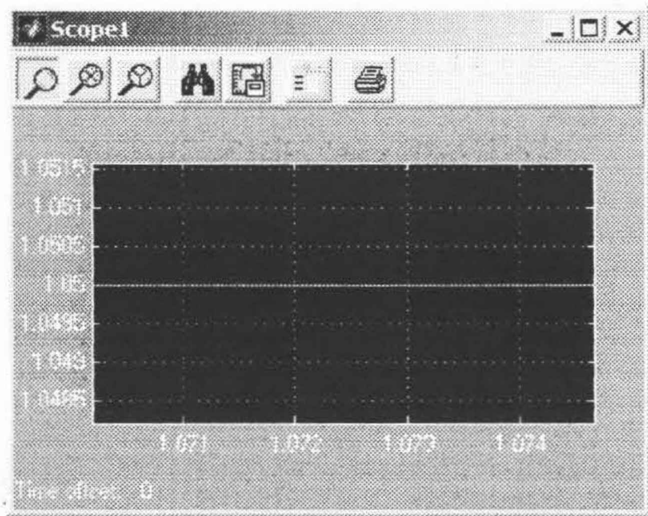


Figure 7-9: Effect 1 Sub-model output L1

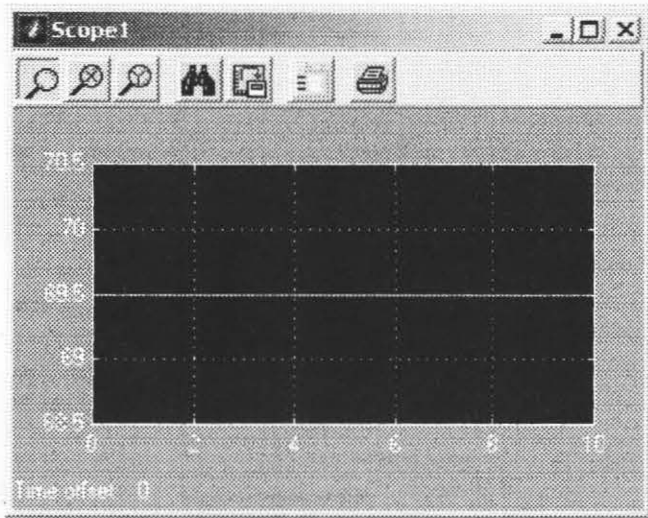


Figure 7-10: Effect 1 Sub-model output T1

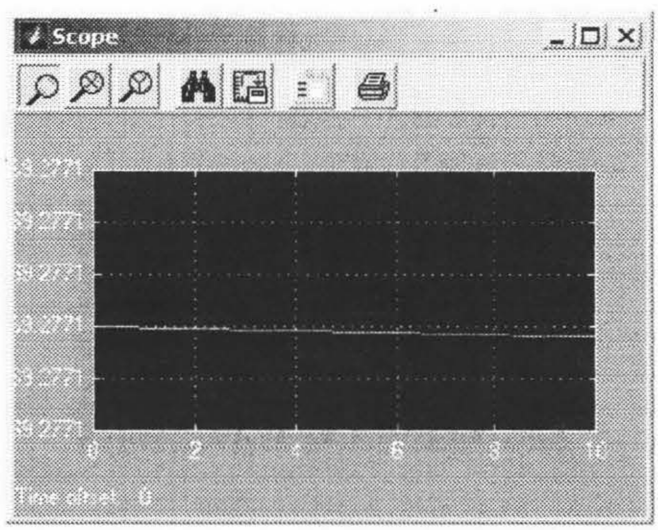


Figure 7-11: Effect 1 Sub-model output T11

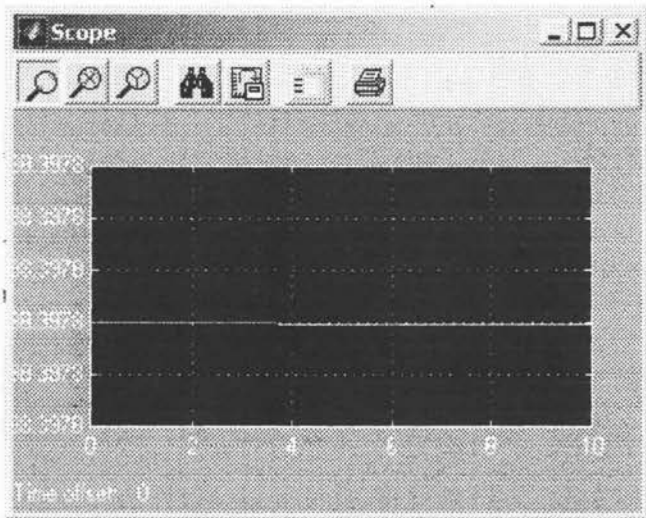


Figure 7-12: Effect 1 Sub-model output Qp1

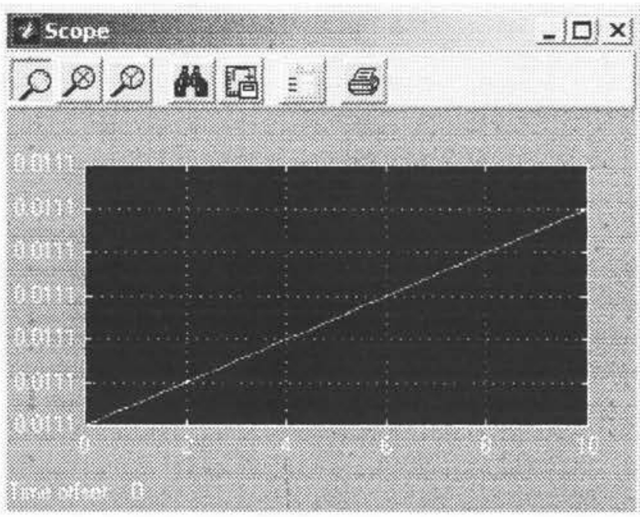


Figure 7-13: Effect 1 Sub-model output Mv1

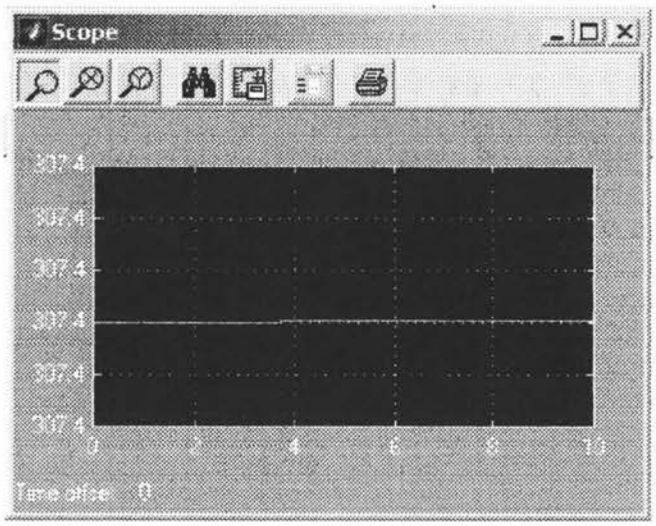


Figure 7-14: Effect 1 Sub-model output Qd1

4. Effect 2 Sub-model Testing

Figure 7-15 shows how the Effect 2 sub-model been tested. Parameter "U" in constant block is the input vector that manually input into "Matlab Command Window" and saved as MAT-file. "U" contains all the sub-model's inputs: Ta, T1, T3, Tl1, N2, Qp1. The outputs of the sub-model (L2, T2, Tl2, Qp2, Mv2) are adjusted into steady state by adjusting the state vectors of the sub-model. The other figures show the steady state value of the sub-model outputs.

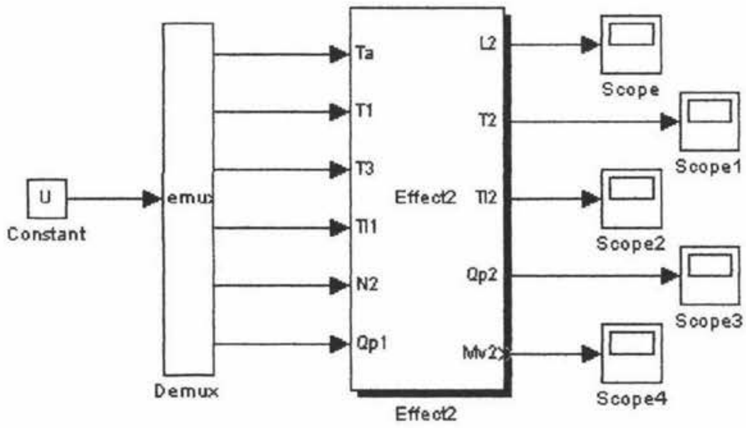


Figure 7-15: Effect 2 Sub-model Testing

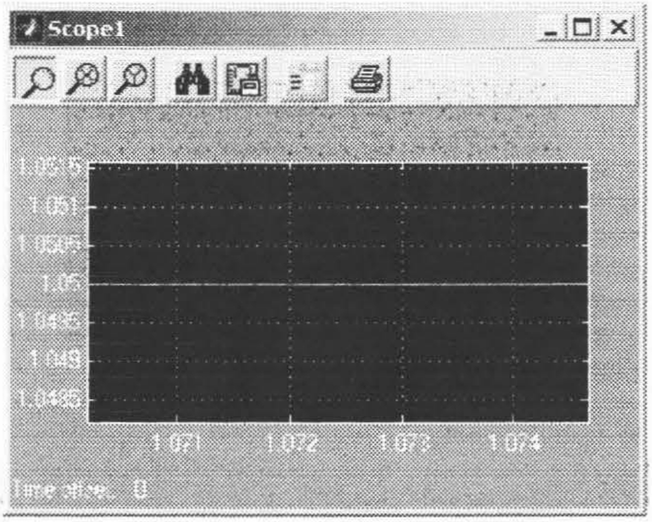


Figure 7-16: Effect 2 Sub-model output L2

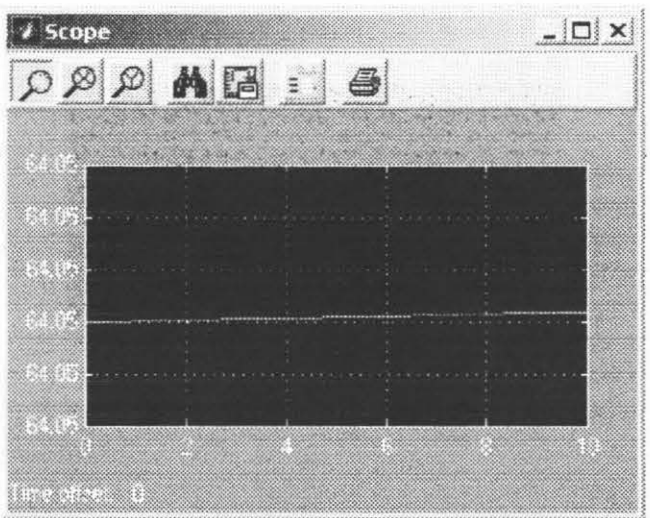


Figure 7-17: Effect 2 Sub-model output T2

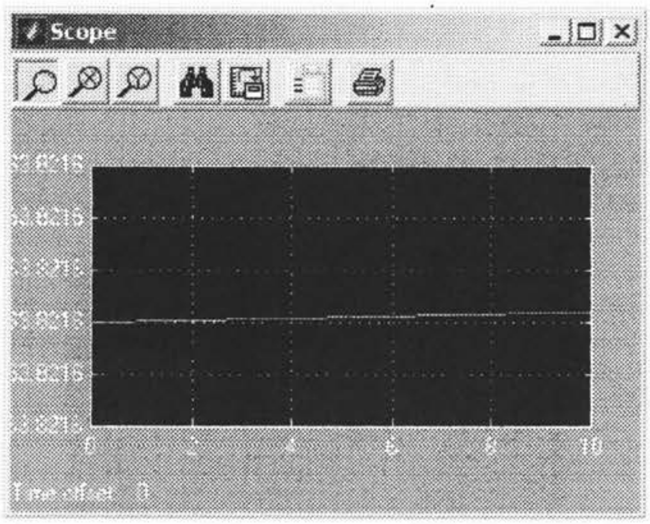


Figure 7-18: Effect 2 Sub-model output Tl2

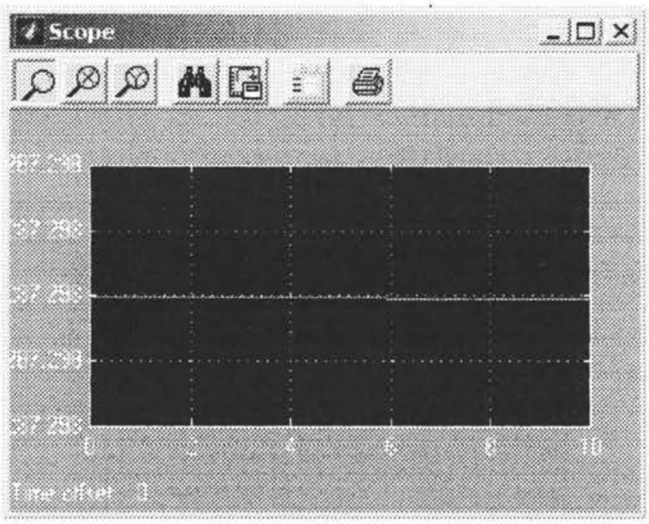


Figure 7-19: Effect 2 Sub-model output Qp2

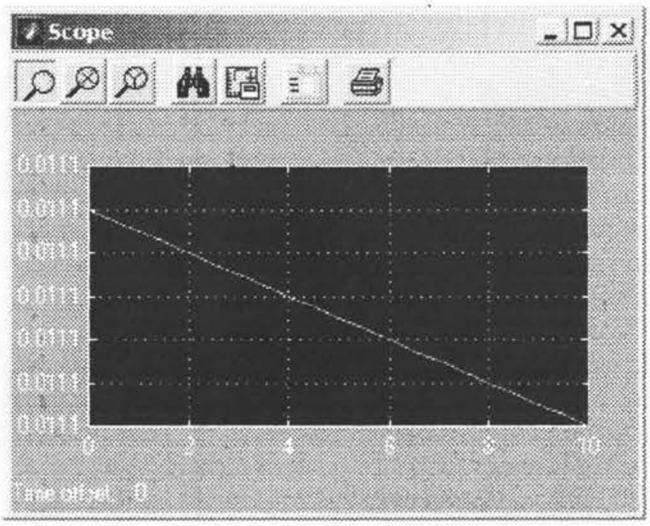


Figure 7-20: Effect 2 Sub-model output Mv2

5. Effect 3 Sub-model Testing

Figure 7-21 shows how the Effect 3 sub-model been tested. Parameter "U" in constant block is the input vector that manually input into "Matlab Command Window" and saved as MAT-file. "U" contains all the sub-model's inputs: Ta, Pa, T0, Tph1, T2, Tl2, N3, Qp2, mvPh1, V. The outputs of the sub-model (L3, T3, Tl3, Qp3, Mv3) are adjusted into steady state by adjusting the state vectors of the sub-model. The other figures show the steady state value of the sub-model outputs.

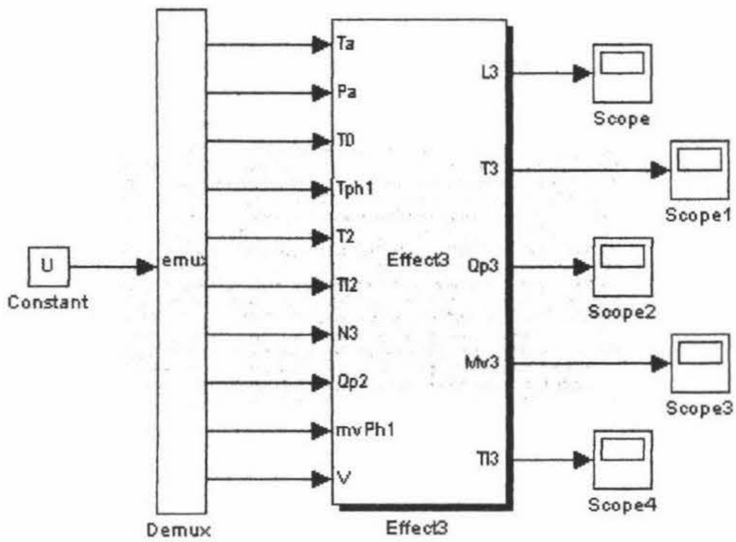


Figure 7-21: Effect 3 Sub-model testing

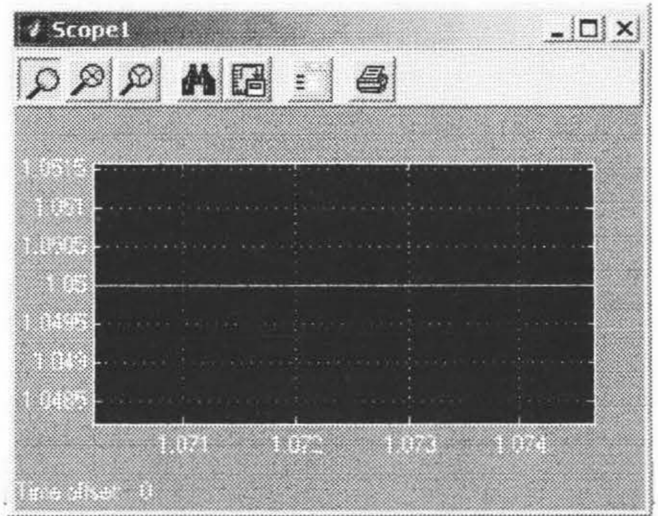


Figure 7-22: Effect 3 Sub-model output L3

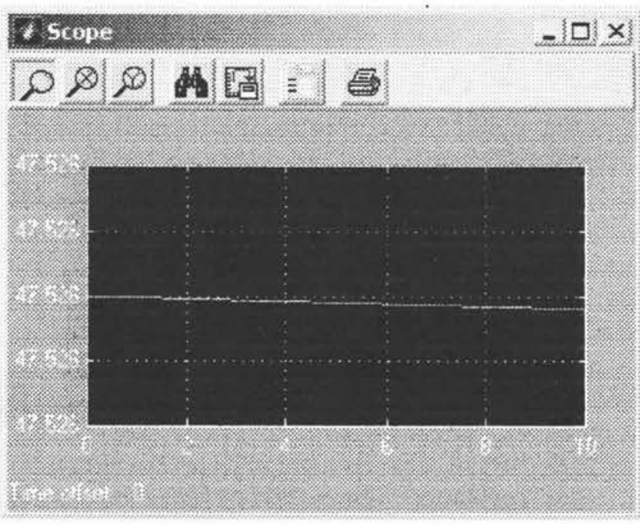


Figure 7-23: Effect 3 Sub-model output T3

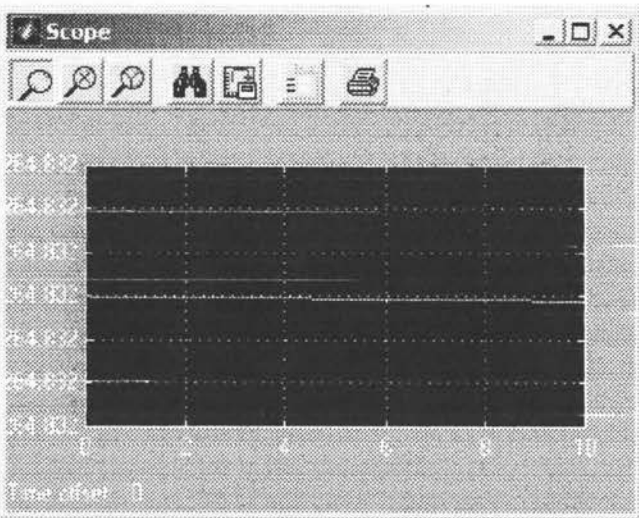


Figure 7-24: Effect 3 Sub-model output Qp3

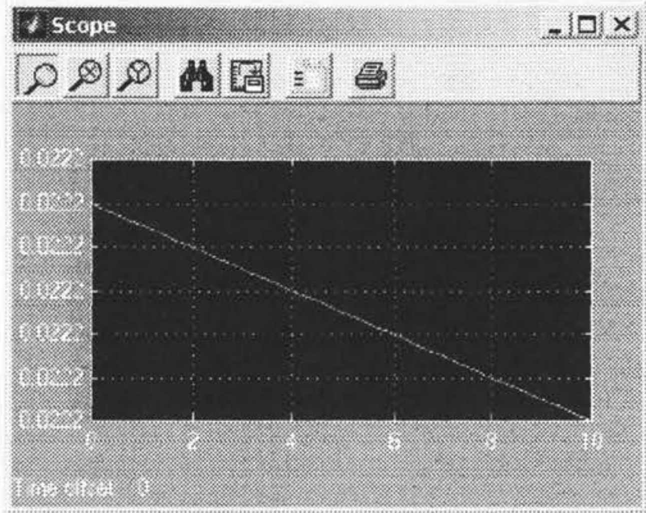


Figure 7-25: Effect 3 Sub-model output Mv3

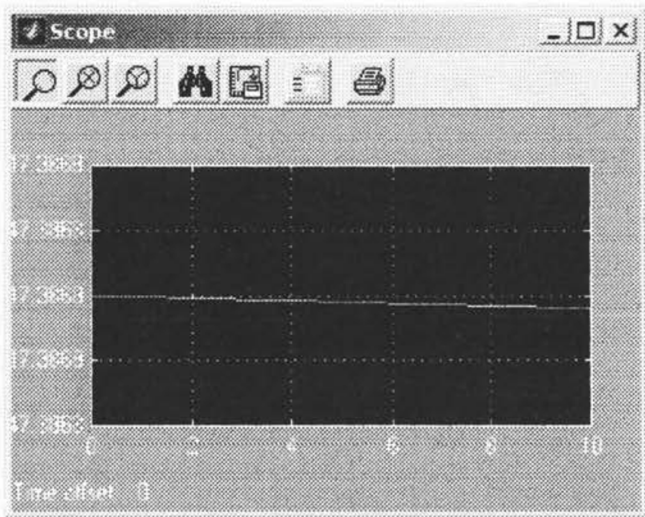


Figure 7-26: Effect 3 Sub-model output Tl3

Appendix 9

The following figures show the Trend pages for each parameter that display in FIX32 SCADA control screens. These Trend pages show the steady state values of the parameters. These values are gained from the real-time simulator Simulink model through the EDA link.

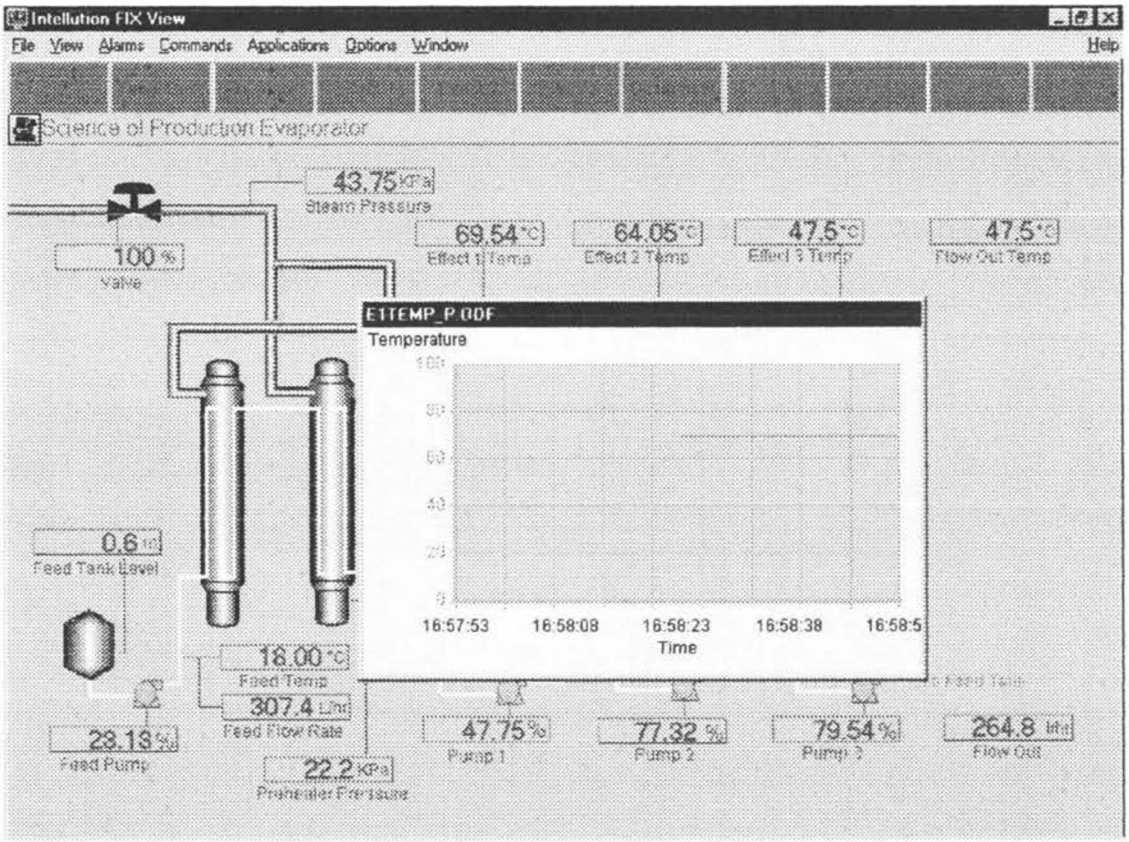


Figure 8-1: Effect 1 Temperature.

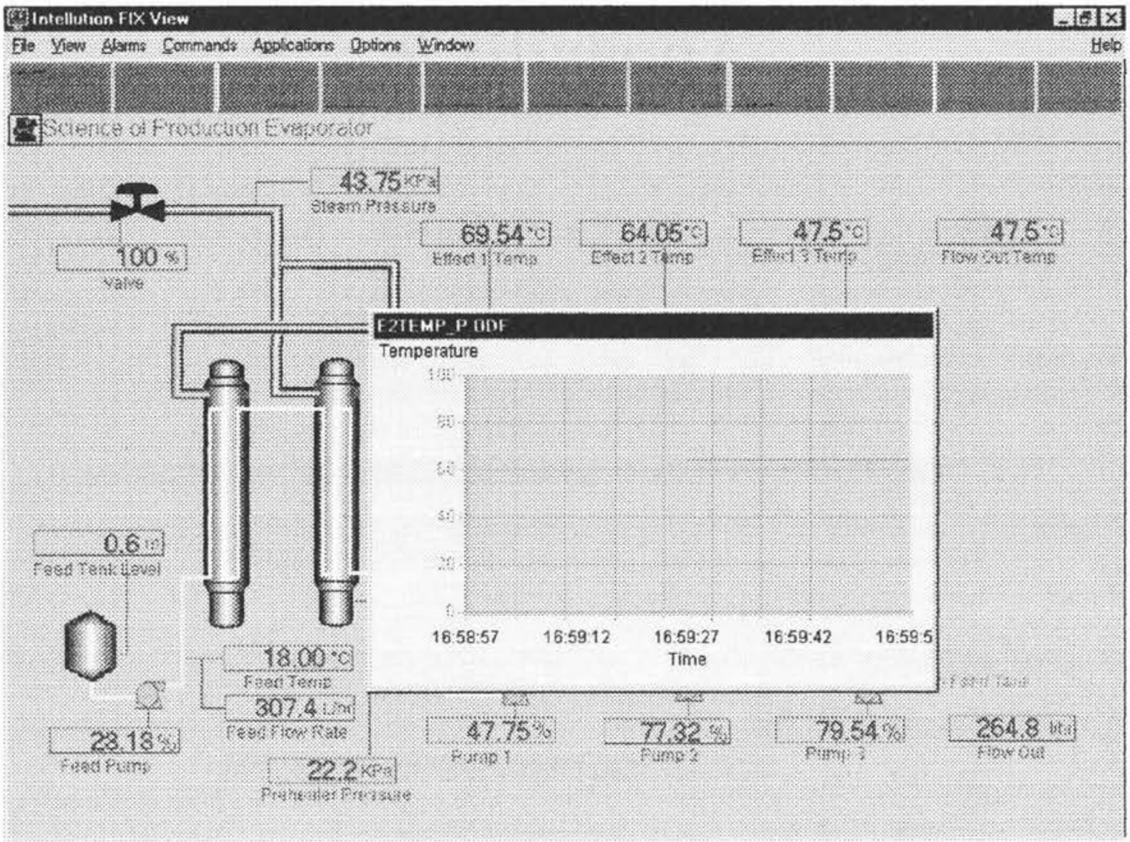


Figure 8-2: Effect 2 Temperature.

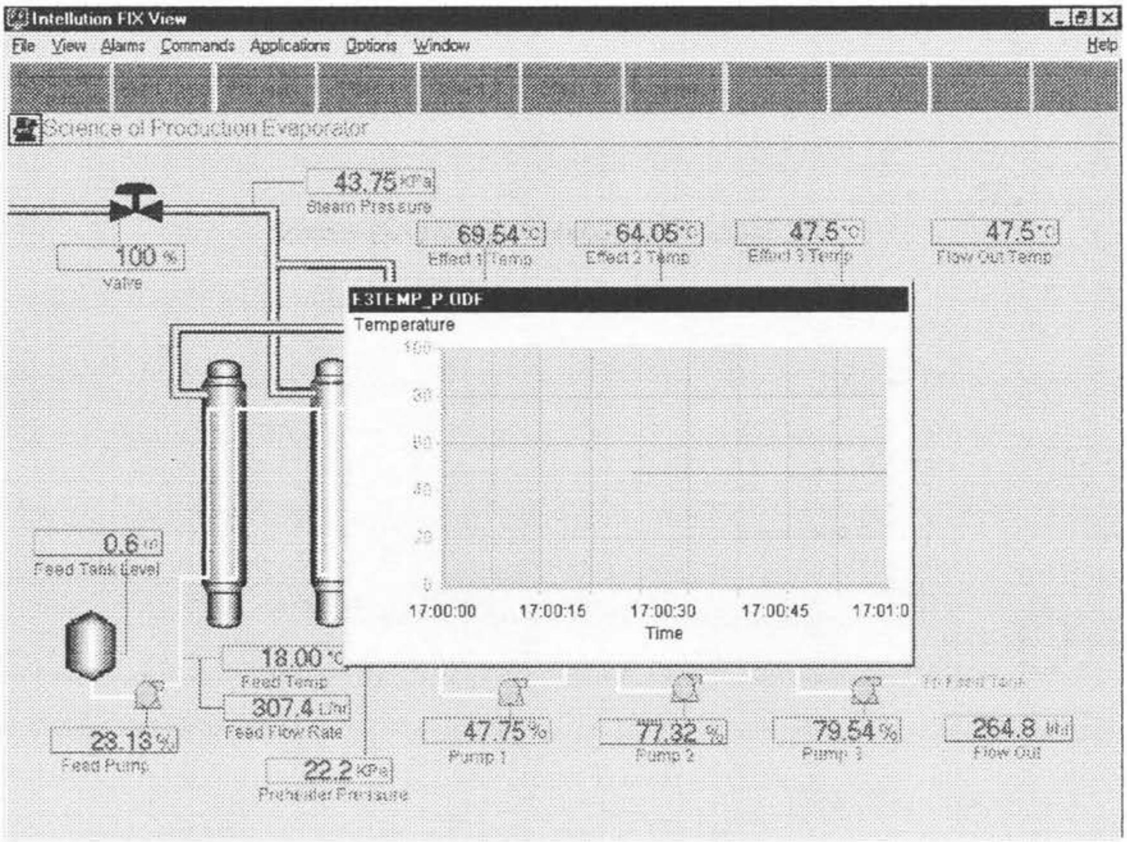


Figure 8-3: Effect 3 Temperature.

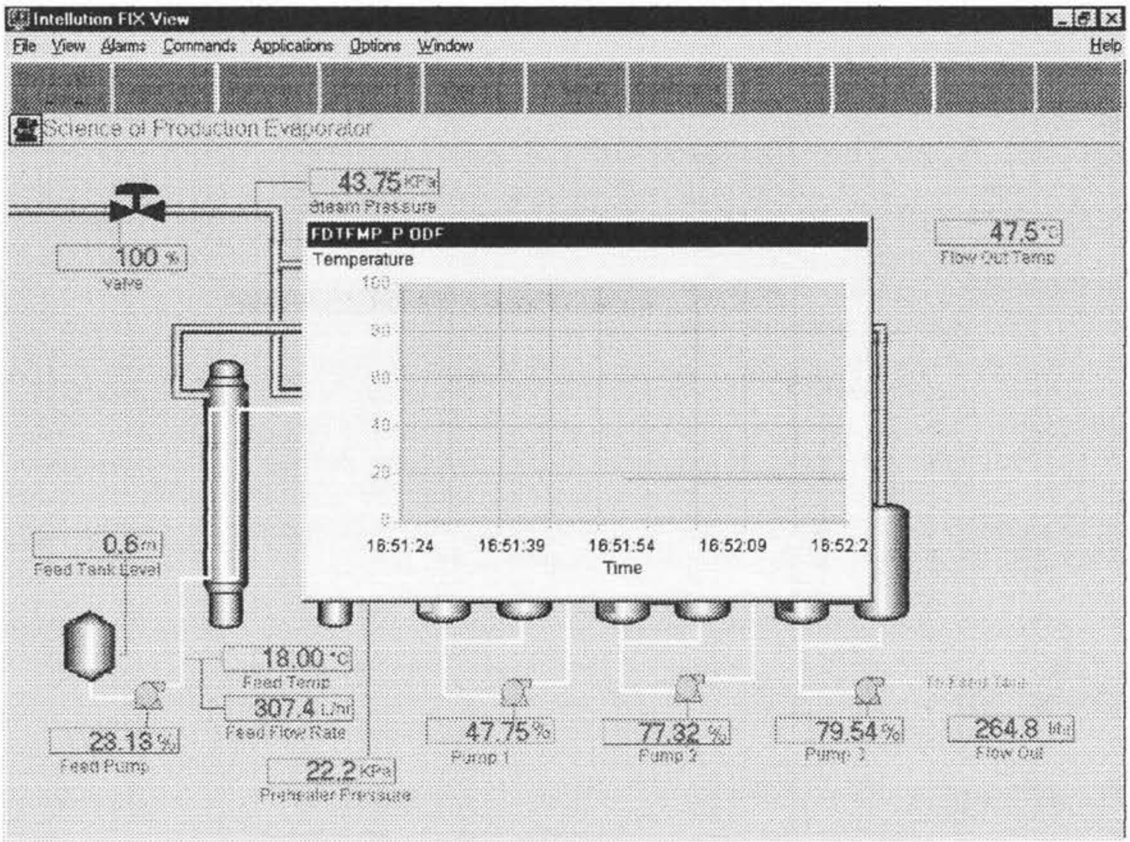


Figure 8-4: Feed Tank Outlet Temperature.

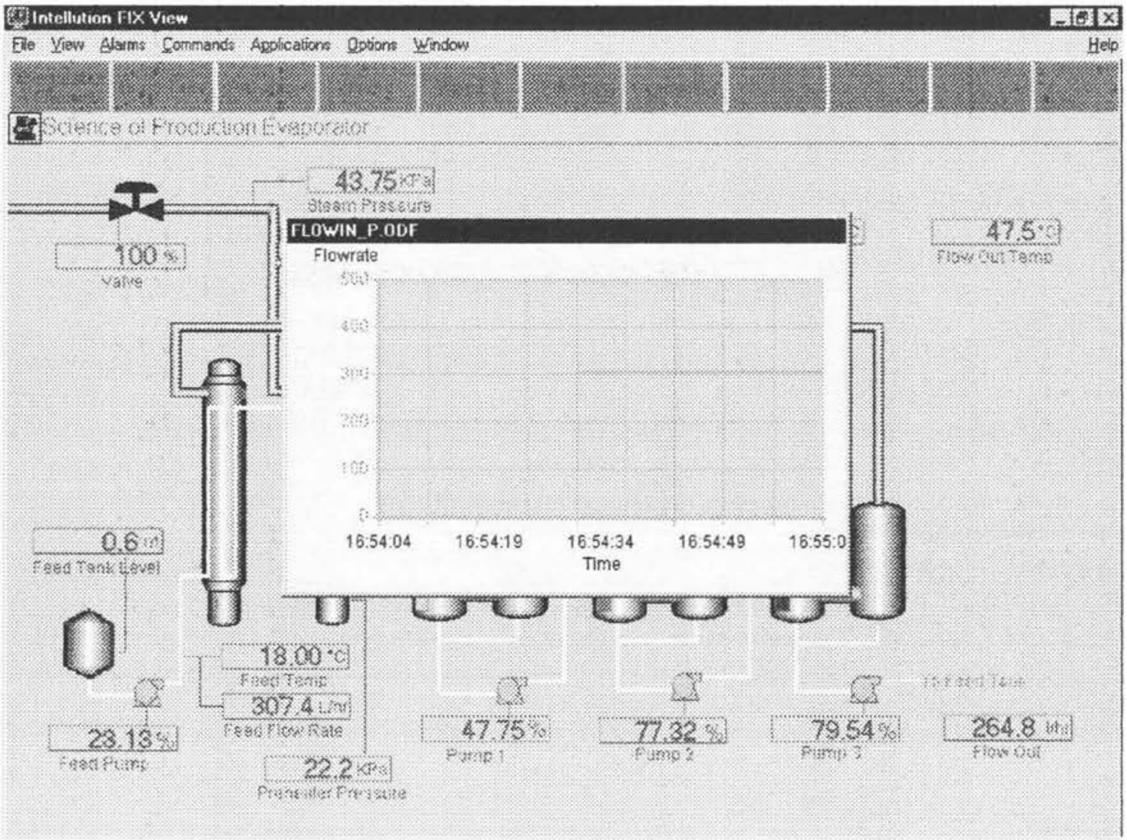


Figure 8-5: Feed Tank Outlet Flowrate.

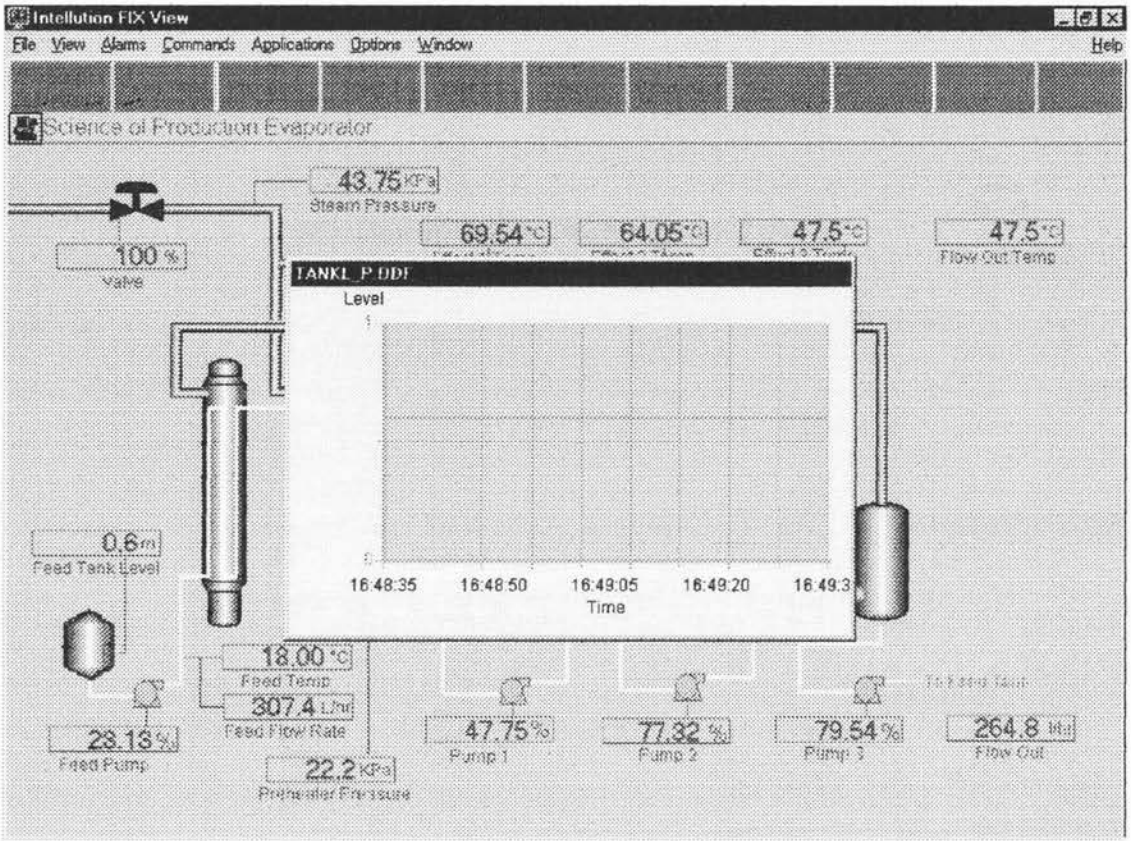


Figure 8-6: Feed Tank Level.

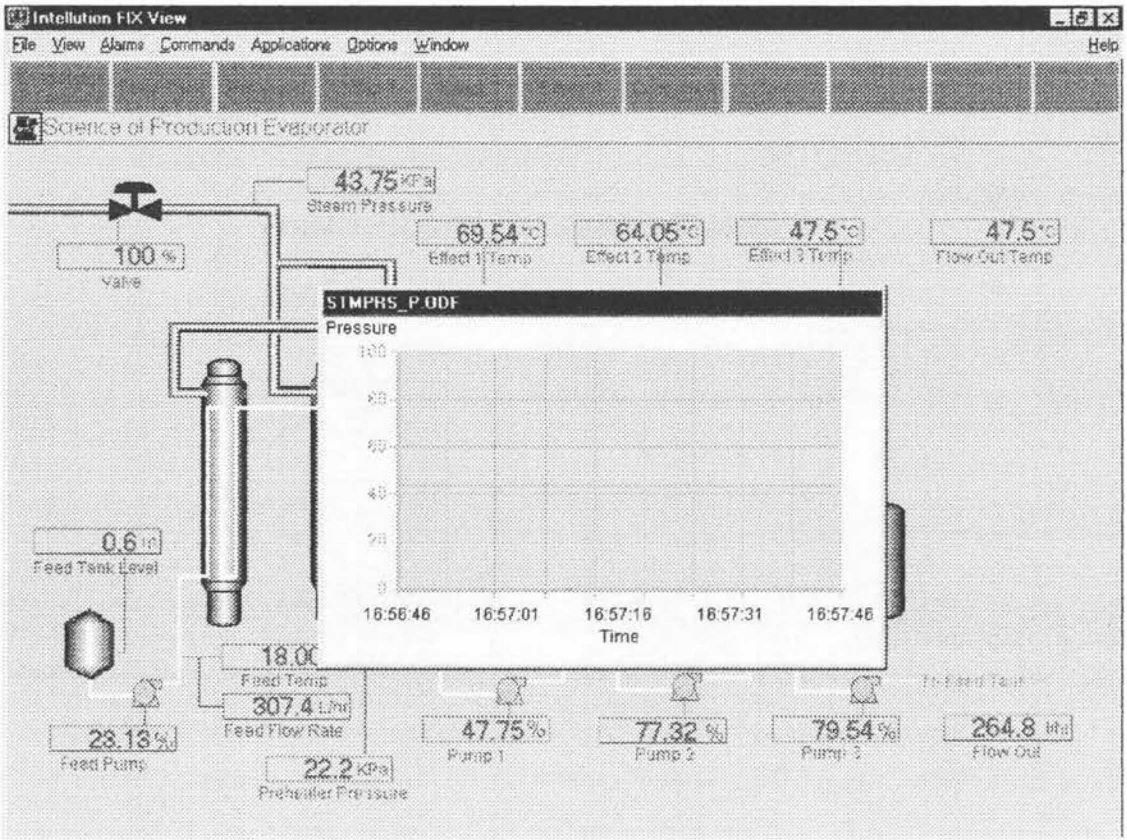


Figure 8-7: External Steam Pressure.

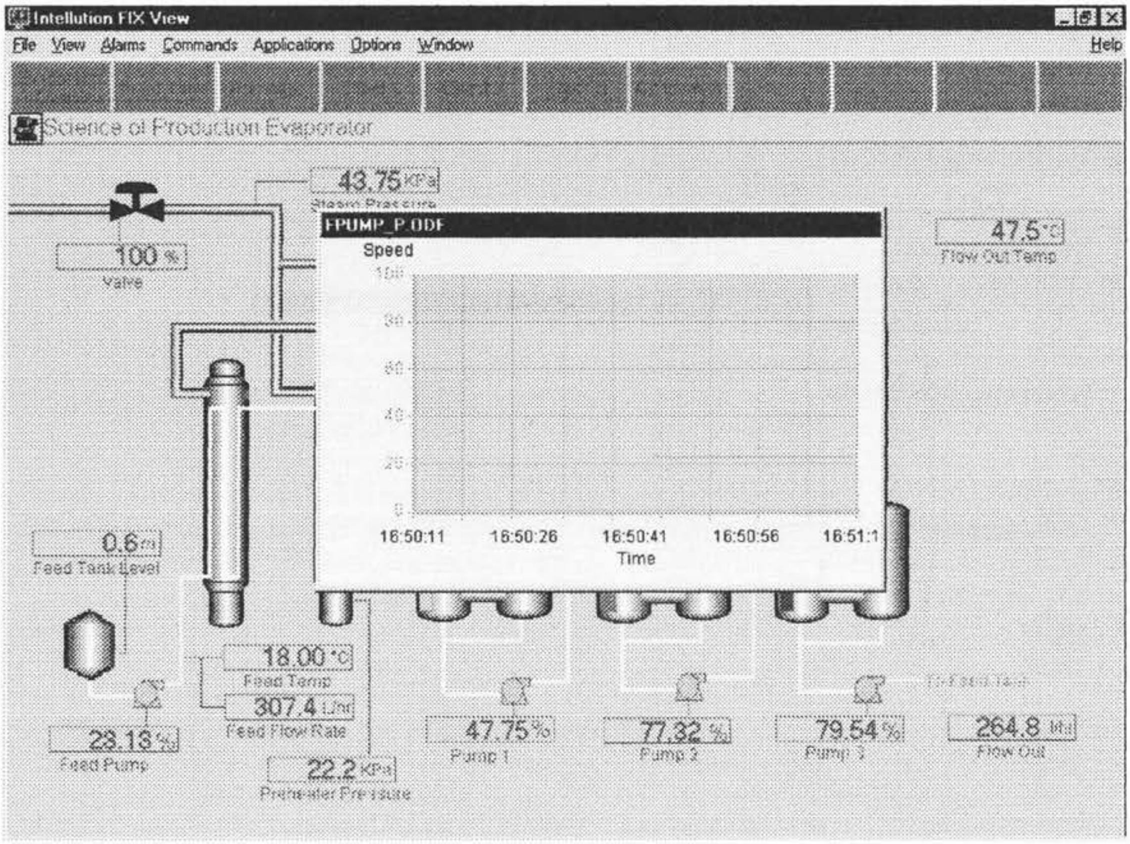


Figure 8-8: Feed Pump Speed.

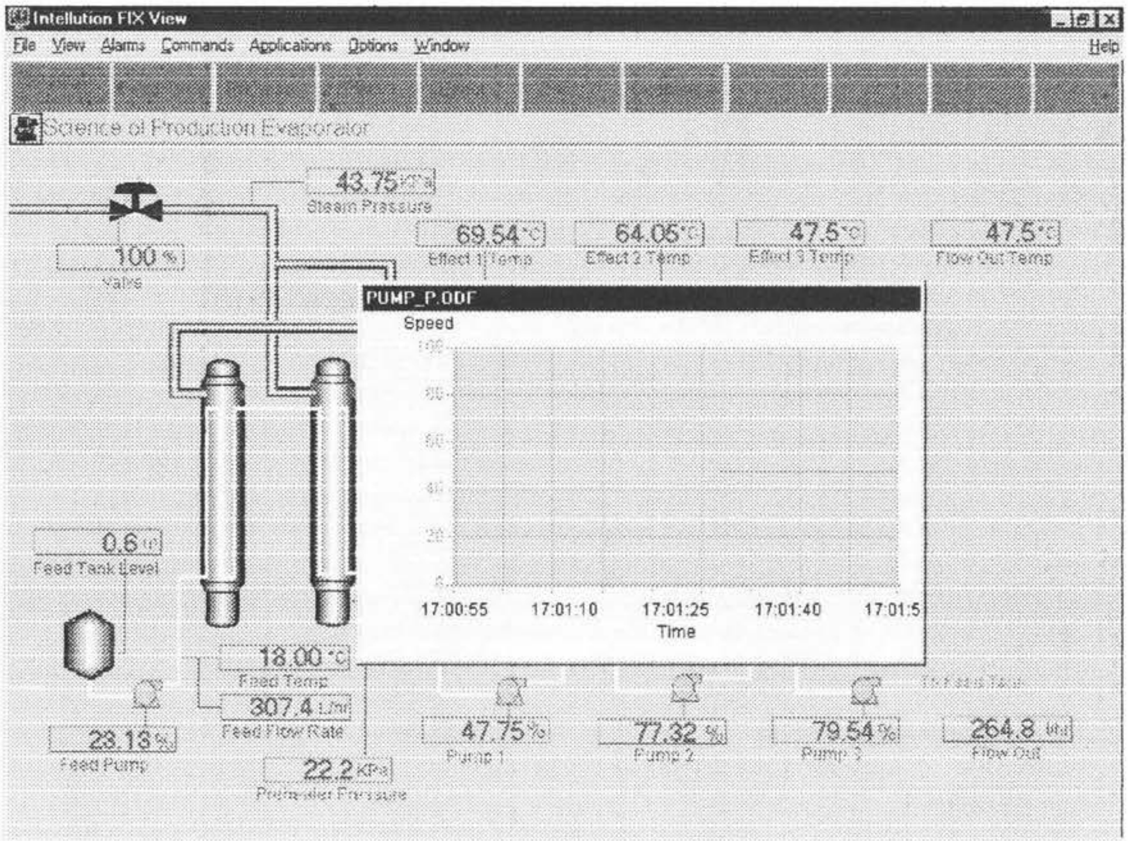


Figure 8-9: Pump 1 Speed.

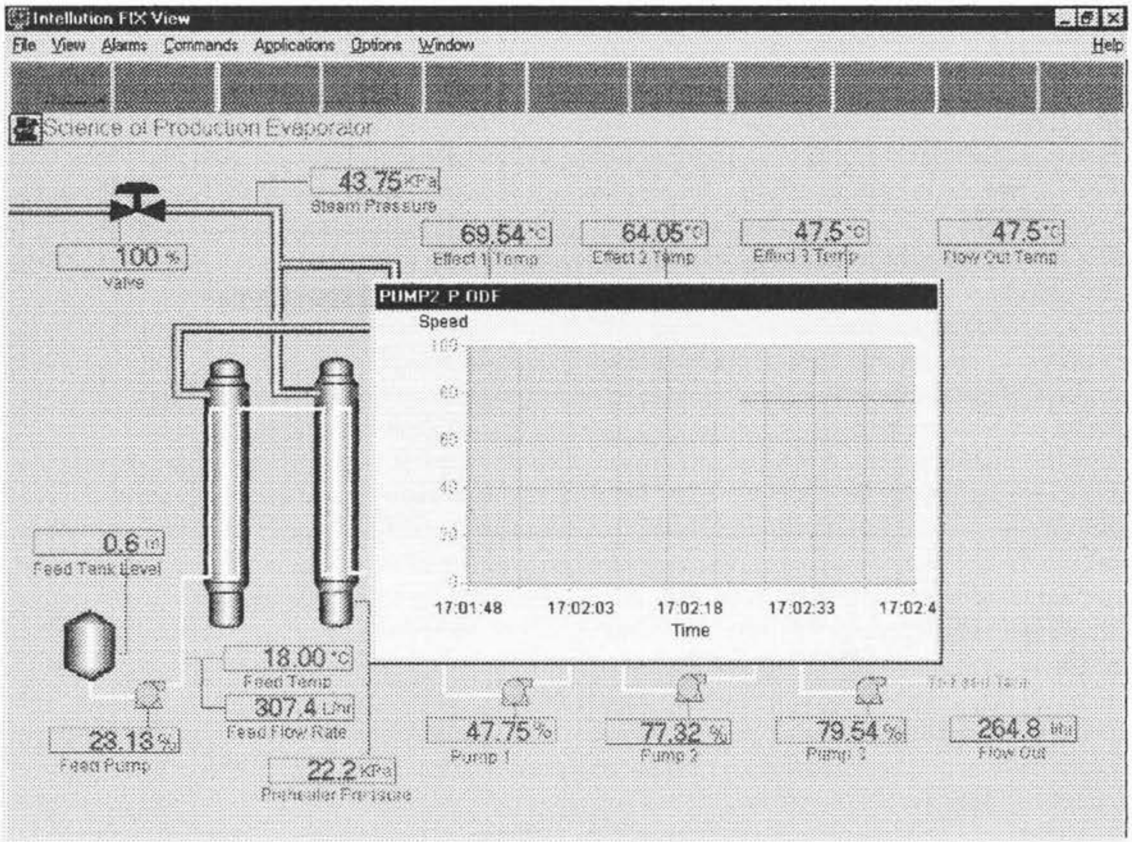


Figure 8-10: Pump 2 Speed.

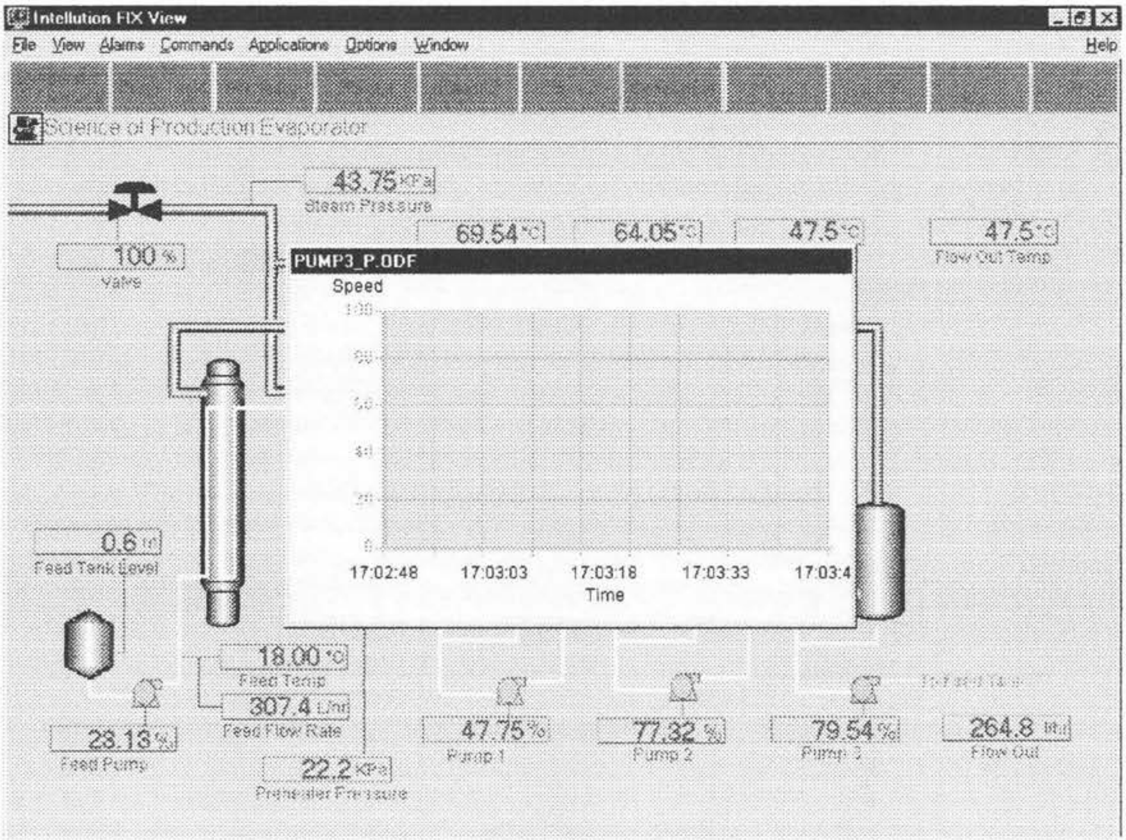


Figure 8-11: Pump 3 Speed.

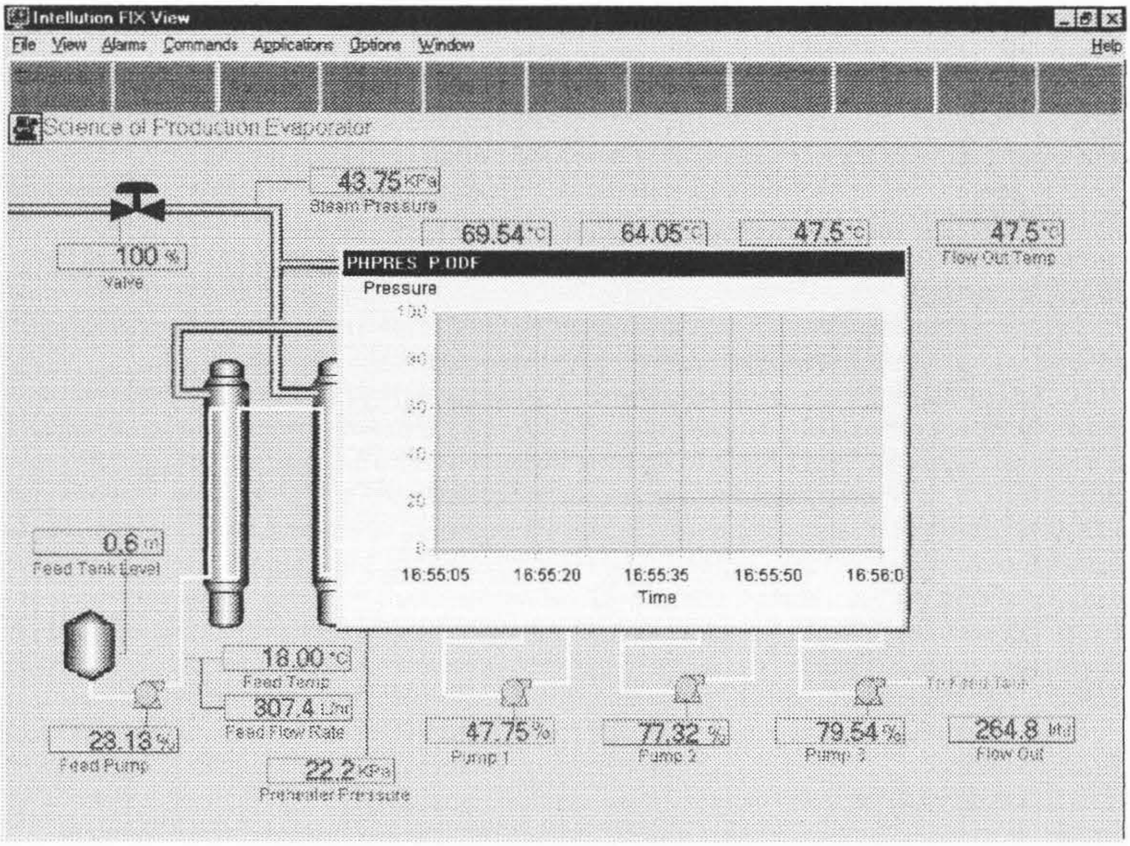


Figure 8-12: Preheater Pressure.

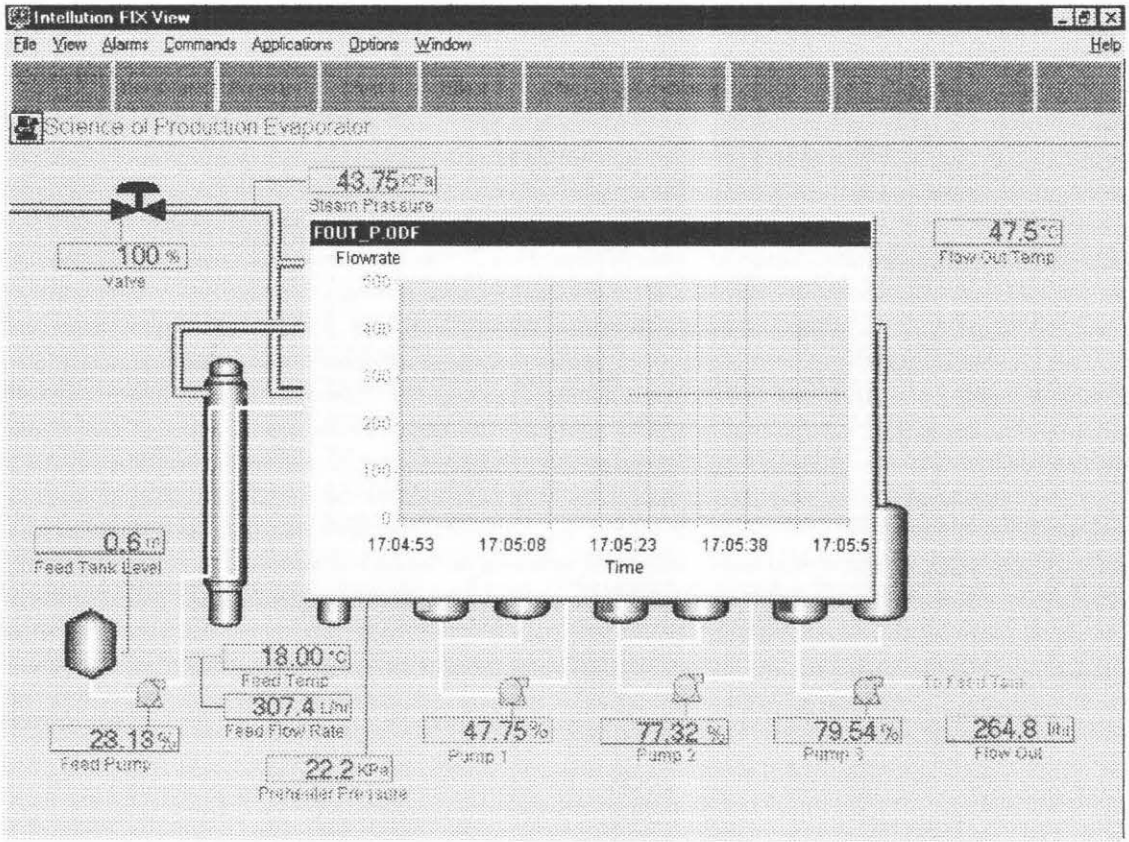


Figure 8-13: Effect 3 Outlet Flowrate.