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**YAKIN DOĞU ÜNİVERSİTESİ**  
**(NEAR EAST UNIVERSITY)**

**Fuzzy Logic Control of Humidity**

Project submitted in partial fulfillment of the requirement of the  
B.Sc. degree in Electrical and Electronic Engineering  
By

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**Project Supervisor:**

**Prof. Dr. Fahrettin Mamedov**

**June 1999**

## PROJECT EXECUTIVE SUMMARY

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**PROJECT TITLE:** Fuzzy Logic Control of Humidity

### 1.Introduction:

Control of humidity forms a vital part of many industrial and process engineering applications. Most humidity control approaches involve blending wet and d& air flows. Such processes are inherently non-linear which poses more challenges for traditional control strategies. This project involves designing and implementing fuzzy logic controllers (FLCs) as applied to a pilot scale humidification plant (Molly).

### 2.Motivation and Objectives

Traditional control strategies use ratio control for blending processes. Modern control paradigms might offer improvements in various performance metrics .

The main objective of this work is to design, test and implement FLCs on the humidity rig , Molly. A traditional ratio control strategy will also be implemented in order to obtain potential benefits and weaknesses of either control strategies.

### 3.Realized Milestones

The humidity rig, Molly was set up performing instrumentation and channel testing. A ratio control strategy was implemented and tuned. Two FLCs were designed , implemented and tested. The three controllers were successfully implemented by a Eurotherm T640 controller using T500 LIN tools software.

### 4.Couclusions

Fuzzy logic control can improve the performance Of some systems when conventional control methods do not achieve the desired requirements. An FLC strategy applied to humidity control achieves good control performance over a wide range of operating points and its response is faster than that of the ratio control .For a small range of operating points, ratio control can give acceptable response, but it tends to be slower than that of the FLCs.

**Student's Signature:**

**Date:** JUNE 99

**Abstract:**

Control of humidity through blending processes is very important in process industry plants. A pilot scale rig, Molly, was set up in the process control lab at the department of Automatic Control and Systems Engineering in order to provide hands on experience and training in the area of process control. It is interfaced to both Supervisory Control and Data Acquisition (SCADA) and Distributed Control System (DCS) systems. This rig mixes wet and dry air flows to achieve the desired humidity. The rig was initially set up by testing the instrumentation and I/O channels. Fuzzy logic controllers (FLCs) were designed and implemented using the SCADA system. A ratio controller was also implemented and tuned using the same system. The performance of all of the controllers was analyzed and compared. A discussion of the potential benefits and weaknesses of various strategies conclude this work.

## Acknowledgments:

*At the beginning I would like to thank parents and my brothers who gave me all support I needed.*

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# **Nomenclature:**

Symbol	Meaning
f	flow rate in kg/hr
r	The required ratio setting
h	humidity in kg/kg
T	The dew point temperature °C
P <sub>s</sub>	The supplied pressure
e	The error signal of the dry flow rate
u	The control action
x <sub>1</sub>	The dry flow valve position
PV	Process variable
SP	Set point
μ	Membership function value

The subscripts used were as follows

- R     Set point (e.g. f<sub>R</sub>, h<sub>R</sub>)
- 1     Dry flow (e.g. f<sub>1</sub>, h<sub>1</sub>)
- 2     Wet flow (e.g. f<sub>2</sub>, h<sub>2</sub>)
- o     Output (e.g. f<sub>o</sub>, h<sub>o</sub>)
- M     Measured (e.g. f<sub>M</sub>, h<sub>M</sub>)

# Chapter 1

## Introduction

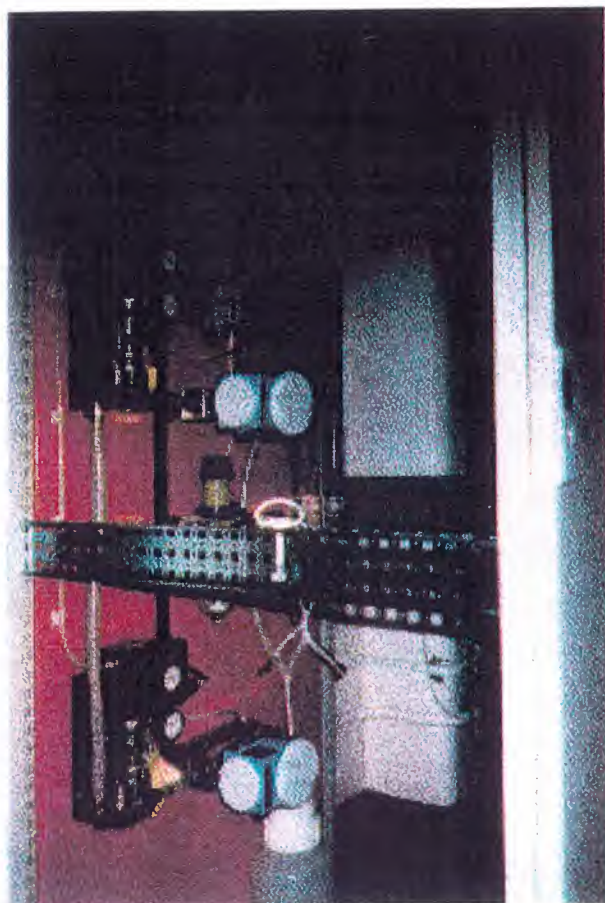
### 1.1 Introduction

Many process industry plants employ a variety of blending processes. Blending implies mixing of two or more streams to produce a combined flow with certain required properties. The work described here is concerned with blending of dry and wet air streams in order to control humidity. Ratio control strategies are most common within the process industry for blending processes [3]. Emerging control paradigms are beginning to see applications in industry. One such technique is fuzzy logic control (FLC). The main objective of this work is to investigate fuzzy logic humidity control using blending of dry and wet air streams. To benchmark the performance of the fuzzy controllers, a ratio control strategy is applied and tuned on the same process.

All the practical work carried out during this work is applied to a pilot scale humidification rig (MOLLY) in the Process Control Lab at the Department of Automatic Control and Systems Engineering.

### 1.2 Project Context

MOLLY is one of a variety of process control simulators set up recently in the Process Control Lab at the Department of Automatic Control and Systems Engineering. These rigs provide hands on experience and training in the area of process control. MOLLY is designed to demonstrate ratio control for blending processes (Figure 1.1 shows a photograph of this rig). The rig comprises the instrumentation necessary for realizing indirect ratio control with feedback trimming of the ratio setting. The input to this rig is air which is supplied by a compressor. The output is moist air and this is the controlled variable. The required humidity level is maintained by controlling the ratio between the wet and dry air streams.



**Figure 1.1** A Photograph of Molly

There are two proprietary control systems interfaced to Molly. A Honeywell Distributed Control System (DCS) and Eurotherm Supervisory Control and Data Acquisition (SCADA) system. Process control via computer systems provides precision and fast control action which results in a better response of the system and higher quality of the output. The FLC strategies can be implemented using either of the two systems above.

This project comprises setting up and tuning of an existing ratio control strategy for MOLLY. FLC strategies will then be investigated. Suitable FLC designs are identified and implemented for MOLLY. Both ratio control and FLCs are implemented using the SCADA system.

### **1.3 An Overview of MOLLY**

The input air flow to the rig is supplied by a compressor. The output is moist air which flows into the ambient lab environment. The humidity of the compressed air supply



depends on atmospheric conditions and the compression process. Air is composed of non-condensable gases such as Nitrogen, Oxygen, etc. It also contains water vapor. Humidity is the mass of vapor per unit mass of dry air (kg/kg). It is measured indirectly by its dew point temperature using the Psychometric Chart (Appendix A). In order to obtain this measurement air is cooled until the onset of condensation, which gives a measure of the dew point.

In this process it is assumed that the supplied air is dry (0% wet). This air is split into two parts, dry and wet streams. The wet stream is obtained by bubbling the flow through a bottle of water which will give a 100% wet stream. The two streams are blended together to give the moist air whose humidity depends on the ratio between the two flow rates. The control strategy is tasked with maintaining the ratio between wet and dry flows to produce the desired humidity output level.

#### 1.4 Project Objectives

The main objectives can be summarized as follows:

1. Implementation and tuning of the ratio control strategy .
2. Designing fuzzy logic controllers.
3. Implementation and tuning of the Fuzzy logic control strategy.
4. Explore the effectiveness of each of the control strategies in terms of rejecting disturbances and dealing with the non-linearity of the process.

The project will comprise the following steps:

1. Testing the instrumentation and the I/O channels.
2. Developing the data base.
3. Designing the ratio controller.
4. Implementing the ratio control strategy.
5. Tuning the control system.

6. Designing the fuzzy logic controllers
7. Implementing and testing the fuzzy logic controller.
8. Tuning the fuzzy logic controller.
9. Comparing the performance of the system using both types of controllers.

### 1.5 Potential problems

Some difficulties might be faced when implementing control strategies for this rig. These difficulties might arise due to some or all of following:

1. The process has non-linear dynamics (the relationship between the flow rates and the dew point temperature is non-linear).
2. The valves response is non-linear.
3. The effect of the sensors (measuring elements) on the system performance. The effect of the sensors and their delays is due to the dynamic and static characteristics of the measuring elements which affect the indication of the actual value of the humidity of the output air flow. The sensors play an important role in determining the overall performance of the control system, for example the sensor determines the transfer function in the feedback path as will be seen in chapter two.
4. The delays encountered by the valves response times and the delay encountered in measuring the dew point temperature.

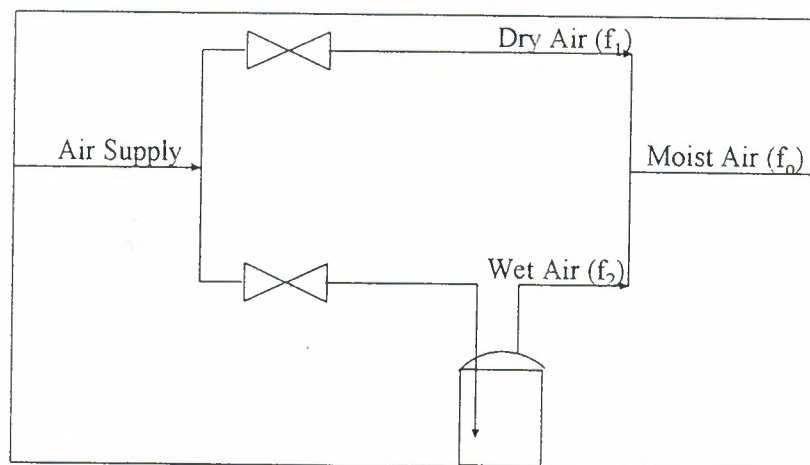
## Chapter 2 Process Modeling

This chapter gives a conceptual description of Molly. A mathematical model and block diagram description are also explained.

Note: The description and the model are for the system with the ratio control strategy as implemented at the beginning of this work.

### 2.1 Introduction

Figure 2.1 gives a simplified representation of the operation of Molly.



**Figure 2.1** The Humidification Process

Air is supplied by the compressor. The humidity of the supplied pressure depends on the atmospheric conditions and the compression process. Air supplied under normal conditions can be considered as dry air (0% humidity). The air flow is split into two streams. One is bubbled through a bottle of water where it becomes saturated (100% humidity). The other stream is assumed to be dry air. At the outlet, both streams are blended together to form the moist air stream. The humidity of this moist air depends on the ratio between the flow rates and the atmospheric conditions (for example, if the weather is rainy, the humidity of the input stream cannot be 0%). To maintain the desired flow rate ratio, an indirect ratio control strategy is employed. This strategy can

be summarized as follows (full description can be found in chapter 4): The flow rate of the wet stream ( $f_2$ ) is measured and then multiplied by the required ratio ( $r$ ) which gives the desired value ( $f_R$ ) of the dry flow rate ( $f_1$ ).  $f_R$  is passed through a PID feedback loop controlling the dry air flow  $f_1$ . So, by keeping  $f_1$  and  $f_2$  in proportion, the moist air stream can be maintained at a constant humidity. Since it is unlikely that the desired level of humidity will be achievable (this is due to the system's characteristics), it is therefore necessary to measure the moist air humidity and use it to trim the ratio setting. Therefore, the ratio is the output of another controller which has the desired humidity as it's set point. Figure 2.3 is a detailed block diagram of the control process [7].

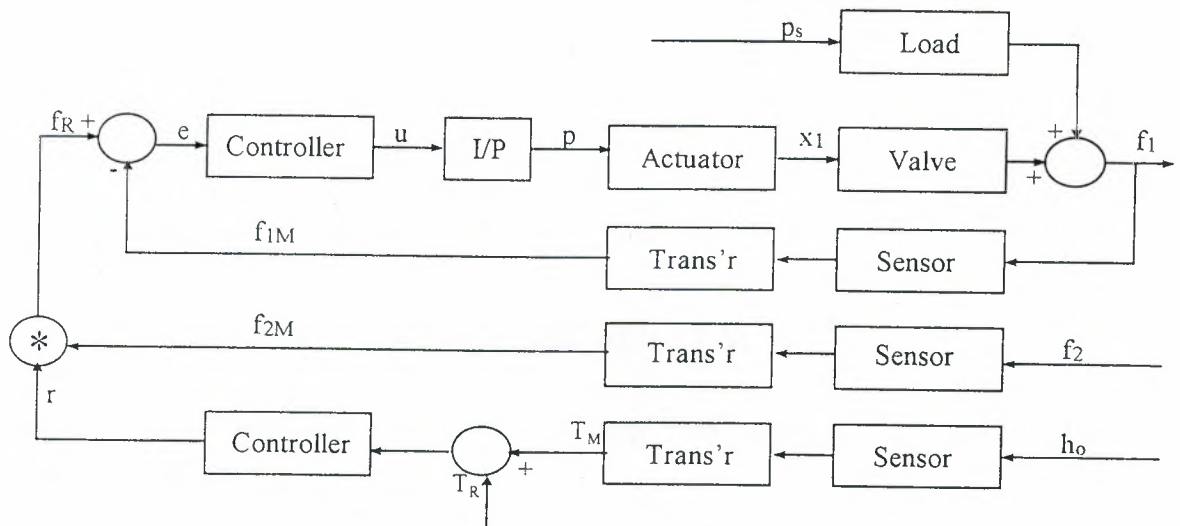


Figure 2.2 Process Block Diagram [7]

## 2.2 Mathematical Modeling

Molly is a zero capacity system, as it cannot and does not store mass. The transfer functions of zero capacity systems are simply steady state gains. In such cases the dynamics of the associated pipe work, pumps and valves become dominant [3].

The output flow can be represented as follows:

$$f_1 + f_2 = f_o \quad 2.1$$

The humidity relation can be represented as follows:



$$f_1 h_1 + f_2 h_2 = f_o h_o \quad 2.2$$

Under normal atmospheric condition, the following conditions apply:

$$h_1 = 0, \quad h_2 = \text{Constant} \quad 2.3$$

Substituting in equation 2.2 results in:

$$h_2 f_2 = h_o f_o \quad 2.4$$

But  $f_o = f_1 + f_2$ , so substituting this equation into equation 2.4 gives:

$$h_2 f_2 = h_o (f_1 + f_2) \quad 2.5$$

Putting into deviation form,

$$h_1 (\bar{f}_1 + \Delta f_1) = (\bar{f}_1 + \Delta f_1 + \bar{f}_2 + \Delta f_2) (\bar{h}_1 + \Delta h_1) \quad 2.6$$

Expanding equation 2.6 gives:

$$h_1 \bar{f}_1 + h_1 \Delta f_1 = \bar{f}_1 \bar{h}_1 + \bar{f}_1 \Delta h_1 + \Delta f_1 \bar{h}_1 + \Delta f_1 \Delta h_1 + \bar{f}_2 \bar{h}_1 + \bar{f}_2 \Delta h_1 + \Delta f_2 \bar{h}_1 + \Delta f_2 \Delta h_1 \quad 2.7$$

Ignoring the second order terms and subtracting from equation 2.7 the steady state:

( $h_2 \bar{f}_2 = \bar{f}_1 \bar{h}_o + \bar{f}_2 \bar{h}_o$ ) results in:

$$h_1 \Delta f_1 = \bar{f}_1 \Delta h_1 + \Delta f_1 \bar{h}_1 + \bar{f}_2 \Delta h_1 + \Delta f_2 \bar{h}_1 \quad 2.8$$

Dropping the  $\Delta$  notation and transforming gives:

$$h_2 f_2 = (\bar{f}_1 + \bar{f}_2) h_o + \bar{h}_o (f_1 + f_2)$$

$$= \bar{f}_o h_o + \bar{h}_o (f_1 + f_2)$$

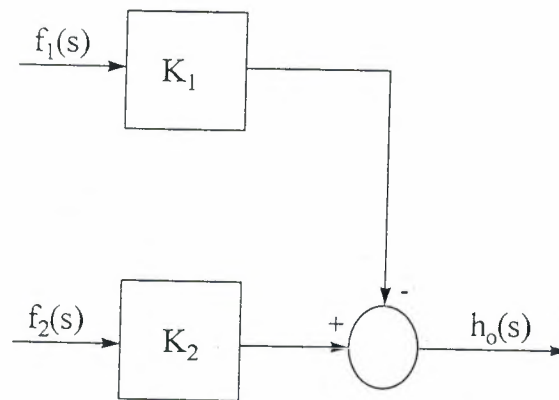
2.9

Transforming equation 2.9 and rearranging gives:

$$h_o(s) = \frac{h_2 - \bar{h}_o}{\bar{f}_o} \times f_2(s) - \frac{\bar{h}_o}{\bar{f}_o} \times f_1(s)$$

$$= K_2 f_1(s) - K_1 f_1(s) \quad 2.10$$

Equation 2.10 proves that the system is a zero capacity system as mentioned earlier in this section. The revised diagram in figure 2.3 describes this system.



**Figure 2.3** The Basic Process

For a successful control strategy, the following issues must be observed:

1. The humidity measurement is critically important for two main reasons:
  - a- Depending on this value, the necessary ratio ( $r$ ) required to obtain the desired value of ( $f_1$ ) will be calculated by means of the feedback controller in the main loop.
  - b- Using this value, the humidity of the output air can be controlled and set to the desired value.
2. Since it is very unlikely to get air which has the required dew point temperature, the humidity feedback loop gives the desired ratio between dry and wet flow rates. This is controlled by means of a PID controller to trim the ratio setting.
3. The flow rates are controlled by means of PID controllers in order to allow for set point changes and external disturbances.

4. The dew point sensor can be represented mathematically by a first order lag. ( $1/(Ts+1)$ ). The same is true for the container, but this is ignored because the time constant of the container is approximately zero.

5. There is a time delay ( $L$ ) encountered in this process. This is due to distance velocity effects between the mixing junction and the dew point sensor.

Figure 2.4 gives a mathematical model of the system, as controlled using ratio control.

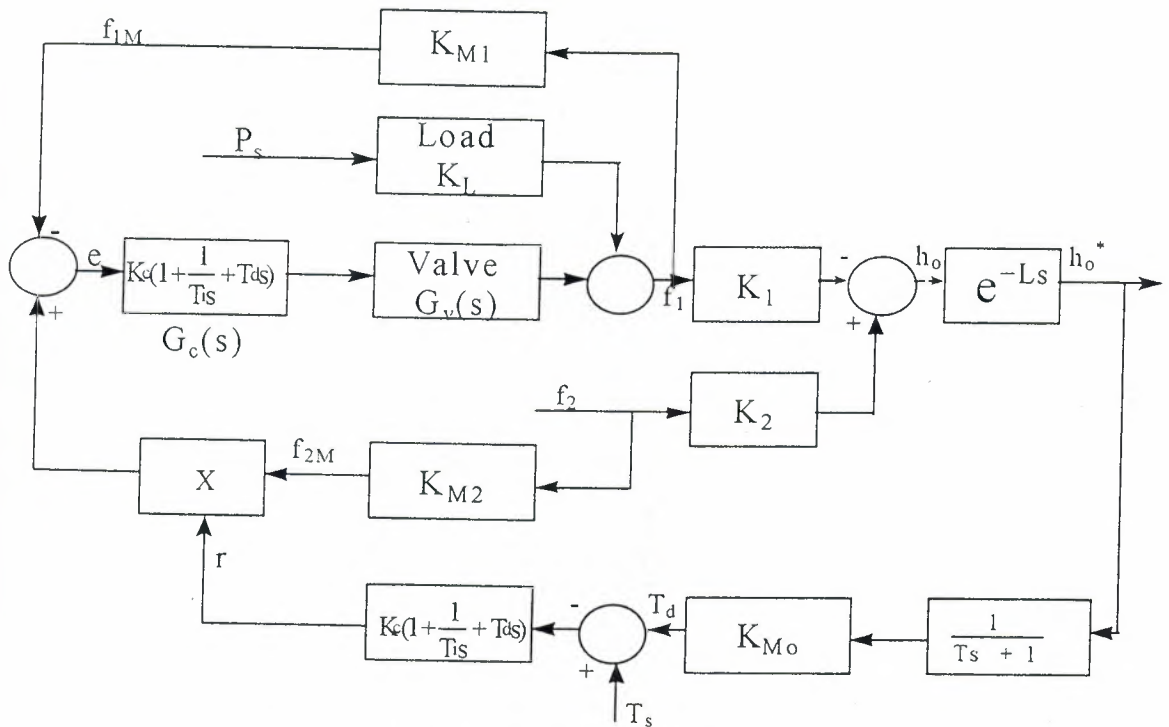


Figure 2.4 Mathematical Model of the Process

From figure 2.4:

$$f_1(s) = e(s)G_v(s)G_c(s) + K_L P_s(s)$$

$$= (f_{1r} - f_1 K_{M1})G_v(s)G_c(s) + K_L P_s(s)$$

2.11

$\Rightarrow$

$$f_1(1 + K_{M1}G_v(s)G_c(s)) = f_{1r}G_v(s)G_c(s) + K_L P_s(s)$$

So,

$$\begin{aligned}
 f_1(s) &= \frac{G_v(s)G_c(s)}{1+K_{M1}G_v(s)G_c(s)}f_{1r}(s) + \frac{K_L}{1+K_{M1}G_v(s)G_c(s)}P_s(s) \\
 &= G_1(s)f_{1r}(s) + G_2(s)P_s(s)
 \end{aligned}
 \quad 2.12$$

Also, the wet flow is controlled by a PID control loop.

From equation 2.12 figure 2.4 can be simplified to:

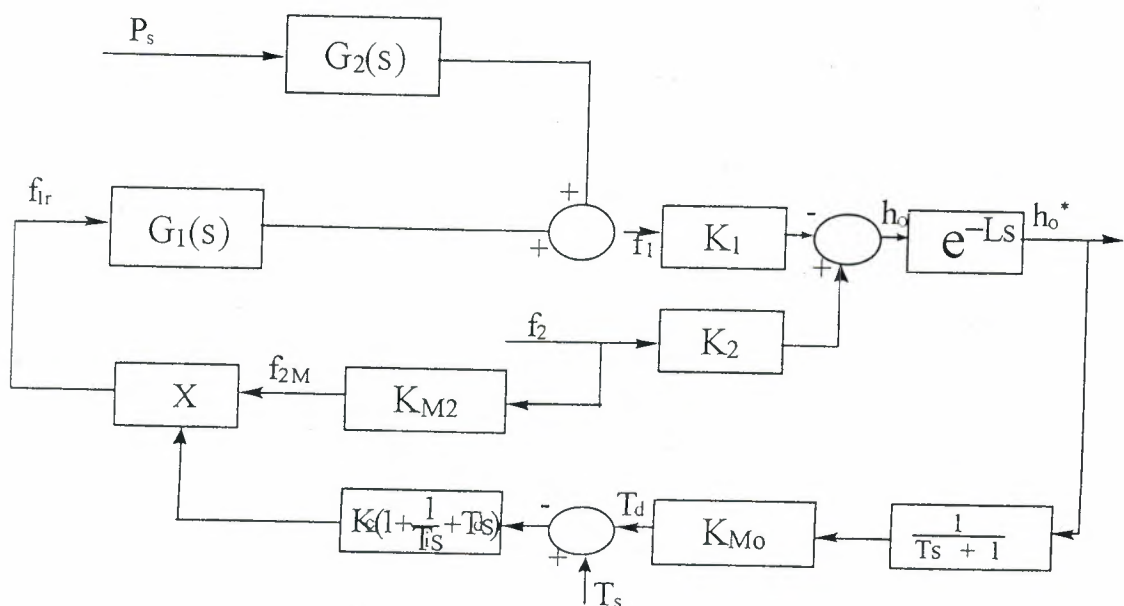


Figure 2.5 Simplified Block Diagram OF Molly With Ratio Control

### 2.3 Practical Considerations and measures

- It was found that the effect of the time delay ( $L$ ) is not significant, so it will not be considered more for the remainder of this work.
- The transfer function for the valves can be approximated by first order lag functions ( $1/(Ts+1)$ ).
- **Normal Operating conditions:**

Wet Flow Rate = 0.25 kg/h

Dew Point Temperature = 10.5 °C



- **Effective Range of Operation:**

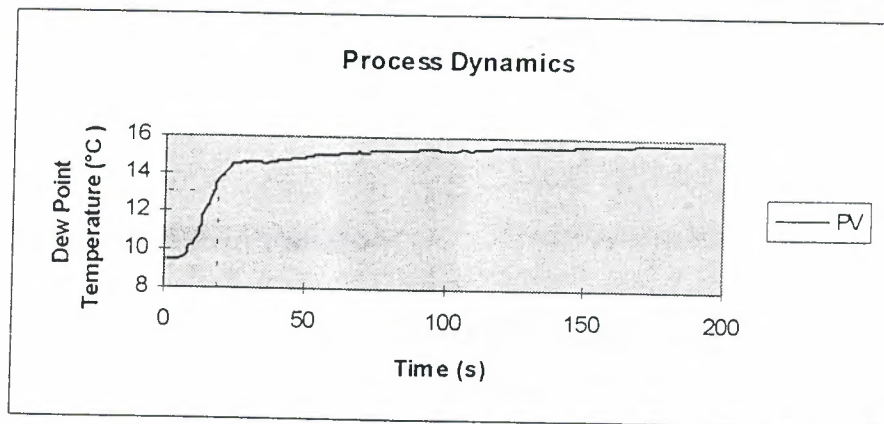
Dry Flow: 0 to 1.04 kg/h

Wet Flow: 0 to 0.94 kg/h

Dew Point Temperature: -4.8 to 20 °C

- **Process Dynamics**

In order to calculate the dynamics of the process, a step change in the dry flow was applied and the resultant behavior of the dew point temperature is shown in figure 2.6



**Figure 2.6** Process Dynamics

The time constant of the process was found to be equal to 18.2 seconds (the time at which the response reached 63.2% of its final value, which in this case was the time at which the dew point was equal to 13.38°C). This value leads to the presence of noise behavior (shattering) in the response of about  $\pm 2\%$  of the dew set point temperature. This is due to the short computation time of the control action by the PC station which is 0.1 second.

## Chapter 3

# Molly Instrumentation

In this chapter the equipment and the software packages used in conjunction with **Molly** are described. The plant instrumentation is interfaced with the **T640** controller which consists of four single loop controllers (Designed by Eurotherm). This is interfaced to a PC workstation using the Eurotherm T500 LINtools and the T3000 SCADA package. Here follows a description of the instrumentation, the input/output channels and the software packages.

### 3.1 Channels and Instrumentation

A piping and instrumentation (P&I) diagram of the rig, which shows the functional relationship between various control loops is given in figure 3.1. The organization of the instrumentation into channels, the three control loops (dew point, wet air flow and dry air flow), and the connections to the T640 controller are shown in the wiring diagrams in figures 3.2 to 3.4. The symbols and the letter codes/numbers (tag nos.) conform with the Instrumentation Society of America (ISA) standards S5.1 and S5.3. The instrumentation used, the tag nos., I/O ranges and the manufacturer of each component are all summarized in table 3.1.

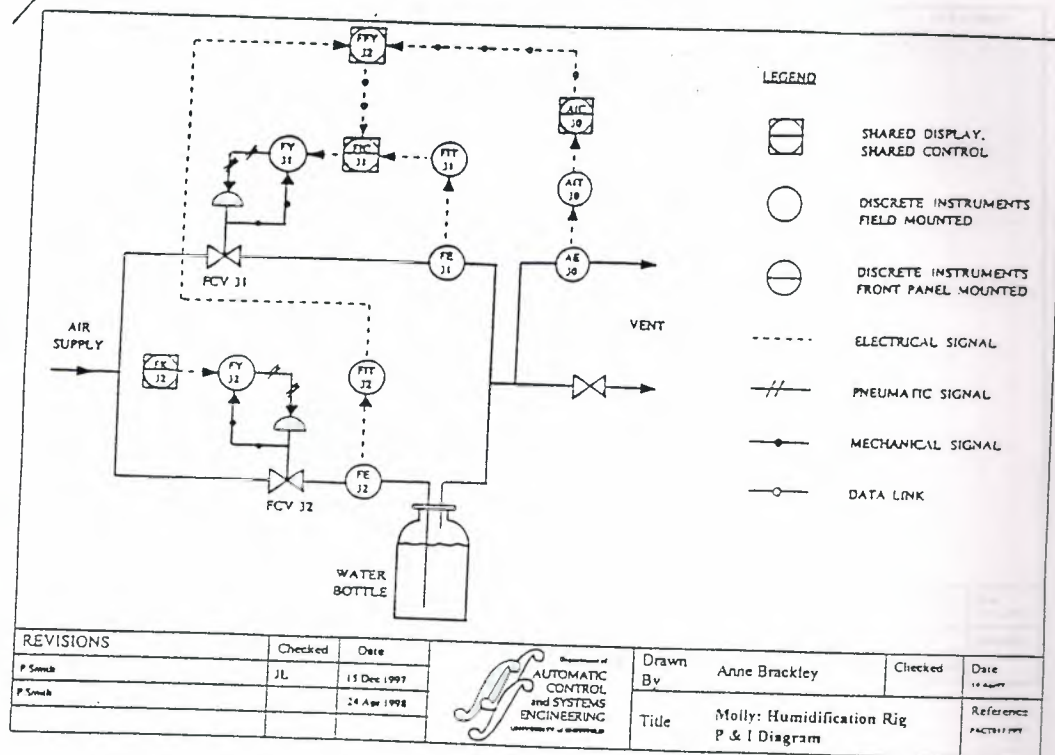


Figure 3.1 P&amp;I Diagram of the Humidity Rig (Molly)

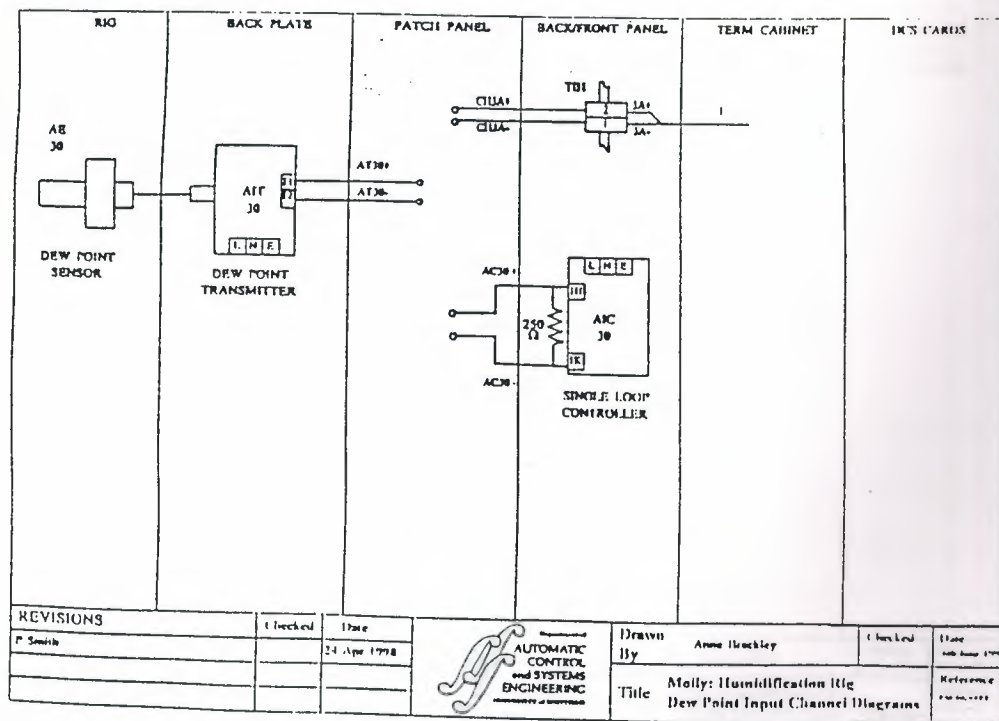


Figure 3.2 Dew Point Input Channel Diagrams

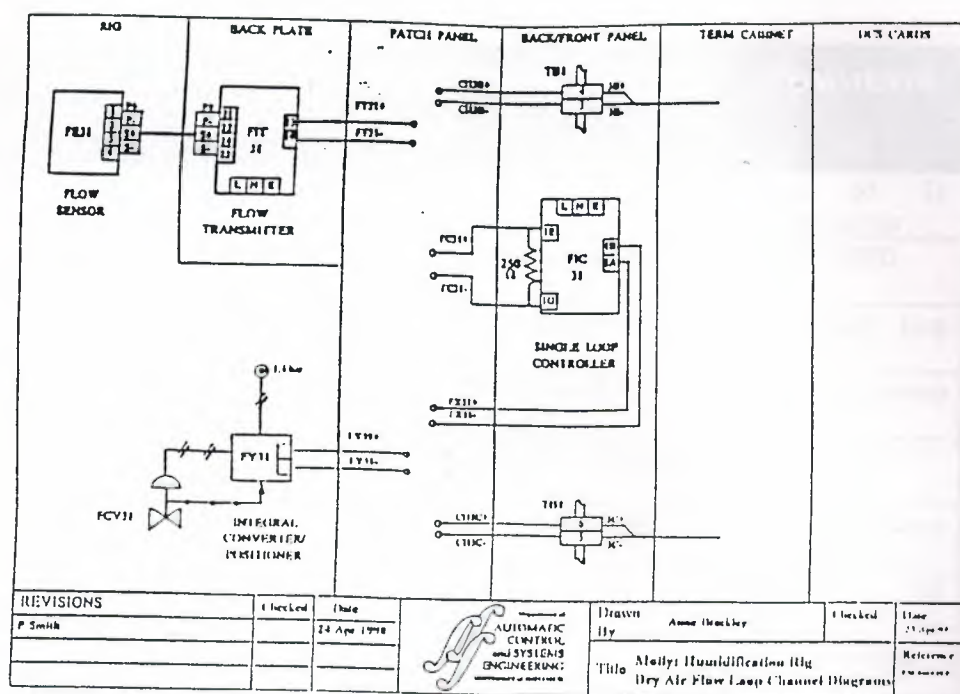


Figure 3.3 Dry Air Flow Loop Channel Diagrams

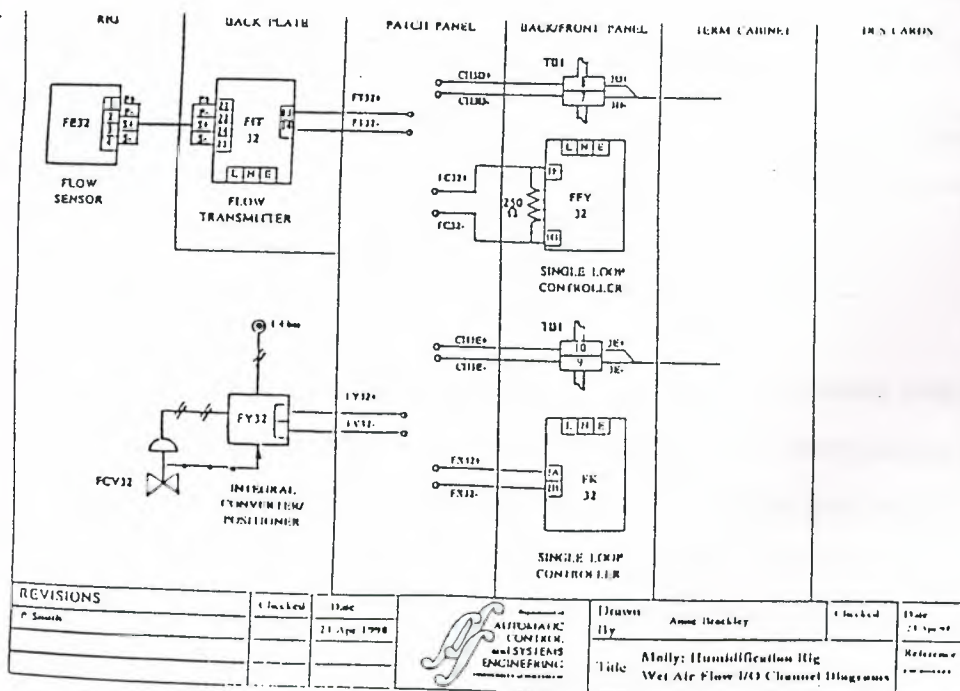


Figure 3.4 Wet Air Flow I/O Channel Diagrams

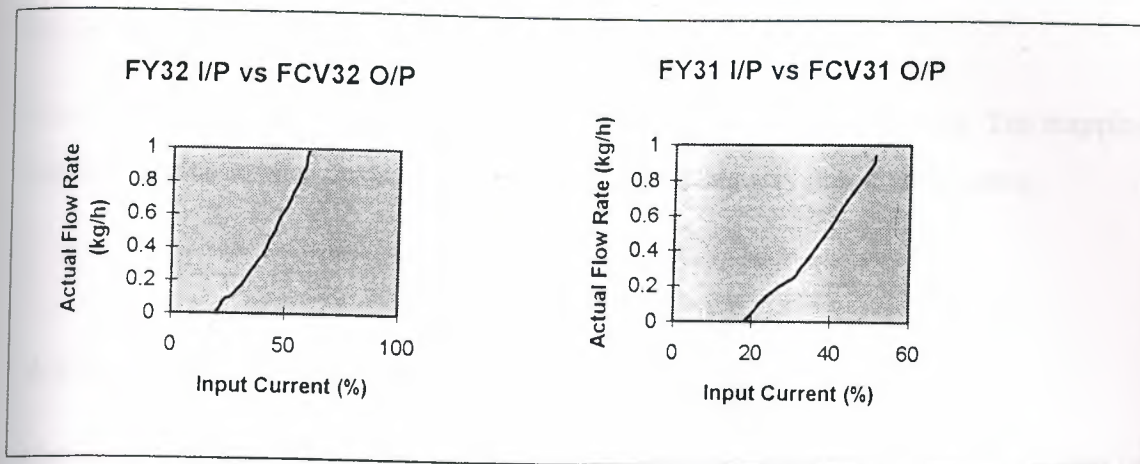


TAG NO.	DESCRIPTION	INPUT RANGE	OUTPUT RANGE	MANUFACTURER	COMMENTS
AE30	Dew point sensor	-10 to 20°C	0-100%	Michell Instruments	Type 60 D, Cooled mirror
AIT30	Dew point transmitter	0-100%	4-20 mA	Michell Instruments	Model 3000D
AIC30	Dew point controller	4-20mA	4-20mA	Eurotherm	T640 single loop controller
FE31	Flow sensor	0-1kg/hr	0-100%	Endress & Hauser	Heated filament mass flow
FIT31	Flow transmitter	0-100%	4-20mA	Endress & Hauser	
FIC31	Dry flow controller	4-20mA	4-20mA	Eurotherm	T640 single loop controller
FY31	Valve positioner	4-20mA	14-24psi	Bauman	Integral I/P converter, air supply of 60 psi
FCV31	Control valve	14-24psi	0-1kg/hr	Bauman	
FE32	Flow sensor	0-1kg/hr	0-100%	Endress & Hauser	Heated filament mass flow
FIT32	Flow transmitter	0-100%	4-20mA	Endress & Hauser	
FK32	wet flow controller	0-100%	4-20mA	Eurotherm	T640 single loop controller
FY32	Valve positioner	4-20mA	14-24psi	Bauman	Integral I/P converter, air supply of 60 psi
FCV32	Control valve	14-24psi	0-1kg/hr	Bauman	
FFY32	Ratio controller	4-20mA	0-100%	Eurotherm	T640 single loop controller

Table 3.1 Molly Instrumentation

### 3.1.1 Valves

The characteristics of the valves have been investigated by connecting a current source to the input terminals of FY31 & FY32. The valves were found to have non-linear response. The relationship between the input current (represented as a percentage of the full range 4-20mA) and the actual flow rate is non-linear (figure 3.5). The effective range of control for the valve is 18.6 to 51% for wet flow, and 20 to 60.4% for dry flow. This should be taken into consideration in the design of the control strategy.



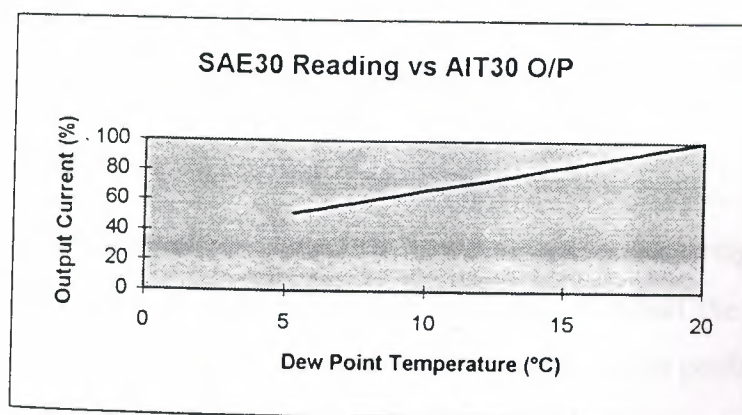
**Figure 3.5 Valve Characteristics**

The maximum possible flow rates are 0.94 kg/h for wet flow and 1.04 kg/h for dry flow.

### 3.1.2 Dew Point Sensor

The characteristics of the dew point sensor and dew point transmitter were investigated. They were found to have a linear response (figure 3.6).

The dew point temperature of a completely wet flow stream is 22°C and that for a completely dry flow stream is -4.8°C.



**Figure 3.6 Dew Point Sensor Characteristics**

(Note: In figures 3.5 and 3.6 the current is represented as a percentage of the full range 4-20mA)



### 3.1.3 Computer Interface

Functionality testing of the computer interface to the rig was carried out. The mapping between the controller outputs and the actual rig inputs was found to be linear.

## 3.2 Overview Of The T640 Controller

The T640 controller is a multi-purpose integrated loop processor which is capable of controlling up to four loops. It can either be incorporated into a distributed control system, or used as an independent controller. It comes from the manufacturer loaded with four different control strategies (Control Databases) from which the appropriate control strategy can be selected. Any other control strategy, or any modification or addition to the available control strategies, can be made using the LINtools software package and then downloaded to the T640 controller. In essence, a control database is a collection of blocks linked together to perform a particular task [2]. Figure 3.7 is a photograph of T640 front panel.

Text, numerical and bargraph data can be displayed (figure 3.7). For this rig, information is available for the following parameters:

1. The task and loop numbers.
2. The flow rates of both the dry and wet flow air streams.
3. The dew point temperature at the output.

Stability and performance of the system can be monitored by observing the columns to the left of the front panel, which represent the set point value and the current value of the different variables. The maximum number of tasks that can be performed is four.

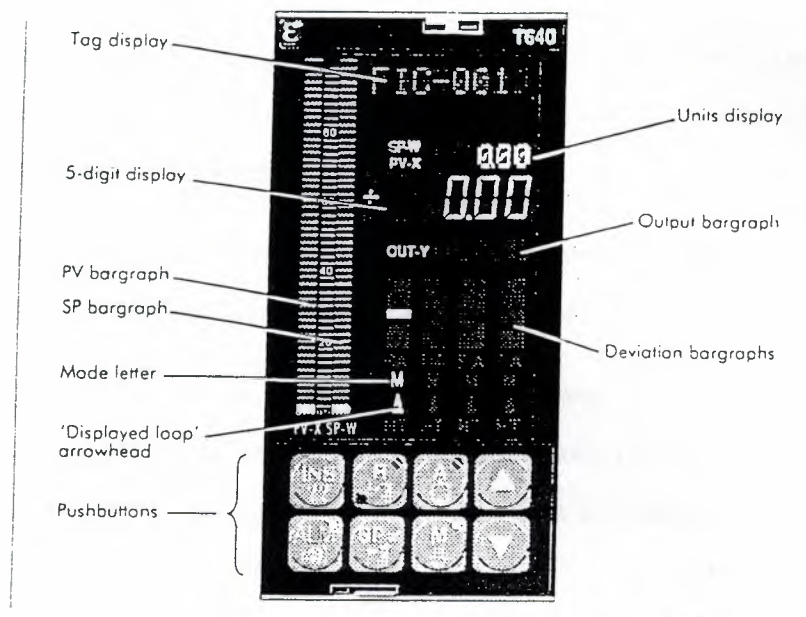


Figure 3.7 The T640 Controller Front Panel

### 3.3 The Software Packages

#### 3.3.1 The LINtools (*Local Instrument Network*) package.

LINtools is a powerful multipurpose PC-based software package designed by Eurotherm to be compatible with the T640 controllers. It can be used both on- and off-line. LINtools is used to build the database which is downloaded to the T640 controller. The control database is a collection of blocks linked together to perform a particular task. The types of blocks available are categorized into groups depending on their functions. The first step in developing a control strategy is to define the inputs and outputs which will be used. The connections to the T640 controllers are made via either analogue or digital I/O Blocks. In this work analogue I/O blocks will be used. The site number, channel number and the type of signal to be used should be defined for each block [1]. The wiring diagrams (figures 3.2 to 3.4) show which instruments are connected to which channels, the site and channel number, and the type of I/O signals.



***Procedure for building a control strategy :***

- i. Building up the strategy: This is done by choosing the *Configuration (CFIG)* option from the menu, composing the blocks using the library of available blocks, and specifying their parameters.
- ii. The blocks should be wired up, taking care in wiring the required variables from each block. The whole strategy should then be saved as a *humidity.DBF* file.
- iii. Using the *UTIL* option from the main menu, every thing should be loaded to the T640. This must be done to establish communications between the rig and the PC station. Using the same, option the *Linfiler* should be chosen and from there the following steps should be performed.
- iv. From the *Linfiler*, all old files should be deleted from *node 30*.
- v. The new strategy should be loaded to *node 30*, also the text files of the action blocks should be copied if any action blocks exist in the control strategy.
- vi. Load all again using the *UTIL Load all* option to the T640, then a view of the system can be obtained using the *View* option from the menu and loading the corresponding file. The *View* option also gives access to changing parameters of certain blocks.

**Notes:** - If any changes are made to the DBF file, they should be saved and all of the above procedure should be repeated.

- In the control strategy, if a certain variable is required to be monitored by SCADA, it should be connected to a PID controller loop.

- **Types of blocks available:**

There are different types of blocks available from the LINtools software: I/O, S6000, CONDITN, CONTROL, TIMING, SELECTOR, LOGIC, MATHS, CONFIG, HIST, DIAG, TAN, and BATCH. The following blocks were used for this work: I/O (ANALOGUE), CONTROL (PID), MATHS (ACTION AND EXPRESSION) and TIMING BLOCK [1]. An example of parameter specifications of some of these blocks is provided in Appendix B.

### 3.3.2 The SCADA package

The T3000 SCADA package gives complete access to the user to determine the required set points and develop graphs of both the input and output signals. This package allows a large number of instruments (run by the LINTools databases) to be connected together and controlled from a single remote PC workstation. This package can also be run from Windows<sup>TM</sup>. Each of the control loops can be viewed using this package. It must be noted that any parameter changes performed in the SCADA environment are not permanent. The optimum controller settings are saved in the control database.

The SCADA has an initial Graphical User Interface screen (GUI). Options are displayed as function keys (figure 2.8). Definitions of these functions follow in table 3.2. Some of the SCADA displays are shown in Appendix D.



Figure 3.8 The SCADA Softkeys

Name of the key	Keyboard key	Job
Overview	F1	Overview page which shows the plants connected to the system and enables the user to chose the desired plant.
Area	F2	Current area display
Group	F3	Current group display, where all the controllers that have been used can be seen.
Point	F4	Point display of the current selected item, showing all the associated block parameter fields.
Alarm	F5	Alarm summary page
Fast	F6	Standard fast trend page, containing graph for all associated blocks parameter fields
Archive	F7	Historical display of data collected from selected points in the database, which can be used for analysis of the system performance.
Mimic	F8	Mimic diagram of the chosen process
MimMenu	F9	Pop-up menu for the available mimics
Alm His	Ctrl A	Alarm history page

Table 3.2 Softkey Functions In The SCADA GUI

- **Procedure for system analysis and set point changing:**

- i. *Group* option should be chosen. This will transfer to group display which shows the variables being controlled by the main PID loops.

- ii. The variable required to be monitored should be chosen and then the point button should be pressed. The required changes and the corresponding response can be observed in the graphical output.

In order to analyze the system performance over a long period of time, a historical display of all of the variables can be obtained.

- **Procedure for building the historical display:**

- i. The *FIXDMDDE*, and *Historical collect* should be running.

- ii. From the *Historical assign*, the limit, the sampling period (the minimum sampling period is 1s), the node name, and the activation and deactivation of the node should be set up.

- iii. Now the system is ready for the historical display, where the chart group which includes the pen and the time groups should be specified, along with the required tags (switching to current time might be necessary).

- iv. The data is then exported to be used within the EXCEL™ using the *Export* option from the file menu.



# Chapter 4

## Ratio Control

One of the conventional control strategies commonly used in process control systems is the *Ratio Control* strategy. It is very widely used in industries where the ratio between flow rates of two or more streams need to be held at a required value. Other conventional control strategies such as Cascaded and Feedforward control strategies are also common in the process industries [3].

This chapter explains briefly some of the various control strategies used in process control systems. It also discusses the ratio control principle, its implementation in *Molly*, and the resultant performance characteristics of the system response.

### 4.1 Conventional control Strategies

Among famous process control principles are Cascaded control, Feedforward control, and Feedback control:

**Cascaded Control:** Basically, cascaded control is nesting one feedback loop inside another feedback loop. It relies on taking the process being controlled and finding some intermediate variable within the process to use as the controlled variable for the inner loop. So, it acts as Slave and Master loops. Cascaded control gives good results when the process to be controlled is very slow [5].

**Feedback Control:** Simply stated, it is realizing the difference between the required set point and the actual value of the output of a certain process in order to take the proper control action and obtain the desired response. This is a very common control strategy in process control, but it results in unsatisfactory response under the conditions of significant process lags and the presence of very large disturbances [5].

**Feedforward Control:** Basically, feedforward control anticipates the effect of disturbances on the process and compensates for them in advance [3].



From the above definitions it can be concluded that feedback control is retrospective. This means it can only respond to the disturbance after it's occurrence. Cascaded control gives a better response, but it is still retrospective. Feedforward control compensates for the disturbance before it happens.

## 4.2 Ratio Control

Ratio control is a common control strategy which is used in process industries where the ratio between two flow streams should be kept at a pre-set level. It is different from the other control methods in that it responds to changes by adjusting the ratio between two variables. It is a particular case of the feedforward control. Ratio control might be confused with cascaded control, because in ratio control one loop adjusts another. But ratio control is different in that it uses a conventional flow controller for one of the two streams, and the ratio controller maintains the ratio between the two flow rates.

There are three ratio control approaches:

- The Scaling Approach.
- The Direct Ratio Control Approach.
- The Indirect Ratio Control Approach.

The second and third approaches use PID controllers. All three approaches are explained briefly in this section, and in the following section the implementation of the indirect ratio control is presented.

### 4.2.1 Scaling Approach

This is a simple means of applying the ratio control. It assumes that the flow transmitter is calibrated for it's full range of the wild flow. It also assumes that the valve is carefully sized, so that it's full range of flow is in direct proportion to the full range of the wild flow. In this way the output of the flow transmitter can be applied directly to the valve to obtain the required ratio. But since it is very unlikely that the

relation between the wild flow and the output flow have the desired ratio, a scaling factor, or a ratio station should be used [3].

#### 4.2.2 Direct Ratio Control Approach

In this approach the ratio controller manipulates the flow of one of the streams to achieve the desired ratio,  $R$ . i.e.,  $R = \frac{f_1}{f_2}$ , where  $f_1$  is manipulated by the ratio controller to give the desired ratio  $R_r$  to  $f_2$ . The measured ratio  $R$  is compared with the desired ratio  $R_r$ . The resultant error signal is then fed into the ratio controller, which will generate the required control action [3].

Due to changes in atmospheric conditions, some sort of correction is required. Care should also be taken when dealing with calibration and measurement errors [3].

#### 4.2.3 Indirect Ratio Control Approach

This is a very simple and effective ratio control approach and throughout this work this strategy was applied to **Molly**. It manipulates the flow rate by calculating its desired set point, instead of calculating the ratio, as the case in direct ratio control. Indirect ratio control calculates the desired value of the flow rate itself according to the following equation [3].

$$f_1 = R_r * f_2 \quad 4.1$$

where,  $R_r$  is the desired ratio.

The direct ratio approach is used extensively throughout industry. However, care should be taken because of the potential effect of division by zero which leads to intermediate ratios. Also, division by a flow rate at the bottom of its range leads to very poor quality ratio control. In such circumstances, the indirect approach is more robust and should be used instead. This is also true if the ratio control is used as part of a model based control strategy involving deviation variables [3]. The rest of this chapter illustrates the implementation of this approach.

### 4.3 Ratio Control Implementation

#### 4.3.1 PID Controllers

Throughout this strategy, the basic controllers used are PID controllers. This section explains the PID function and PID controller tuning.

- **PID Control (Proportional, Integral and Derivative).**

The T640 analogue PID control equation is implemented by conventional analogue controllers using operational amplifiers, as shown below[1]:

$$OP = -\frac{100}{XP} \left[ ER + \frac{1}{TI} \int ER \cdot dt + TD \frac{dER}{dt} \right] \quad 4.2$$

Where:

OP = controller output

XP = proportional band,  $\left( \frac{100}{XP} = K_c(\text{proportional gain}) \right)$

TI = integral time constant.

TD = derivative time constant

ER = Error = (PV-SP) (PV is the process variable and SP is the set point of the controller)

The effect of changing each of the three control actions is summarized in the following table:



Action	Change	Effect
P	Increase $K_c$	Increase the sensitivity of the system Reduce offset Makes the response more oscillatory The system becomes less stable
I	Reduce TI	Eliminates offset faster Increase amplitude of oscillations Settling time becomes longer The response becomes more sluggish The system becomes more unstable
D	Increase TD	Stabilizes the system Reduces the settling time Speeds up the response Amplifies noise

Table 4.1 PID Control Actions [3]

- **PID Controller Tuning:**

There are two practical strategies used in tuning the PID controllers: the Continuous Cycling Method and the Reaction Curve Method [3]. The first method was used throughout this work. It uses the Zeigler and Nichols formula (first published 1941) to find the optimum settings as follows:

Type of Controller	$K_c$	TI	TD
P	$K_{cm}/2.0$	-	-
PI	$K_{cm}/2.2$	$P_u/1.2$	-
PID	$K_{cm}/1.7$	$P_u/2.0$	$P_u/8.0$

Table 4.2 Zeigler-Nichols Formula [3]

The continuous cycling method relies on changing the controller's proportional gain incrementally, while there is no integral and derivative actions (i.e.  $TI=\infty$  and  $TD=0$ ), until oscillations of the same magnitude are obtained (i.e. the system is critically stable). To apply the formula in table 4.2,  $K_{cm}$  denotes the gain at which oscillations occurred and  $P_u$  is the time period of the oscillations. When applying this method it is important to notice that sinusoidal oscillations of constant amplitude are obtained. These can be confused with limit cycles which are of constant amplitude but not sinusoidal. Limit cycles occur when the system is in oscillation and at least one signal is saturated. The most likely signal to saturate is the controller output, which might saturate at either the top or the bottom of its range [3].



• **The Sequence of Tuning The PID Controllers Used in the Ratio Control Strategy Applied to Molly:**

- i. The wet flow PID loop was tuned first (the set point = 0.25 kg/h).
- ii. The flow PID loop was then tuned (the set point = 0.25 kg/h), after observing the desired average value of that flow.
- iii. Finally, the humidity PID loop was tuned at the end (the set point = 10.5 °C).

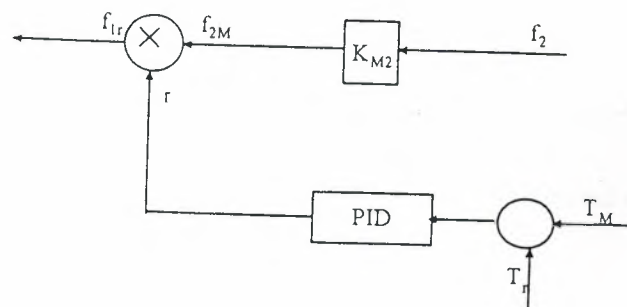
### 4.3.2 Implementation On Molly

The application of this approach on Molly is mathematically easy. This is because the flow rate of wet air ( $f_2$ ) is measured and then it is multiplied by the required ratio ( $r$ ), to give the desired dry air flow rate ( $f_1$ ) (figure 2.5) :

$$f_1 = f_2 * r \quad 4.3$$

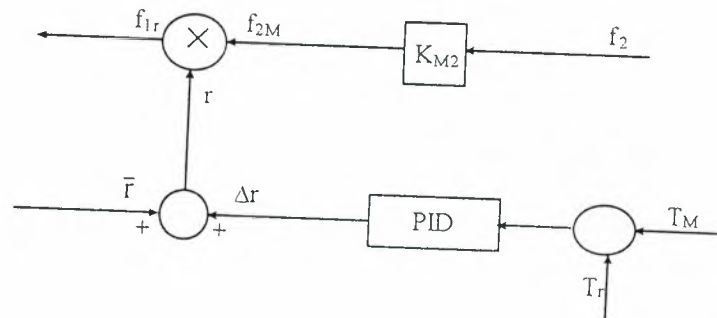
Three schemes of applying the indirect ratio control were identified, they are as follows:

**Scheme 1:** This is the scheme which was applied, it uses the dew point temperature control loop to find the desired ratio between the wet and the dry flow rates. Multiplying this ratio by the wet flow rate obtains the required set point for dry flow. This scheme is illustrated in the block diagram in figure 4.1.



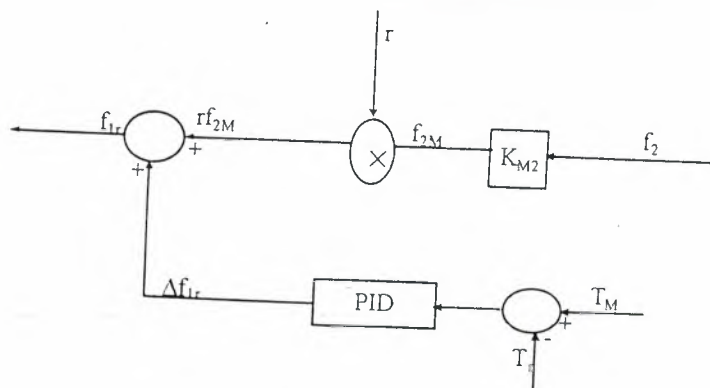
**Figure 4.1** Indirect Ratio Control Scheme 1

**Scheme 2:** This scheme is very similar to scheme 1. The difference is that it uses the average value expected for the desired ratio  $\bar{r}$ . The dew point temperature control loop is then used to find the desired change in that ratio  $\Delta r$ . This scheme is illustrated in the block diagram in figure 4.2.



**Figure 4.2** Indirect Ratio Control Scheme 2

**Scheme 3:** This scheme is different when compared to the other two schemes. The difference is that it uses the dew point temperature control loop to find the required change in the dry flow rate after calculating the value as from equation 4.1. This scheme is illustrated in the block diagram in figure 4.3.



**Figure 4.3** Indirect Ratio Control Scheme 3

**Note:** The block diagrams in figures 4.1 to 4.3 represent the process required in order to calculate the set point of the dry flow, and not for the entire system.

Scheme 1 was implemented using LINTools (figure 4.4). Table 4.2 gives the optimum controllers settings found by tuning the PID controllers using the Continuous Cycling method.

Controller	SP	TI	TD
FFY32	125.00	4.00	0.50
FIC32	160.00	3.50	0.60
AIC30	170.00	3.50	0.70

Table 4.3 Optimum Controllers Settings

Where:

FFY32 is the controller of the dry flow loop

FIC32 is the controller of the wet flow loop

AIC30 is the controller of the dew point temperature (humidity) loop

Figure 4.4 shows the strategy as it was applied in LINTools. Values for the parameters of these blocks can be found in Appendix B. The strategy employs three analogue inputs, which are the dew point temperature (AT30), the dry flow (FT31) and the wet flow (FT32), and two analogue outputs, the dry flow (FX31) and the wet flow (FX32). The result of the expression block (EXPR 2) is used as a set point of the dry flow control loop (FFY32), while the wet flow is controlled by an independent control loop (FIC32). AIC30 is the controller connected to the dew point temperature input in order to find the desired ratio between the two flow rates.

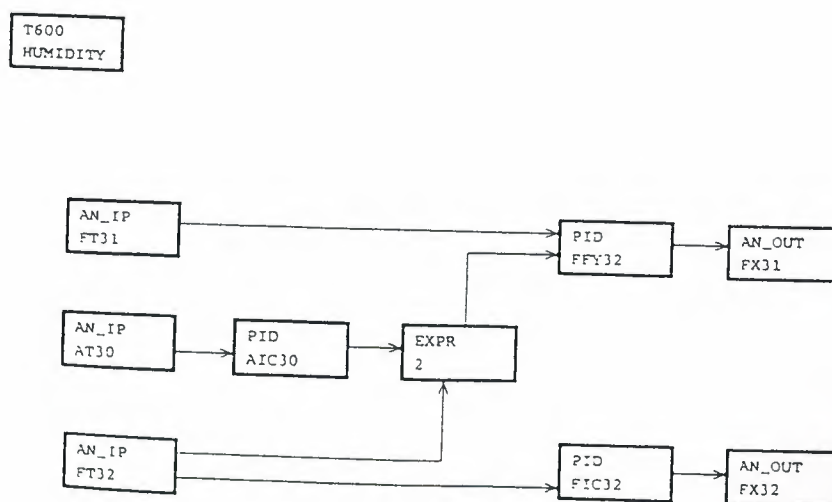
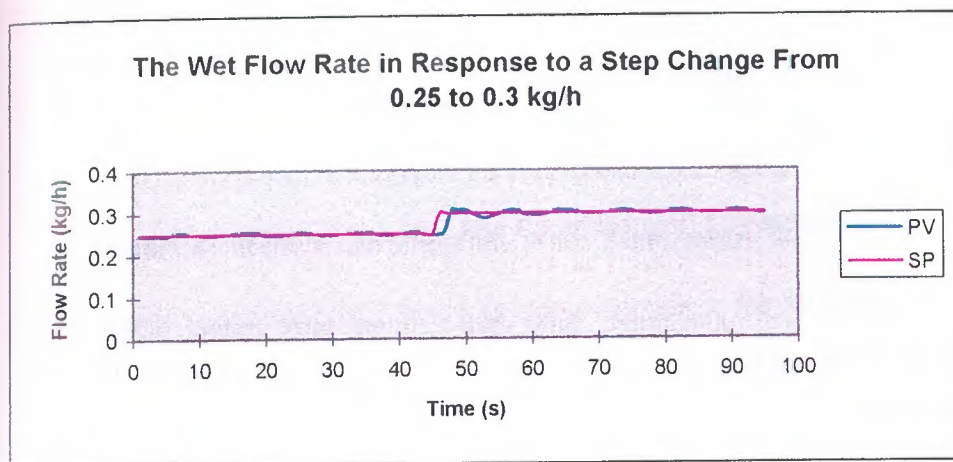


Figure 4.4 Indirect Ratio Control LINTools Strategy (Scheme 1)

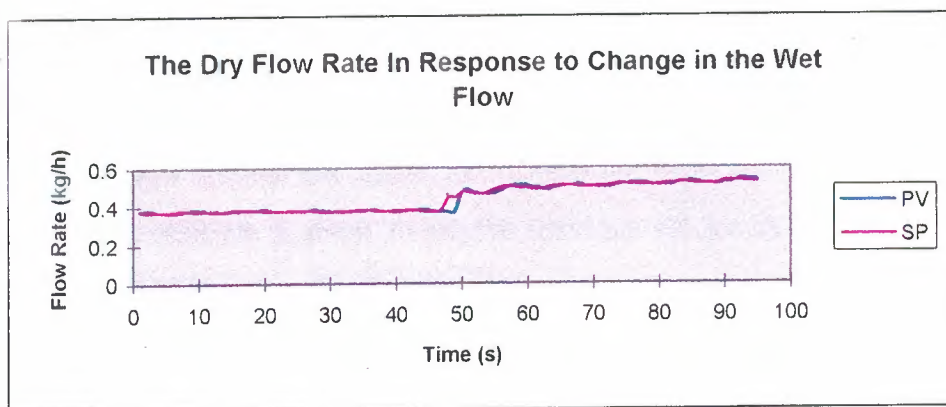


## 4.4 Results

The response of the ratio control scheme (scheme 1) to a step change in the wet flow from 0.25 to 0.3 kg/h is as follows (figures 4.5 to 4.7):

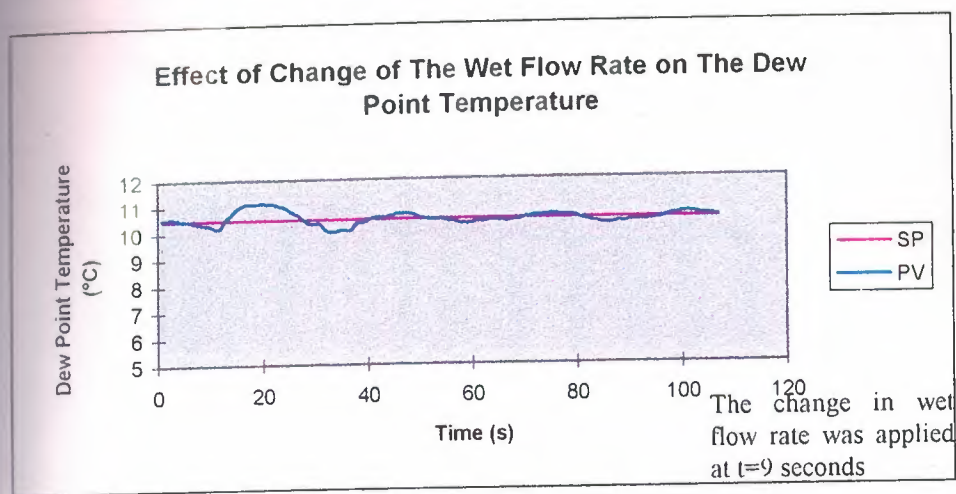


**Figure 4.5** Ratio Controller Wet Flow Response



**Figure 4.6** Ratio Controller dry Flow Response



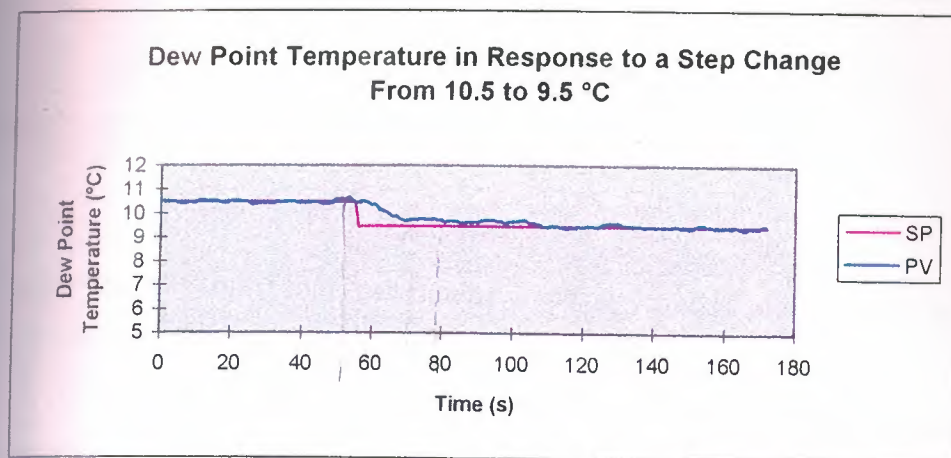


**Figure 4.7** Ratio Controller Dew Point Temperature Response

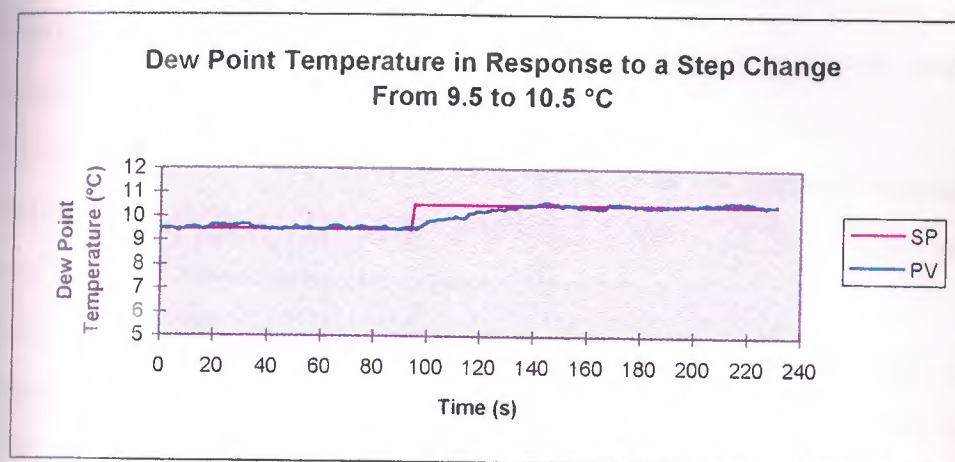
The wet flow PID control loop can deal with small changes in the set point of the flow rate. For a step change from 0.25 to 0.3 kg/h, the time required to reach the new set point was less than 2 seconds (figure 4.5). The dry flow change in response to a change in the wet flow was quite smooth, not abrupt. The dry flow PID control loop coped with that change (figure 4.6), which resulted in a smooth response for the dew point temperature of the moist air at the output of the rig (figure 4.7). It took 29 seconds to reject this disturbance.

The responses were smooth and stable, but it must be noted that if the main supply pressure dropped suddenly to about 40 psi, the response will not be very smooth and it will take longer time to reject this disturbance.

The humidity of the moist air in response to a step change from 10.5 to 9.5 °C is shown in figure 4.8, the wet flow was constant throughout this change at 0.25 kg/h. Figure 4.9 shows the effect of step change in humidity from 9.5 to 10.5 °C.



**Figure 4.8** Ratio Controller Dew Point Temperature Response



**Figure 4.9** Ratio Controller Dew Point Temperature Response

From figures 4.8 and 4.9, the settling time was 40 seconds for the step drop and 35 seconds for the step rise. These results are reasonable time for these step demand changes in such a process where the controlled variables are air flow rates. The response was, to a reasonable degree, a smooth one.

This controller was found to wind up for considerably large changes in the set point of the dew point temperature. This is due to the non-linearities of the rig.

## Chapter 5

# Fuzzy Logic Control

Fuzzy logic control (FLC) applications in industry started in the 1970's in Japan. The motivations behind using FLCs were [4]:

1. The real world is too complicated and the fuzzy concept helps in obtaining a reasonable models for real world processes.

2. Human knowledge is becoming more and more important, and the fuzzy concept can formulate this knowledge in a systematic manner and give it an engineering flavour.

Fuzzy logic can combine human experience with the sensory measurements and mathematical models. One of the important features of fuzzy logic is that it can accommodate non-linearity and external disturbances [4].

Fuzzy logic has many industrial applications these days such as health management systems, image process equipment, temperature control, gas turbine engines, etc.[10]. This chapter illustrates the principle of fuzzy logic control and presents FLC designs for Molly.

### 5.1 Fuzzy Logic Control Principles and Design

Basically, fuzzy logic handles variables which are qualitative and vague. These variable are manipulated by linguistic statements to produce a crisp output. It is important to note that the output of the fuzzy logic controller is deterministic (has a specific value) [4].

#### 5.1.1 The Controller Structure

The basic fuzzy logic structure used FLC design is the one developed by Mamdani and shown in figure (5-1) [3].



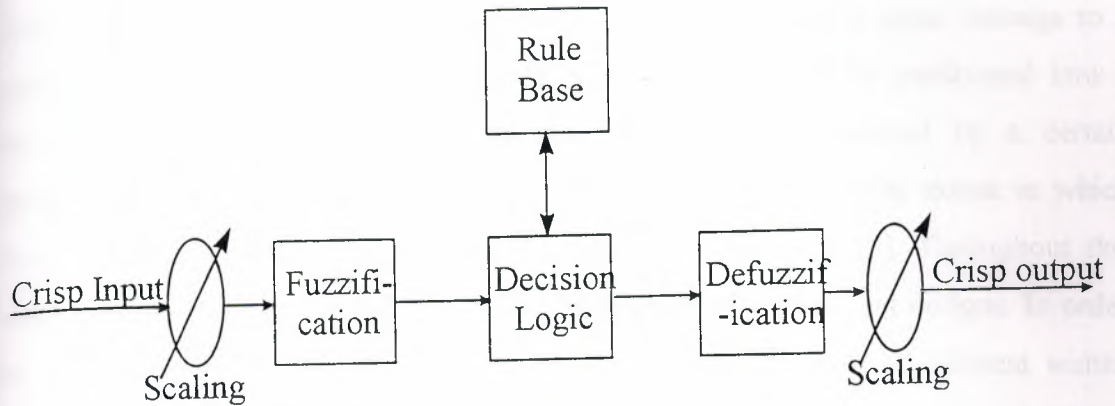


Figure 5.1 Mamdani Fuzzy Logic Structure [3]

Note: The input and output of this structure are crisp values.

#### • FLC Components:

The fuzzy logic controller consists of three steps [4]:

1. *Fuzzification* : Inputs are fuzzified using input fuzzy sets.
2. *Fuzzy Processing*: Processing fuzzy inputs according to a rule base which yields fuzzy outputs.
3. *Defuzzification*: Producing a crisp real value from a fuzzy output.

These steps are explained in the subsequent sections.

#### 5.1.2 Fuzzification

Fuzzification converts the crisp input signals into fuzzy sets. There are different types of fuzzifiers which can be used such as Singleton, Gaussian or Triangular fuzzifiers. Throughout this work the Gaussian fuzzifier was used. This is represented in the following equation [8]:

$$\mu(x) = \exp\left(-\frac{(x - \bar{x})^2}{\sigma^2}\right) \quad 5.1$$

Where:

$\mu(x)$  is the membership function.

$x$  is the process variable.

$\bar{x}$  is the value at which the value of the membership function is highest

$\sigma^2$  is the width of the Gaussian function.



The membership function is a measure of the extent to which a signal belongs to a particular subset. The complete universe of discourse should be partitioned into a certain number of subsets. Each of these subsets is represented by a certain membership function. The choice of the number of subsets, and the extent to which they overlap is a design decision and an application dependent [3]. Throughout this work the universe was divided into 3 and 5 subsets for two different designs. In order to compensate for the system's non-linearity, Gaussian functions of different widths were used for the inputs, while the Gaussian functions for the output employed a fixed width.

### 5.1.3 Fuzzy Rule Base

Establishing a rule base is by no means a trivial task. The function of the rule base is to relate the input fuzzy sets with the output fuzzy sets. Each rule consists of two parts, the antecedent and the consequence:

**If (Some Condition) and/or (Some Other Condition) Then (Some Outcome)**

The design of the rule base is application dependent, it is based on the knowledge and the understanding of the process [3]. However the design of any rule base should aim to achieve the following attributes [4]:

1. **Complete** : A set of rules is complete if any combination of input values results in an appropriate value. Any combination should fire at least one rule.
2. **Consistent** : There should be no contradictions in the rules.
3. **Continuous** : There is no neighboring rules with output fuzzy sets that have empty intersection, or in other words small changes in the inputs should not result in a jump in the control action, the transfer between consecutive control actions should be smooth [4].

### 5.1.4 Defuzzification

There are many defuzzification methods, but the two that are mostly used are [4]:

- 1- **Mean of Maxima Method (MOM)**. It is a computationally simple method. It chooses the range of the output that has the highest membership value and takes the output as the midpoint of this range.

2- *Center of Average Method (COA)*. It is more complicated than the MOM. It uses the following equation:

$$o p = \frac{\sum \mu x}{\sum \mu} \quad 5.2$$

Both methods were applied to Molly. Due to the limitations of the computational facilities offered by LINTools, the implementation of COA (Appendix C, figure C.2) was much more complicated than the implementation of MOM. Also, due to the same reason the COA resulted in a poorer response than that of the MOM.

## 5.2 Implementation Of FLC on Molly

Through out this work the Fuzzy PD Controller was used which is explained in figure 5.2 (it is a form of the Mamdani type presented in figure 5.1).

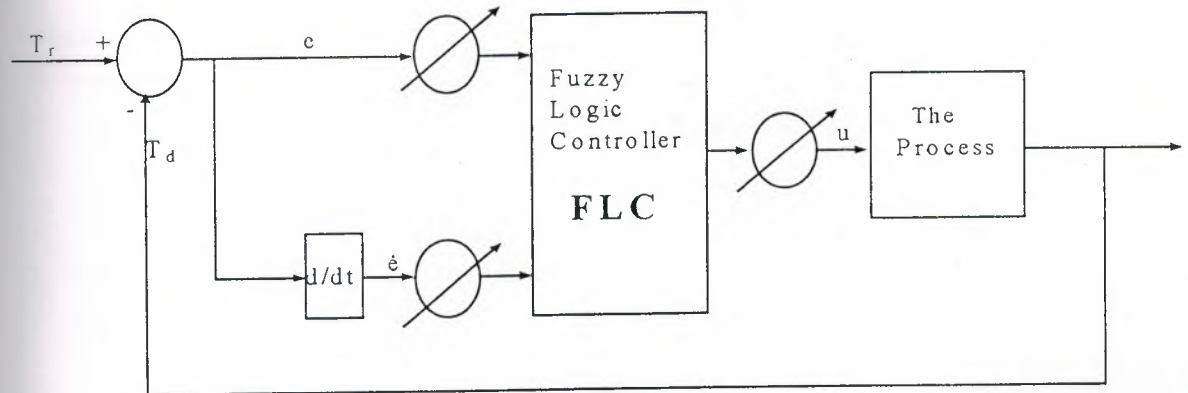


Figure 5.2 The PD Fuzzy Logic Controller

- **Input variables:**

$$e = PV - SP$$

$$\dot{e} = \dot{PV}$$

PV is the measured dew point temperature and SP is the set point of the dew point temperature.

Various FLC schemes were considered:

1. A 9-rule base FLC for both flows (FLC1).
2. A 25-rule base FLC for the dry flow (FLC2).

3. A 9-rule base for the dry flow (FLC3).

(All of the above use the MOM method for defuzzification).

4. A 9-rule base for the dry flow using the COA method for defuzzification (FLC4).

The first two schemes gave the most acceptable results and are explained below. The rest are explained in Appendix(C)

### 5.2.1 The First Design (FLC1)

The first design uses the FLC to control both flow rates, wet and dry. The control signal  $\Delta u$  is used to modify both flow rates, the design is as follows:

**Fuzzification:** The complete universe was partitioned into three subsets, negative (N), zero (Z), and positive (P). Normalized Gaussian equations were used. The Gaussian functions used were as shown in figure 5.3. In the definition of these fuzzy sets the value of the N membership function was zero for positive variables ( $e$  or  $\Delta u$ ). Also, the value of the P membership function was zero for negative variables ( $e$  or  $\Delta u$ ) (figure 5.3).

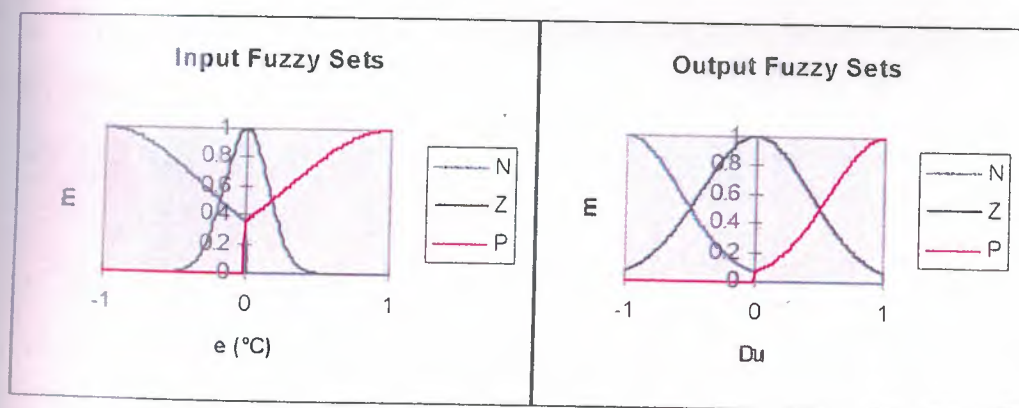


Figure 5.3 I/O Fuzzy Sets for FLC1

**Fuzzy Rule Base:** The following tables explain the rule base used for this design. The inputs to these tables are  $e$  (columns), and  $\dot{e}$  (rows), and the output is  $\Delta u$  for the two flows.

	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

Table 5.1 FLC1 Rule Base For The Dry Flow



	N	Z	P
N	P	P	Z
Z	P	Z	N
P	Z	N	N

Table 5.2 FLC1 Rule Base For The Wet Flow

• **Defuzzification:** The defuzzification method used in this design was the MOM method.

Figure 5.4a is an overview of the strategy as implemented using LINTools, and depicts each of the compound function blocks (CMPND). The functionality of each CMPND block is described in more detail in figures 5.4b to 5.4d. The functions of these blocks are summarized as follows:

- PID blocks are used as unity gain blocks to give access for monitoring these variables: the dew point, the dry flow rate and the wet flow rate using SCADA.
- AN\_IP blocks collect analogue output signals and convert them to % units.
- AN\_OUT blocks are responsible for sending the control actions to the associated variables in the plant, namely the wet and dry flow rates.
- TIMER blocks are used to time the control actions to be sent to the plant each 0.2 second.
- ACTION FEEDB and FEEDB1 blocks are for adding the control signal ( $\Delta u$ ) to the previous value of the flow rates.
- EXPR R1 block is for finding the error signal.
- The other EXPR blocks are unity gain blocks.
- CMPND FLC block contains the fuzzy logic controller design (figure 5.4b).

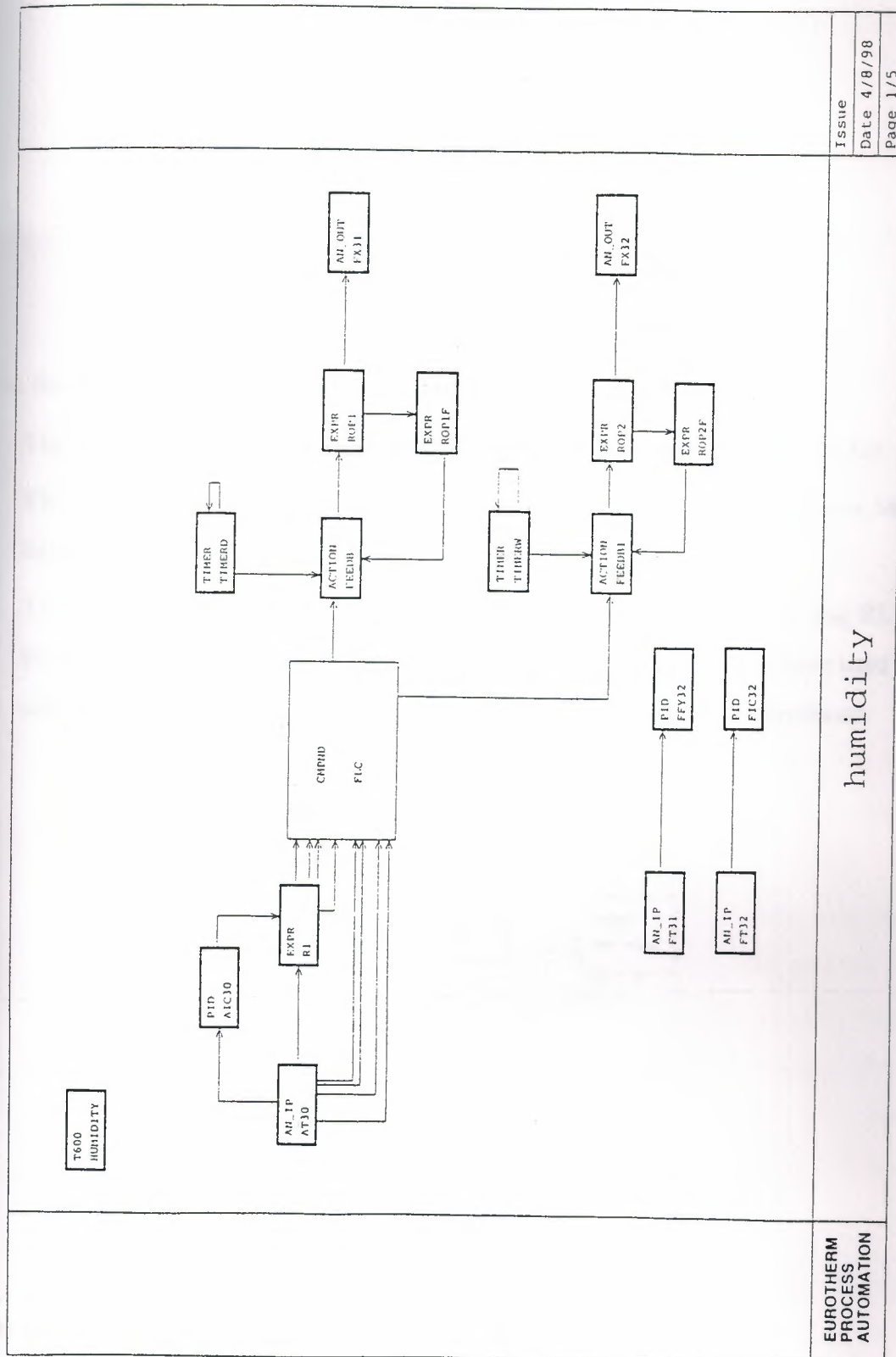
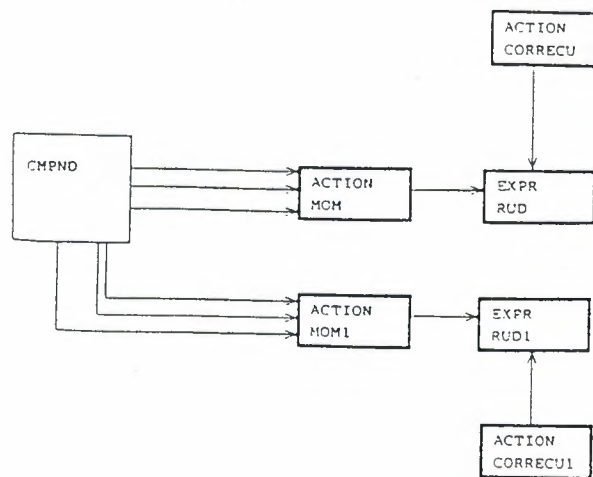


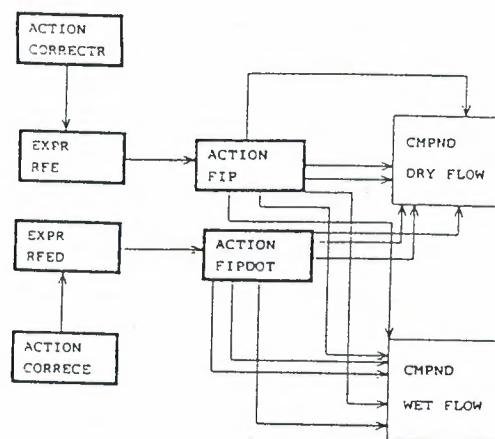
Figure 5.4a FLC1 LINtools Strategy



**Figure 5.4b** FLC1 LINTools Strategy (CMPND FLC)

The functions of the blocks inside the CMPND FLC are as follows:

- The CMPND block contains the fuzzifier and the fuzzy rule base (figure 5.4c).
- The ACTION MOM and MOM1 blocks are the routines which performs MOM defuzzification.
- The ACTION (CORRECU and CORRECU1) and the EXPR (RUD and RUD1) blocks are the output scaling factors. Switching scaling factors have been used (i.e. scaling factors that change their values according to the region of operation).



**Figure 5.4c** FLC1 LINTools Strategy (CMPND)

The functions of the blocks inside the above CMPND are as follows:

- The ACTION FIP and FIPDOT blocks are the fuzzifier blocks.



- The ACTION (CORRECTR and CORRECE) and the EXPR (RFE and RFED) blocks are the input scaling factors.
- The CMPND (DRY FLOW and WET FLOW) blocks are the fuzzy rule bases (figure 5.4.d)

The remaining two CMPND blocks look the same but have different wiring. Their function is to fire the rules in tables 5.1 and 5.2.

The ACTION NRULES fires the negative rules, the ACTION ZRULES fires the zero rules, and the ACTION PRULES fires the positive rules (as in tables 5.1 and 5.2).



Figure 5.4d FLC1 LINTools Strategy (CMPND WET FLOW)

### 5.2.2 The Second Design (FLC2).

The FLC is used to control the dry flow rate, while the wet flow is being controlled by PID controller having the same settings as shown in table (4-3). The control signal  $\Delta u$  is used to modify the dry flow rate, the design is as follows:

**Fuzzification:** The complete universe was partitioned into five subsets, negative large (NL), negative (N), zero (Z), positive (P), and positive large (PL). Normalized Gaussian equations were used. The Gaussian functions used were as shown in figure 5.5. In the definition of these fuzzy sets the values of the N and NL membership functions were zero for positive variables ( $e$  or  $\Delta u$ ). Also, the values of the P and PL membership functions were zero for negative variables ( $e$  or  $\Delta u$ ) (figure 5.5).

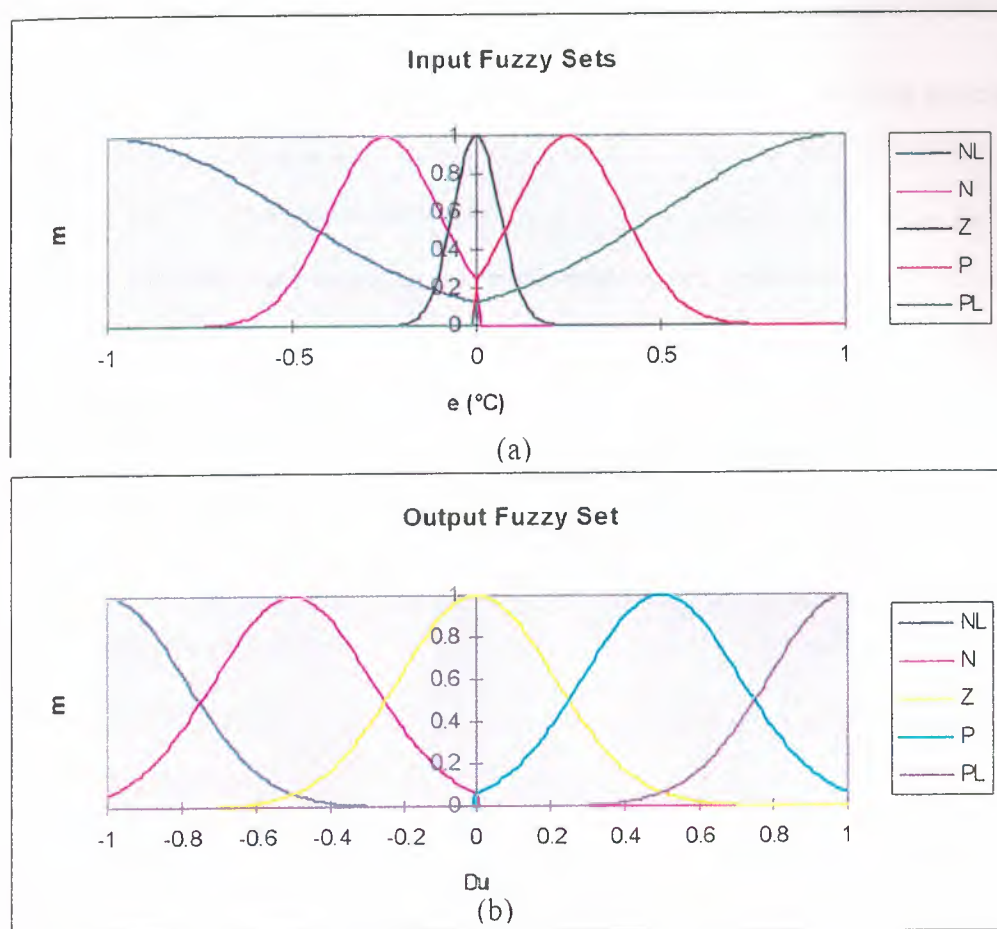


Figure 5.5 I/O Fuzzy Sets for FLC2

**Fuzzy Rule Base:** The following table explains the rule base used for this design. The inputs in this table are  $e$  (columns), and  $\dot{e}$  (rows), and the output is  $\Delta u$  for the dry flow

	NL	N	Z	P	PL
NL	NL	NL	NL	N	Z
N	NL	NL	N	Z	P
Z	NL	N	Z	P	PL
P	N	Z	P	PL	PL
PL	Z	P	PL	PL	PL

Table 5.3 FLC2 Rule Base For The Dry Flow

• **Defuzzification:** The defuzzification method used in this design was the MOM method.

Figure 5.6a gives an overview of the strategy as implemented using LINTools, and depicts each of the compound function blocks (CMPND). The functionality of each

CMPND block is described in more detail in figures 5.6b and 5.6c. The functions of these blocks are summarized as follows:

- PID blocks (FIC30 and FFY32) are used as unity gain blocks to give access for monitoring these variables: the dew point and the dry flow rate using SCADA.
- The PID FIC32 block is used to control the wet flow (it has the same optimum settings as in table 4.2)
- AN\_IP blocks collect analogue output signals and convert them to % units.
- AN\_OUT blocks are responsible for sending the control actions to the associated variables in the plant. Namely the wet (from the PID controller) and dry flow rates (from FLC2).
- ACTION FEEDB block for adding the control signal ( $\Delta u$ ) to the previous value of the dry flow rate.
- EXPR R1 block is for finding the error signal.
- The other EXPR blocks are unity gain blocks.
- CMPND FLC block contains the fuzzy logic controller design (figure 5.6b).
- There were no timers used in this design. The response was acceptable without a timer.



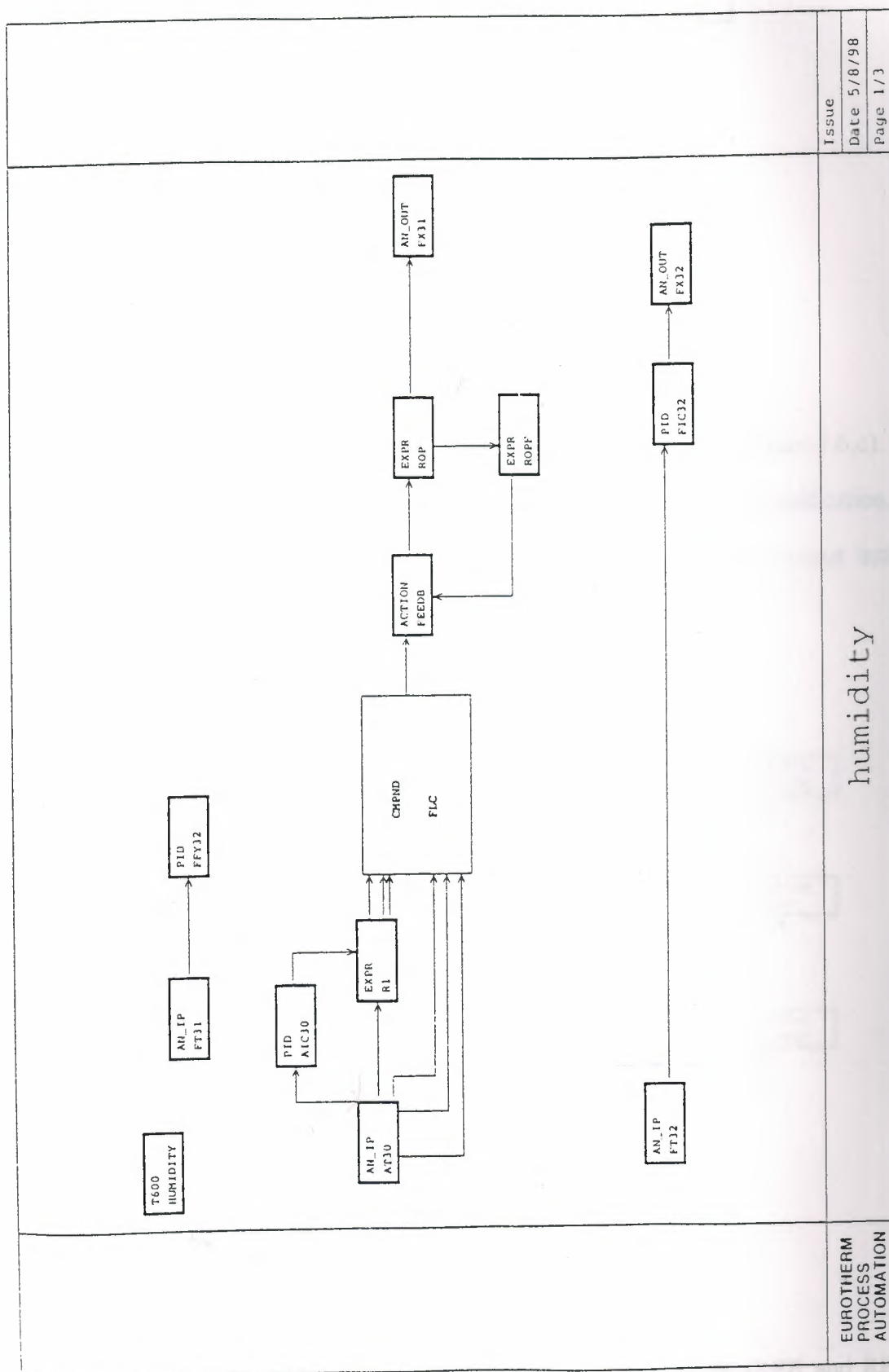
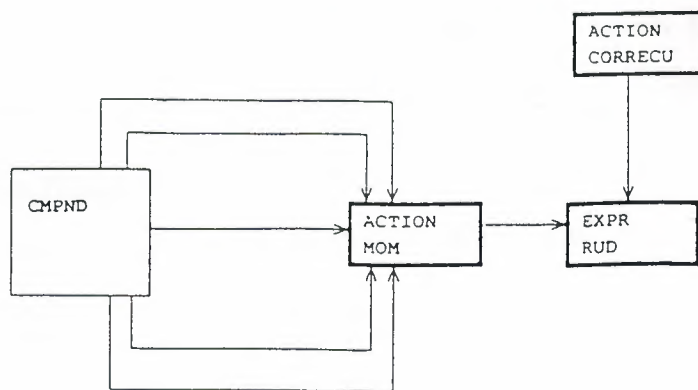


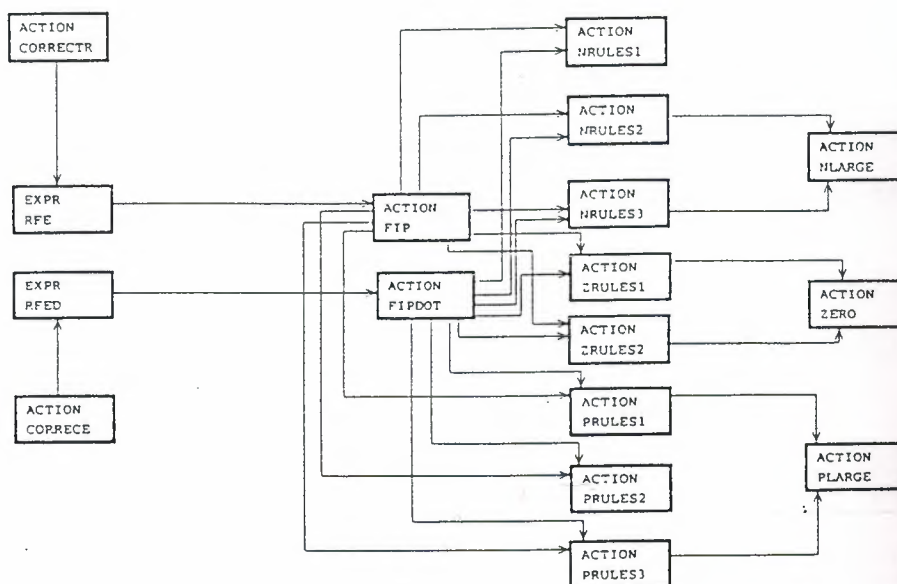
Figure 5.6a FLC2 LINtools Strategy



**Figure 5.6b** FLC2 LINTools Strategy (CMPND FLC)

The functions of the blocks inside the CMPND FLC are as follows:

- The CMPND block contains the fuzzifier and the fuzzy rule base (figure 5.6,c).
- The ACTION MOM block is the routine which performs MOM defuzzification.
- The ACTION CORRECU and the EXPR RUD blocks are the output scaling factors. Switching scaling factors have been used.



**Figure 5.6c** FLC2 LINTools Strategy (CMPND)

The functions of the blocks inside the above CMPND are as follows:

- The ACTION FIP and FIPDOT are the fuzzifier blocks.
- The ACTION (CORRECTR and CORRECE) and the EXPR (RFE and RFED) blocks are the input scaling factors.
- The rest of the action blocks are used to fire the rules as explained in table 5.3.

### 5.3 Results

The performance of both FLCs has been investigated primarily by applying a step change in the set point of the dew point temperature. The results were as follows:

#### 5.3.1 The First Design (FLC1)

Figure 5.7 shows the dew point temperature of the moist air in response to a step change of from 10.5 to 9.5°C

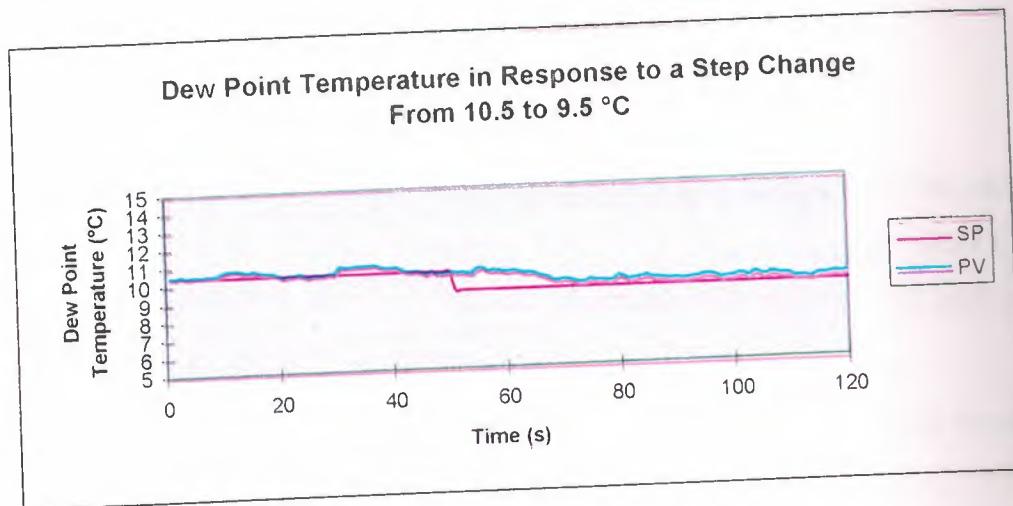


Figure 5.7 FLC1 Dew Point Temperature Response

The dew point temperature of the moist air in response to a step change from 9.5 to 10.5°C is shown in figure 5.8, and the flow rates under these two operating conditions are shown in figure 5.9.

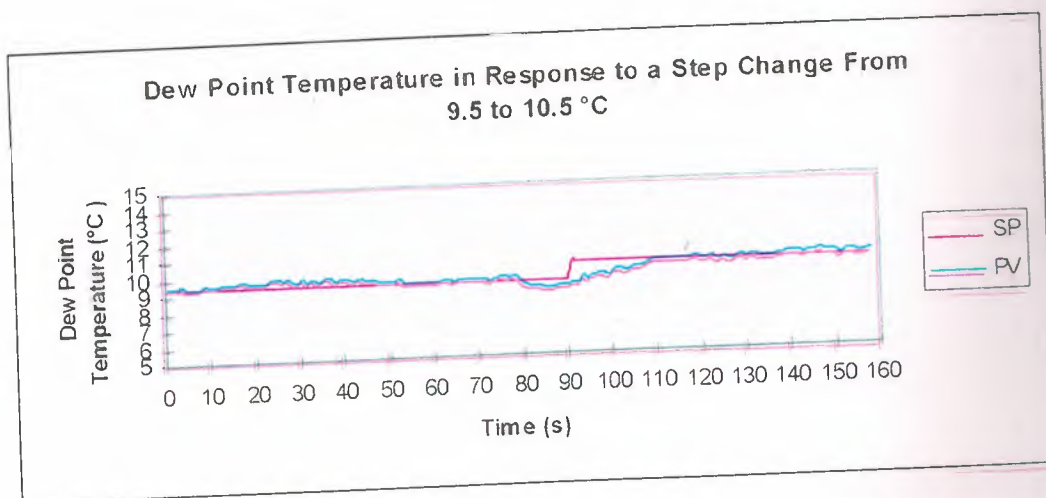
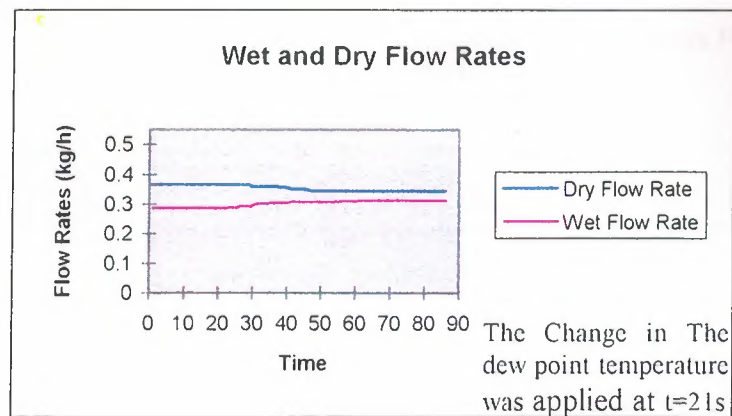


Figure 5.8 FLC1 Dew Point Temperature Response





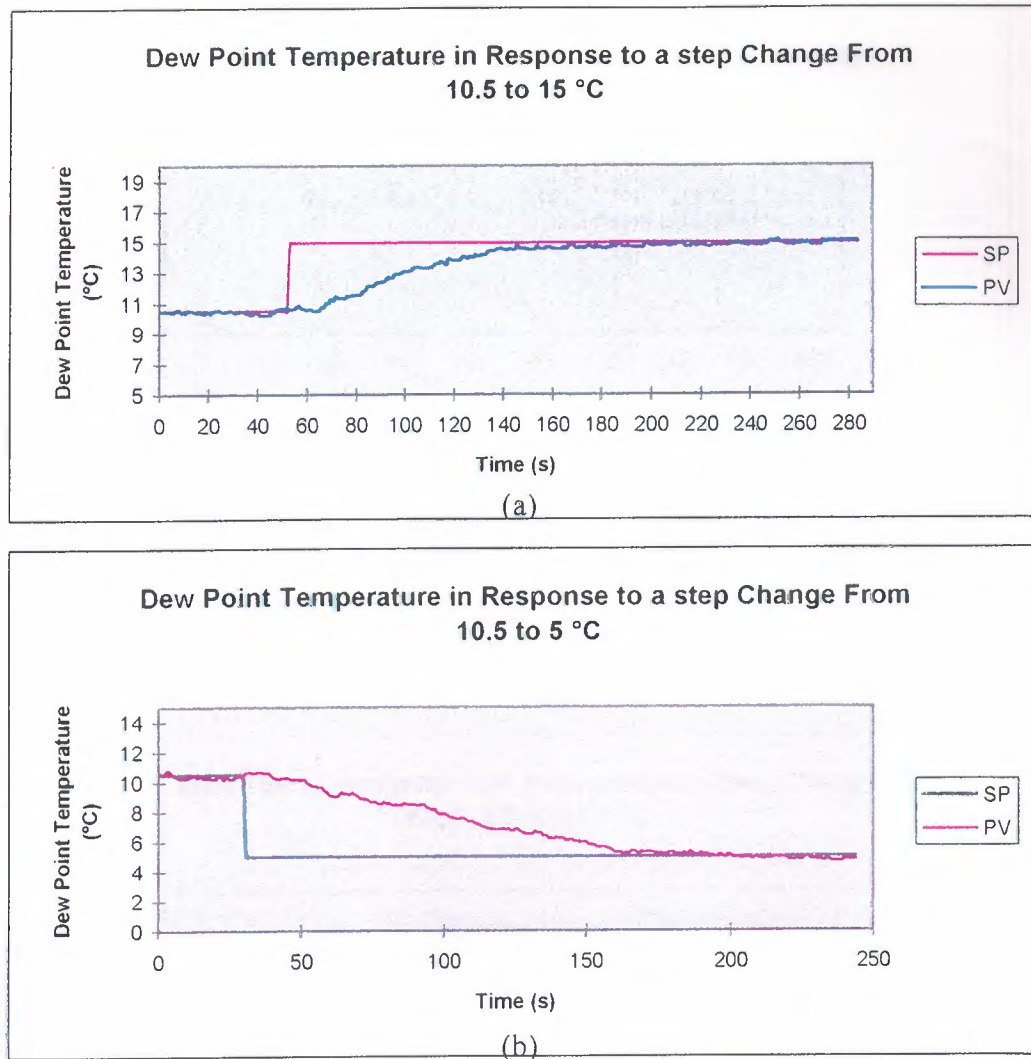
**Figure 5.9** FLC1 Wet and Dry Flow Responses

The responses (figure 5.7 to 5.9) indicate the following:

1. This FLC appears to offer a faster response when compared to the ratio controller described earlier (chapter 4, figures 4.8 and 4.9). The settling time values for the two step changes in demand were 18 and 19 seconds compared to 40 and 35 seconds respectively for the ratio controller.

2. The responses of both wet and dry flows are relatively flat with little or no transient overshoot.

In order to investigate whether FLC1 will operate on a bigger range of operation than that the conventional PID controllers (explained in chapter 4), bigger step changes were applied to the system: from 10.5 to 15 °C, and from 10.5 to 5 °C. Figure 5.10 shows the dew point response.

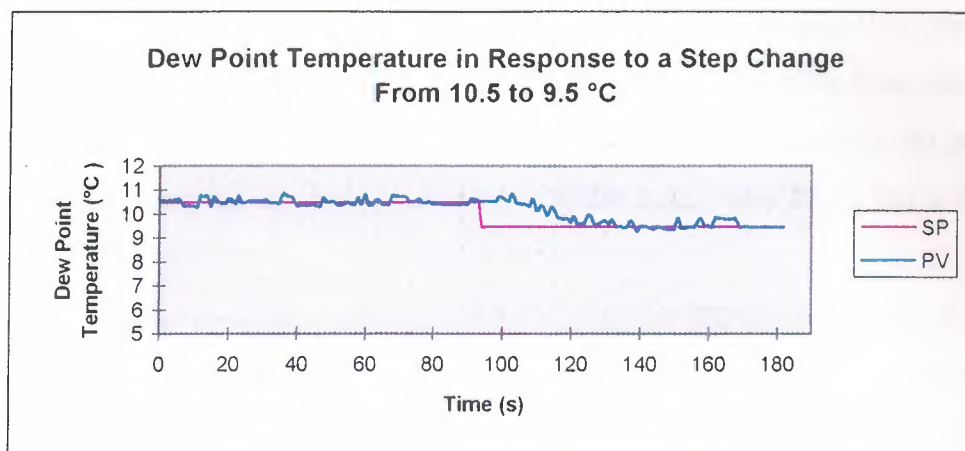


**Figure 5.10** FLC1 Dew Point Temperature Response for Big Step Changes

FLC1 can accept big changes in the set point of the dew point temperature without winding up. The settling time was longer when compared to the first case (about 100 seconds). This is to be expected for a bigger change in demand.

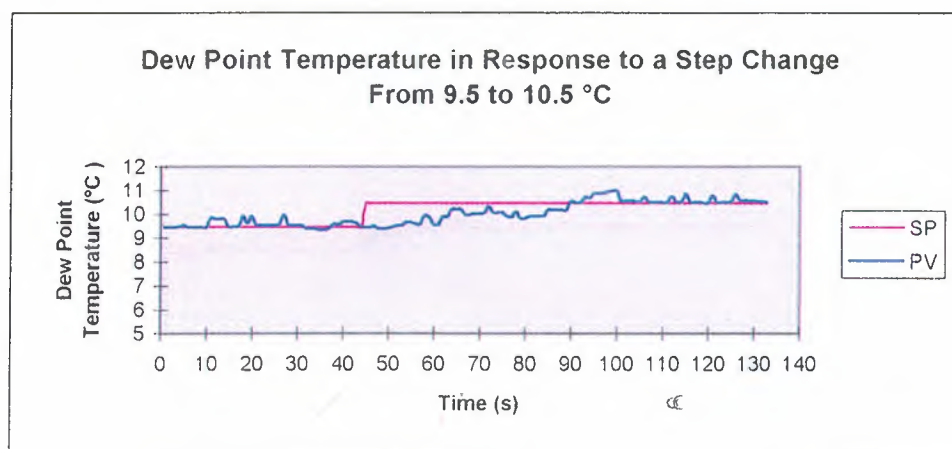
### 5.3.2 The Second Design (FLC2)

Figure 5.11 shows the dew point temperature of the moist air in response to a step change from 10.5 to 9.5°C.

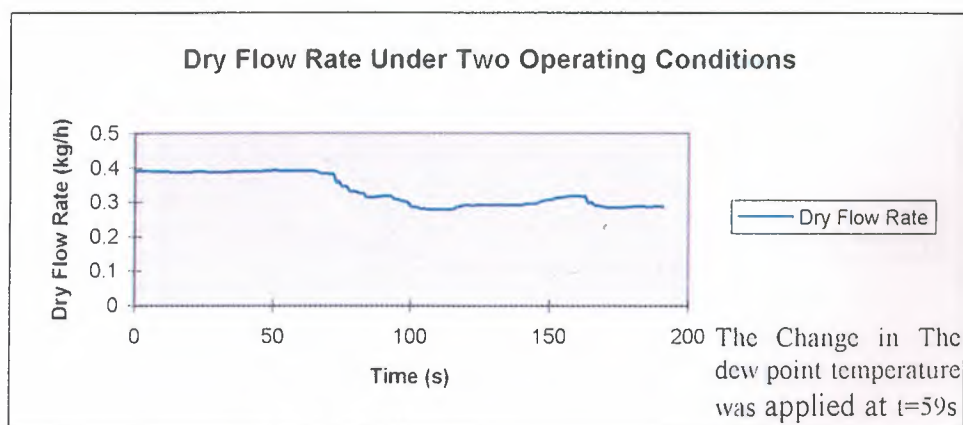


**Figure 5.11** FLC2 Dew Point Temperature Response

The dew point temperature of the moist air in response to step change from 9.5 to 10.5°C is shown in figure 5.12. The dry flow rate under these two operating conditions is shown in figure 5.13. The wet flow was constant at 0.25 (kg/h).



**Figure 5.12** FLC2 Dew Point Temperature Response



**Figure 5.13** FLC2 Dry Flow Response

The responses (figures 5.11 to 5.13) indicate the following:



1. FLC2 appears to offer a faster response when compared to the ratio controller described earlier (chapter 4, figures 4.8 and 4.9). The settling time values for the two step changes in demand were 26 and 28 seconds compared to 40 and 35 seconds respectively for the ratio controller. On the other hand FLC2 has a slower response than FLC1.

2. The wet flow was fixed at 0.25 kg/h using the PID controller tuned earlier (in chapter 4), while the dry flow was controlled using this FLC. The dry flow response was found not to be as flat as the first FLC design where there was a small overshoot (figure 5.13).

Again, bigger step changes were applied to the system, from 10.5 to 12 °C, and from 10.5 to 5 °C. Figure 5.14 shows the dew point temperature response.

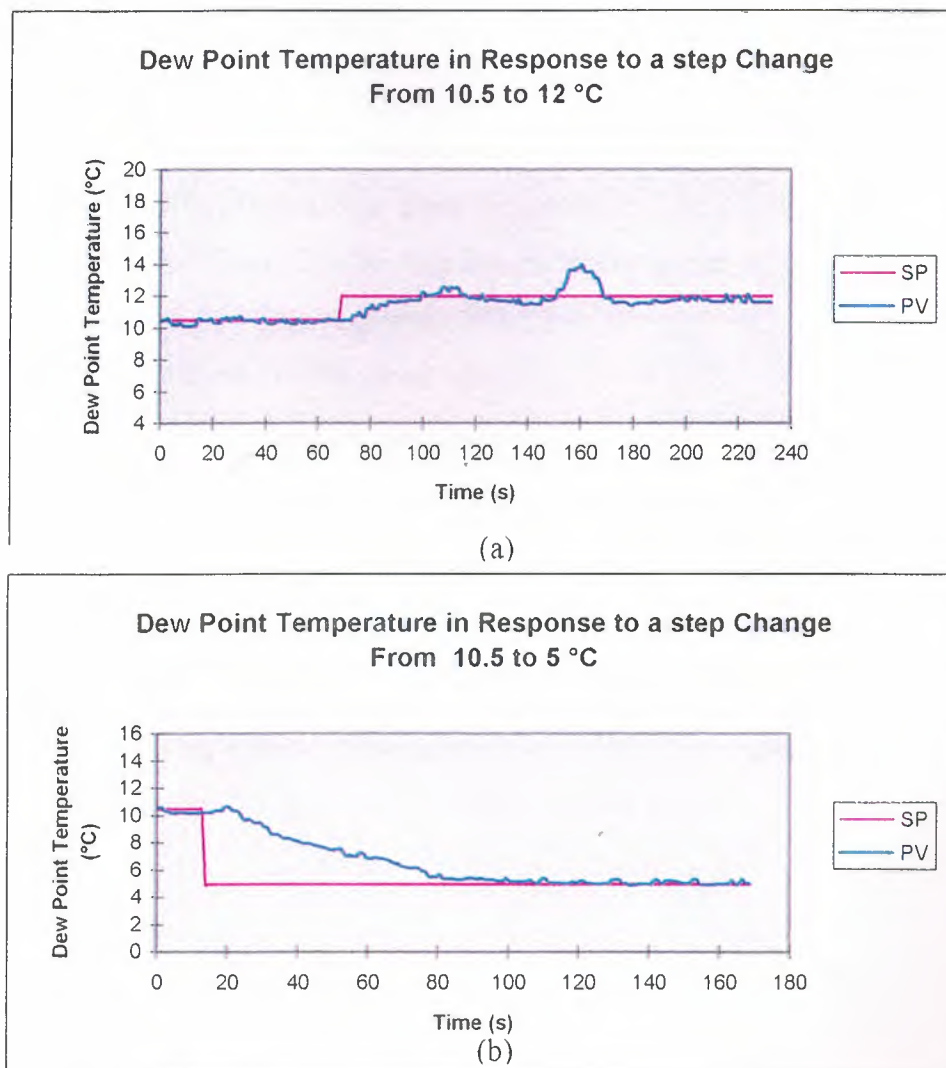


Figure 5.14 FLC2 Dew Point Temperature Response for Big Step Changes

This FLC can accept big changes in the set point of the dew point temperature without winding up. The settling time was longer when compared to small changes. It took about 130 seconds for the system to settle down. This is to be expected for large changes. Also, it was noticed that FLC2 is slower than FLC1 in coping with set point changes.

- **Comparison of the Response of the Two FLCs**

The dew point response is not smooth in the range of  $\pm 2\%$  of the desired set point. This is because of the time lag of the process mentioned in section 2.2. Another reason is that the FLC gives control action for very small errors. No filtering for these errors was applied. This behavior was more significant in FLC2, this is due to the use of timers in FLC1 and also because FLC1 controls both flow rates in order to achieve the required set point.

FLC1 controls both flows. It continuously tries to reach to a compromise between the two flows giving the desired dew point temperature at the output. However FLC2 controls the dry flow only. Due to this reason the response of FLC1 was faster. For the same reason the flow rate response of FLC1 was flatter than that of FLC2. Also, it was noticed that the effect of external disturbances on FLC2 was less than the same effect on FLC1. This is because the disturbance only affects one flow (dry) in the second design, whereas both flows are affected in the first design.

In using the second design for high dew point temperatures ( $>12^{\circ}\text{C}$ ), care should be taken. This is because of the abnormality of the system exhibits at high humidities. For example applying a set point of  $15^{\circ}\text{C}$  to the second design might cause oscillation.

For both of the designs some initialization time of 10-15 minutes should be allowed after downloading the strategy to the T640 for the first time.

## Chapter 6

# Discussion and Conclusion

The main project objectives set out in chapter 1 (page 3) were all met. This chapter summarizes the achievements. A discussion on the merits of the various strategies is presented. Conclusion and suggestions for future work end this final chapter.

### 6.1 Work Summary

- The instrumentation of the rig and the input/output channels were tested, and the behavior of different components was recorded.
- The database was developed.
- The ratio control strategy was implemented, tuned and tested over the range of operation.
- Several fuzzy logic control strategy were implemented, the scaling factors were tuned, and testing over a wide range of operation was performed.

### 6.2 Blending Process Control Strategies

In this work, two FLC controllers for a zero capacity air flow blending system (MOLLY) were presented. To evaluate the performance of these controllers, results for applying ratio control strategy were also provided.

The FLC controllers appear to offer the following advantages:

1. The response of the FLCs was faster than that of the ratio controller. They cope with set point changes in about half of the time required by the ratio controller. FLCs reject disturbances faster, even the effect of some small disturbances can become too small to be observed. However, even small disturbances need longer time to be rejected using a ratio controller.



2. FLC controllers appeared to cope with big changes in the set point. They can be used over wide range of operating points without the need to tune the scaling factors again. Whereas the ratio controller winds up for such big changes, and further tuning of the PID controllers might be required in order to cope with the new set point. This is due to the non-linearity of the system under investigation.
3. FLCs were observed to deal with the non-linearities of the process by using fuzzy sets with different widths, and the non-linearity of the valves by using switching scaling factors at the output of the FLC. This point can be illustrated by the fast response in coping with set point changes, and in rejecting disturbances.
4. FLCs can deal with the abnormalities in the response of the system which occur at high humidities. These occur due to condensation which takes place on the mirror in the dew point sensor pipe work. This is inherently a different problem to the non-linearity in the dew point relationship. FLC1 gave good results even for high dew point temperatures ( $15^{\circ}\text{C}$ ), while FLC2 dealt with it up to  $12^{\circ}\text{C}$ . The ratio controllers gave unacceptable response in this range of operation.
5. The system is very sensitive to changes in atmospheric conditions (for example the values  $-4.8^{\circ}\text{C}$  and  $-7.00^{\circ}\text{C}$  were recorded for the dew point temperature of a completely dry flow at two different occasions). The FLC reduced this sensitivity and performed better than ratio control in dealing with changes in the atmospheric conditions.

On the other hand, the ratio controller appears to offer the following advantages:

1. The ratio controller design was much simpler than that of the FLC. This is due to the computational limitations by LINtools. The LINtools software package was not originally designed for implementing non-conventional techniques. This is due to the limitation of the number of variables allowed in each block, no loops and no usage of matrices can be made. These points increased the complexity of the FLC design, the number of blocks used, and hence the computational complexity.
2. The ratio controller response was smoother in the range  $\pm 2\%$  of the set point than that of the FLC in the same range. This is because of the way the PID controllers were built in LINtools which tends to stop sending a new control action if the error is

small. However the FLC tries continuously to send control actions to the plant to reach to a zero error. Taking also into consideration the long time lag of the process (18.2 seconds) compared to the execution time of strategy (0.1 second). Which means that the computer takes the readings from the rig every 0.1 second and accordingly sends the required control action, but the dew point temperature sensor can not give the final value in 0.1 second.

### 6.3 Conclusions

1. The response of the fuzzy logic controller to set point changes and rejecting disturbances was faster than that of the ratio controller. Also, fuzzy logic control can deal with larger disturbances and changes than ratio control.
2. FLC is more robust than ratio control. It can cope with relatively bigger changes than ratio control. The range of the operating points of FLC is larger than that of ratio control.
3. Controlling the two flow rates using FLCs result in better performance and more robustness in dealing with the abnormalities and the non-linearities of the system.
4. Due to the computational limitation of the LINtools software, fuzzy logic should be implemented just when there is need for it, or at the high levels of operation where the control problem is bigger. That is, if the process is required to work under certain conditions and as long as these conditions undergo little or no change, it might be a good decision to use ratio controller. If the process is required to work under various operating conditions or if the speed of response is of great importance, then FLCs should be used. Such conditions can justify the added expense of designing a more complex controller in the FLC.
5. The performance of the fuzzy logic controller should be investigated at higher levels than conventional methods, that is not just in terms of transient response due to a step change. This was noticed from the acceptable response under relatively different atmospheric conditions and in rejecting disturbances.

## 6.4 Future Work and Possible Improvements

- Adding further timing actions for the control strategies to compensate for the big time lag introduced by the process
- Tuning the PID controller can be made by more accurate and adaptive methods such as genetic programming (GP) with an optimization framework.
- In order to improve the response of the fuzzy logic controller, a routine can be added to filter out very small errors. Making the FLC produce the desired opening of the valve instead of the change in that opening. Also, applying 25-rule base design to both flow rates might lead to better results. The rule bases used were conventional, using non-conventional rule base might result in a better response.
- Investigate optimal control designs that achieve multiple design objectives.
- Investigate possibility of using another toolset that is more flexible for implementing various control strategies efficiently.



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## Appendices

Figure A.1 Psychometric Chart

# Appendix A: Psychrometric Chart

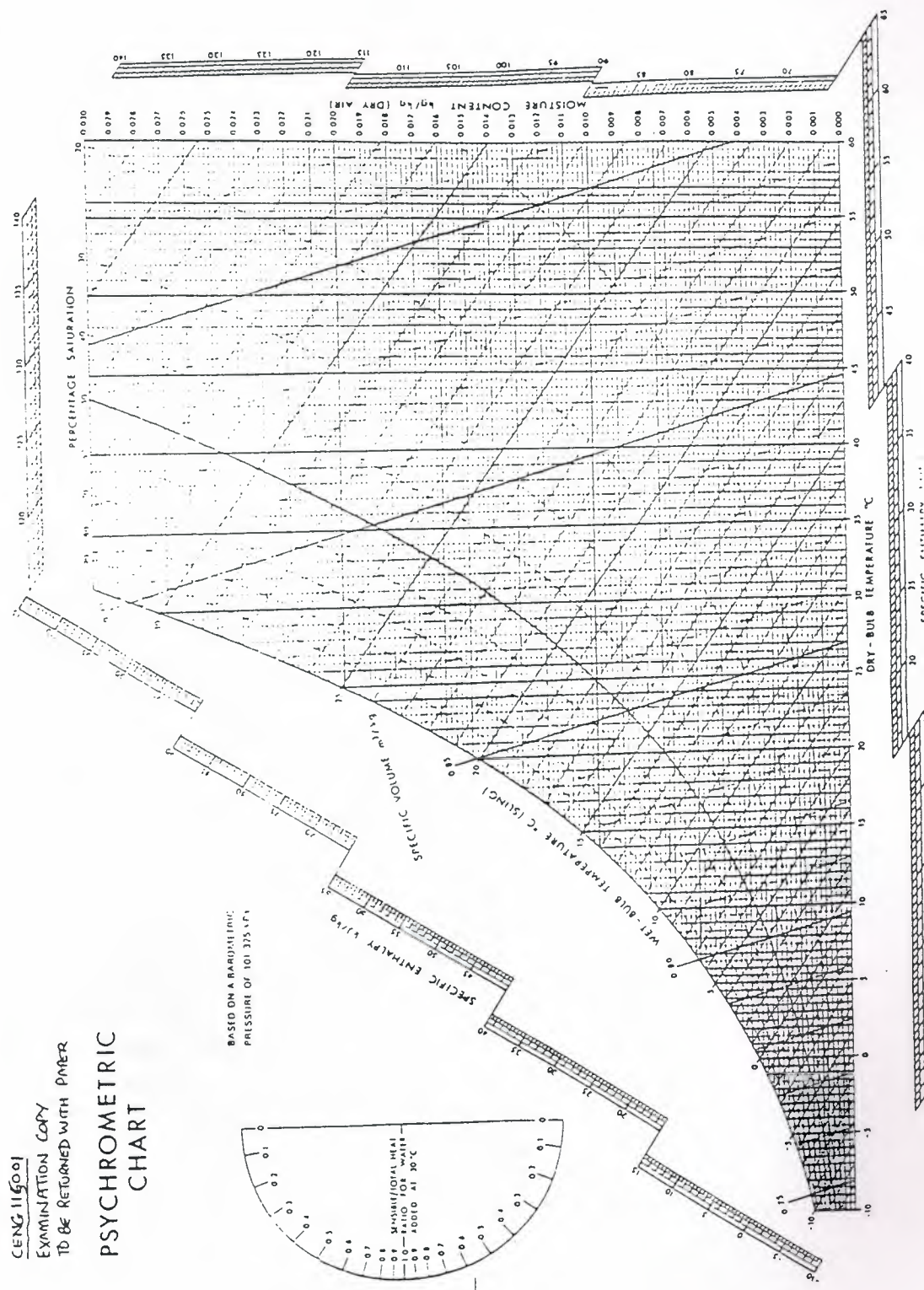


Figure A.1 Psychrometric Chart

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 TO BE RETURNED WITH PAPER  
 PSYCHROMETRIC  
 CHART



## Appendix B: LINtools Blocks' Parameters

The following are the blocks parameters used in the LINtools ratio control strategy presented in figure 4.4. The parameters of the fuzzy logic controllers can be found on the provided diskette.

Eurotherm Process Automation Ltd.

LIN Instrumentation DATABASE file (T Series products)

**Dbase:** <local> **Block:** FT31 **Type:** AN\_IP **Task:** 3

### FIELD VALUES

Field	Value	Units	Field	Value	Units
MODE	AUTO		Alarms		
PV	0.0	kg/h	SiteNo	1	
RateChng	0.000	Eng/Sec	Channel	1	
HR	1.00	kg/h	InType		Volts
LR	0.00	kg/h	HR_in	5.000	
HAA	1.000	kg/h	AI	0.000	
LAA	0.000	kg/h	CJ_temp		0.000
Filter	1.000	Secs	LeadRes	0.000	Ohms
HiCut	1.00	kg/h	Delay	0.000	Secs
HiDflt	1.000	kg/h			
LoCut	0.000	kg/h	Options	>0000	
LoDflt	0.000	kg/h	Status	>0001	
RomChar	None		Total	0	
UserChar			TotFract	0.000	
			PlsSFact	0.000	

**Dbase:** <local> **Block:** AT30 **Type:** AN\_IP **Task:** 2

### FIELD VALUES

Field	Value	Units	Field	Value	Units
MODE	AUTO		Alarms		
PV	0.0	dewpoint	SiteNo	1	
RateChng	0.000	Eng/Sec	Channel	3	
HR	20.00	dewpoint	InType		Volts
LR	-10.00	dewpoint	HR_in	5.000	
HAA	20.00	dewpoint	AI	0.000	
LAA	-10.00	dewpoint	CJ_temp		0.000
Filter	2.000	Secs	LeadRes	0.000	Ohms
HiCut	20.00	dewpoint	Delay	0.000	Secs

HiDflt	20.00	dewpoint	
LoCut	-10.00	dewpoint	Options >0000
LoDflt	-10.00	dewpoint	Status >0001
RomChar	None		Total 0
UserChar			TotFract 0.000
			PlsSFact 0.000

**Dbase: <local> Block: FT32 Type: AN\_IP Task: 1**

## FIELD VALUES

Field	Value	Units		Field	Value	Units
MODE	AUTO			Alarms		
PV	0.0	kg/h		SiteNo	1	
RateChng	0.000	Eng/Sec		Channel	1	
HR	1.00	kg/h		InType		Volts
LR	0.00	kg/h		HR_in	5.000	
HAA	1.000	kg/h		AI	0.000	
LAA	0.000	kg/h		CJ_temp		0.000
Filter	1.000	Secs		LeadRes	0.000	Ohms
HiCut	1.00	kg/h		Delay	0.000	Secs
HiDflt	1.000	kg/h				
LoCut	0.000	kg/h		Options	>0000	
LoDflt	0.000	kg/h		Status	>0001	
RomChar	None			Total	0	
UserChar				TotFract	0.000	
				PlsSFact	0.000	

**Dbase: <local> Block: AIC30 Type: PID Task: 2**

## FIELD VALUES

Field	Value	Units		Field	Value	Units
Mode	REMOTE			Alarms		
FallBack	REMOTE			HAA	20.00	
PV	0.0	dewpoint		LAA	-10.00	
SP	0.0	dewpoint		HDA	20.00	
OP	0.0	eng		LDA	-10.00	
SL	0.0					
TrimSP				TimeBase		Secs
RemoteSP	10.5	dewpoint		XP	170	%
Track	0.0	eng		TI	3.50	
				TD	0.700	

HR_SP	20.00	dewpoint		
LR_SP	-10.00	dewpoint	Options	00100001
HL_SP	20.0	dewpoint	SelMode	00001100
LL_SP	-10.00	dewpoint		
			ModeSel	00001001
HR_OP	3.000	eng	ModeAct	00001000
LR_OP	0.2	eng		
HL_OP	3.000	eng	FF_PID	1.600 eng
LL_OP	0.2	eng	FB_OP	0.000 eng

**Dbase:** <local> **Block:** FFY32 **Type:** PID **Task:** 3

## FIELD VALUES

Field	Value	Units	Field	Value	Units
Mode	REMOTE		Alarms		
FallBack	REMOTE		HAA	20.00	
PV	0.0	kg/h	LAA	-10.00	
SP	0.0	kg/h	HDA	20.00	
OP	0.0	%	LDA	-10.00	
SL	0.0				
TrimSP			TimeBase		Secs
→RemoteSP	0.00	kg/h	XP	125	%
Track	0.0	eng	TI	4.00	
			TD	0.50	

HR_SP	1.000	kg/h		
LR_SP	0.00	kg/h	Options	00100001
HL_SP	1.00	kg/h	SelMode	00001100
LL_SP	0.00	kg/h		
			ModeSel	00001001
HR_OP	100.0	%	ModeAct	00001000
LR_OP	0.00	%		
HL_OP	100.0	%	FF_PID	40.0 %
LL_OP	0.00	%	FB_OP	0.00 %

**Dbase:** <local> **Block:** FIC32 **Type:** PID **Task:** 1

## FIELD VALUES

Field	Value	Units	Field	Value	Units
Mode	REMOTE		Alarms		
FallBack	REMOTE		HAA	20.00	
PV	0.0	kg/h	LAA	-10.00	



SP	0.0	kg/h	HDA	20.00
OP	0.0	%	LDA	-10.00
SL	0.0			
TrimSP			TimeBase	Secs
→RemoteSP	0.00	kg/h	XP	160.0 %
Track	0.0	eng	TI	3.500
			TD	0.600
HR_SP	1.000	kg/h		
LR_SP	0.00	kg/h	Options	00100001
HL_SP	1.00	kg/h	SelMode	00001100
LL_SP	0.00	kg/h		
			ModeSel	00001001
HR_OP	100.0	%	ModeAct	00001000
LR_OP	0.00	%		
HL_OP	100.0	%	FF_PID	40.0 %
LL_OP	0.00	%	FB_OP	0.00 %

**Dbase: <local> Block: FX31 Type: AN\_OUT Task: 3**

#### FIELD VALUES

Field	Value	Units	Field	Value	Units
Mode	AUTO		Alarms		
Fallback	AUTO		SiteNo	1	
OP	0.0	%	OutType	mA	
HR_OP	100.0	%	HR_out	20.00	
LR_OP	0.0	%	LR_out		4.00
AO	0.0	%	Status	>0001	
Track	0.0	%	Options	>00	
SelTrack	FALSE		Channel	3	
Invert	FALSE				
NotAuto	FALSE				

**Dbase: <local> Block: FX32 Type: AN\_OUT Task: 1**

#### FIELD VALUES

Field	Value	Units	Field	Value	Units
Mode	AUTO		Alarms		
Fallback	AUTO		SiteNo	2	
OP	0.0	%	OutType	mA	
HR_OP	100.0	%	HR_out	20.00	
LR_OP	0.0	%	LR_out		4.00

AO	0.0	%	Status	>0001
Track	0.0	%	Options	>00
SelTrack		FALSE	Channel	3
Invert		FALSE		
NotAuto		FALSE		

**Dbase:** <local> **Block:** 2 **Type:** EXPR **Task:** 1

EXPR a\*b

A ENG A

B ENG B

C ENG C

D ENG D

HL\_OP 100.0

LL\_OP 0.00

## Appendix C: FLC3 and FLC4 LINTools strategies

### C.1 FLC3 LINTools Strategy

Figure C.1a is an overview of the strategy as implemented using LINTools, and depicts each of the CMPND function blocks. The functionality of each CMPND block is described in more detail in figures C.1b and C.1c.

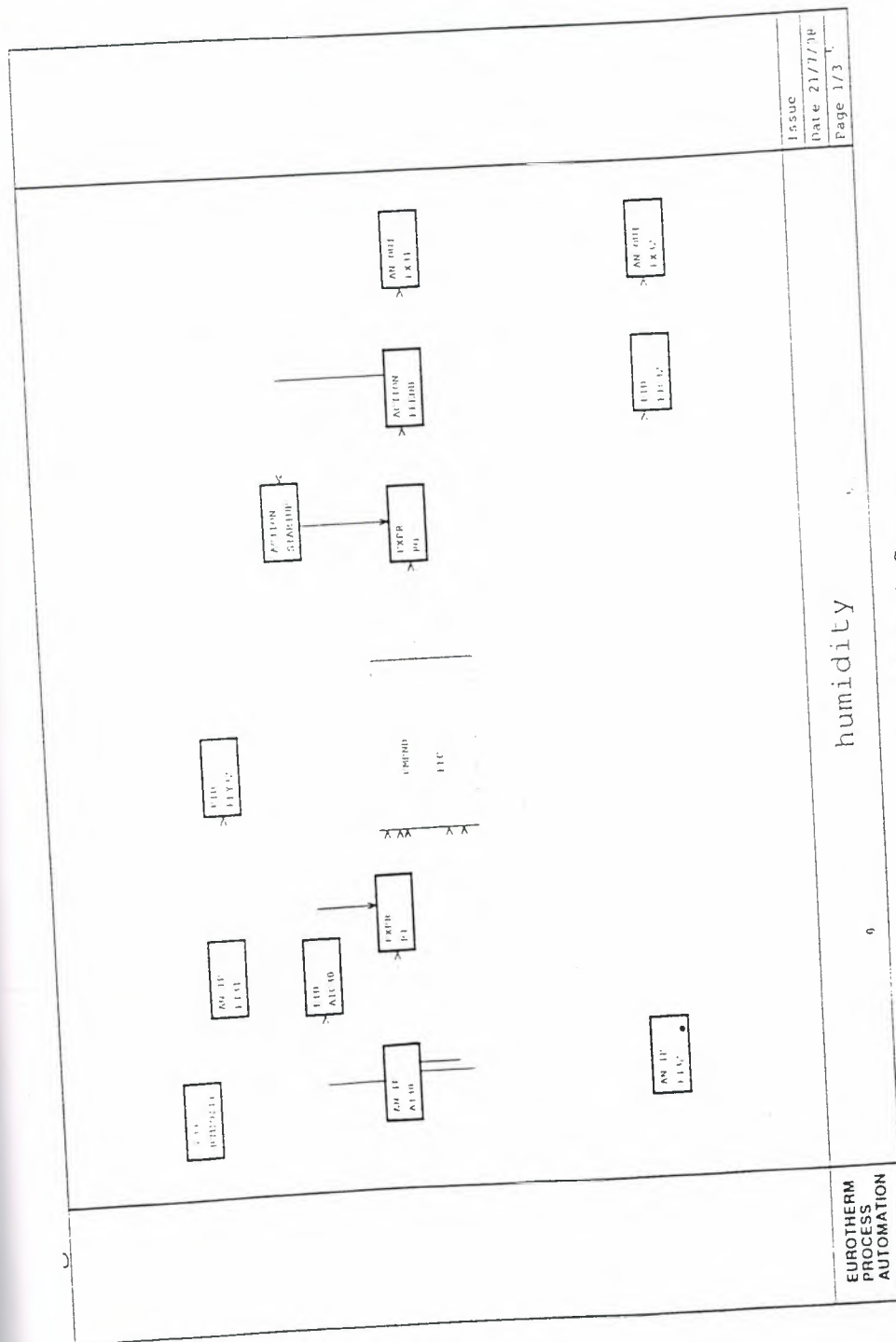


Figure C.1a FLC3 LINTools Strategy



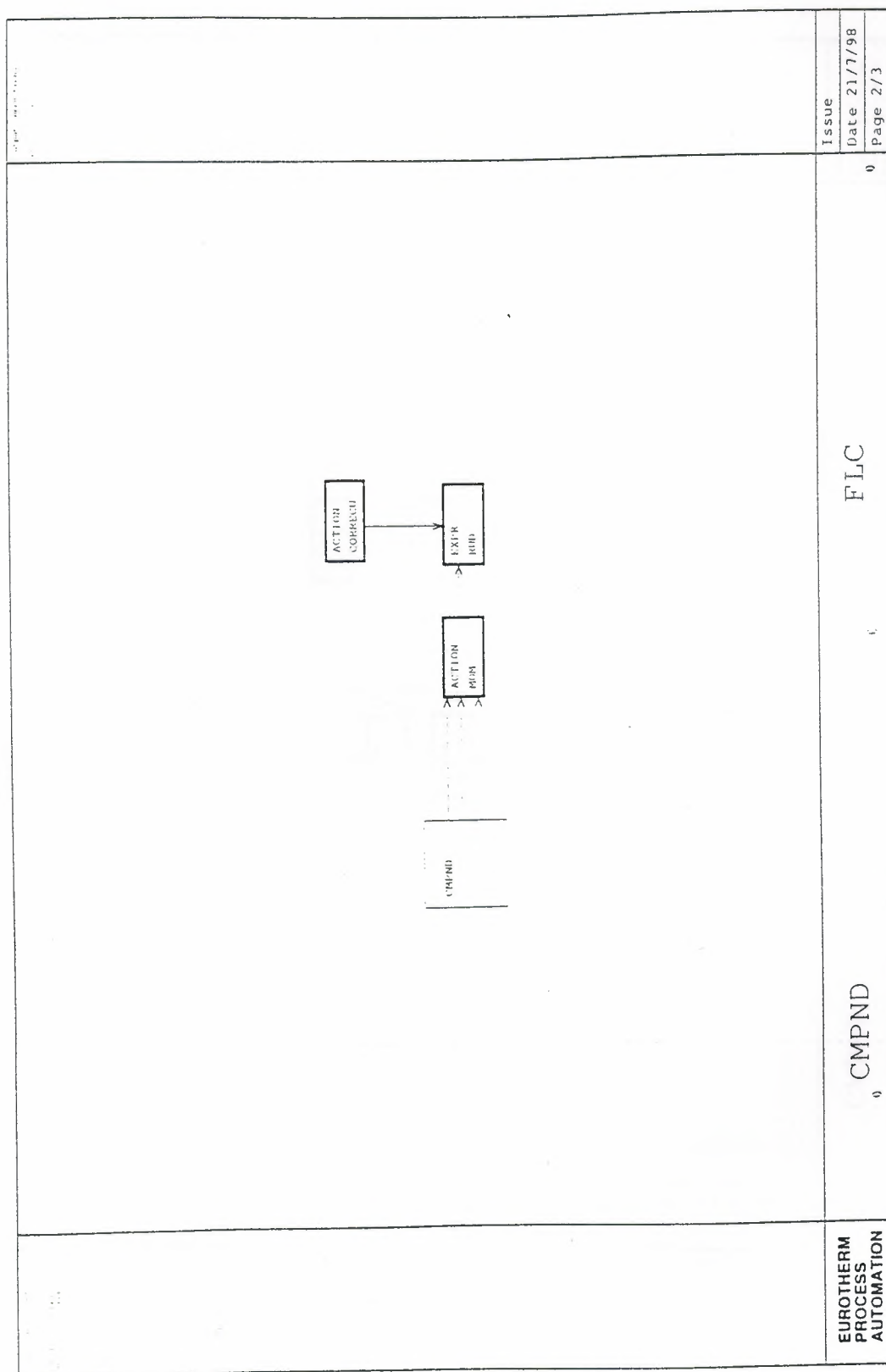


Figure C.1b FLC3 LINtools Strategy (CMPND FLC)

[illegible]

**Figure C.1c FLC3 LINTools Strategy (CMPND)**







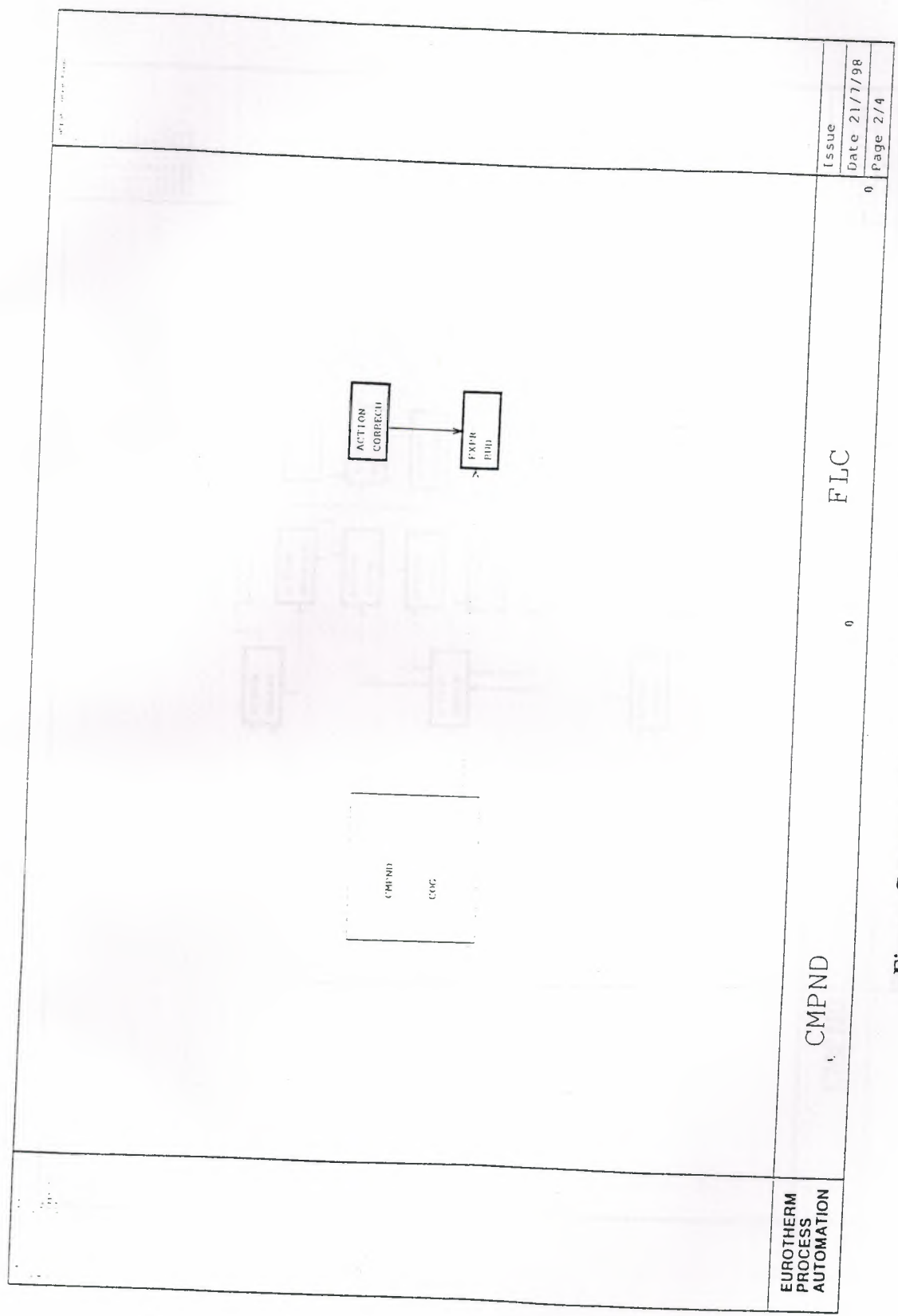
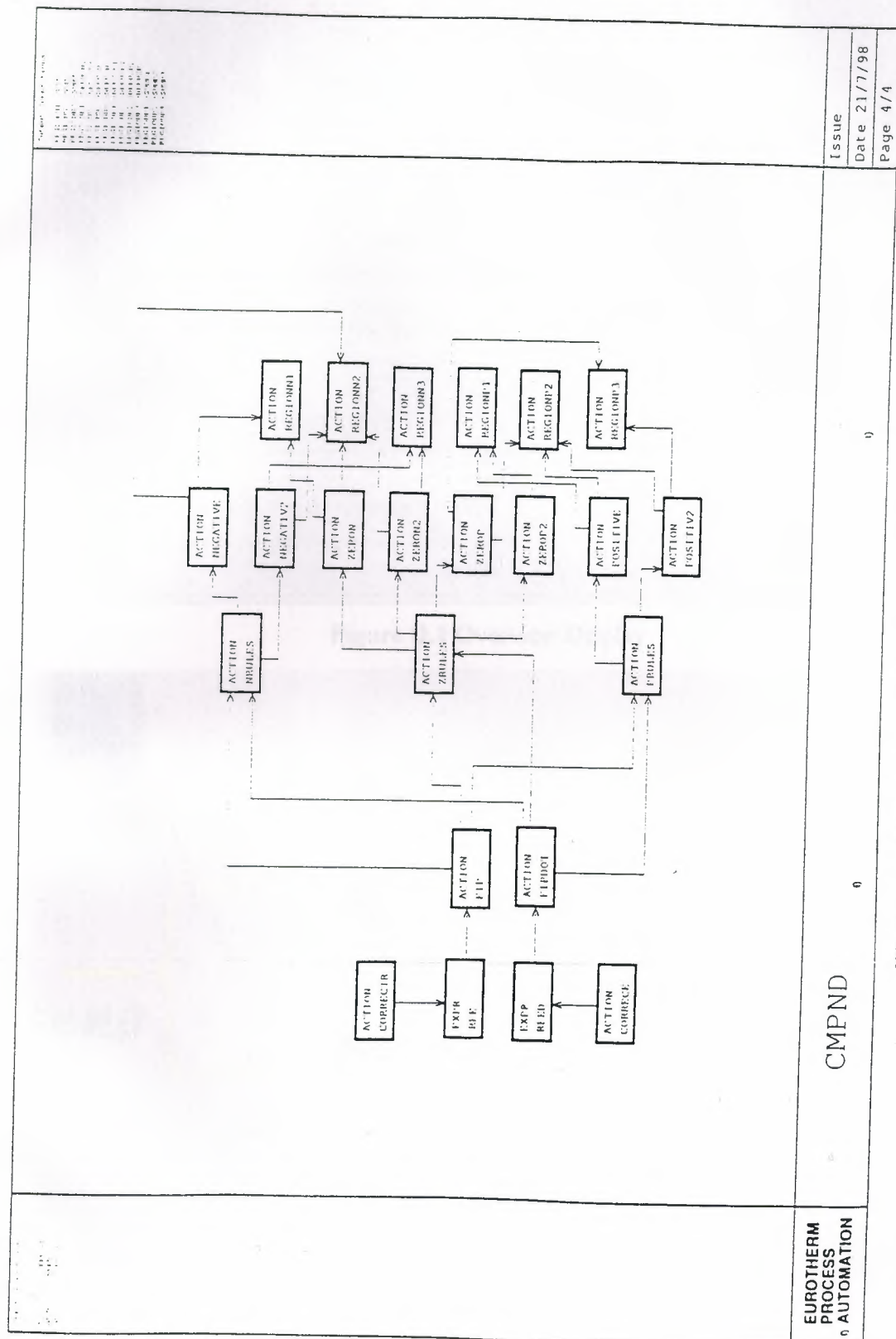


Figure C.2c FLC3 LINtools Strategy (CMPND COG)





## Appendix D: The SCADA Displays

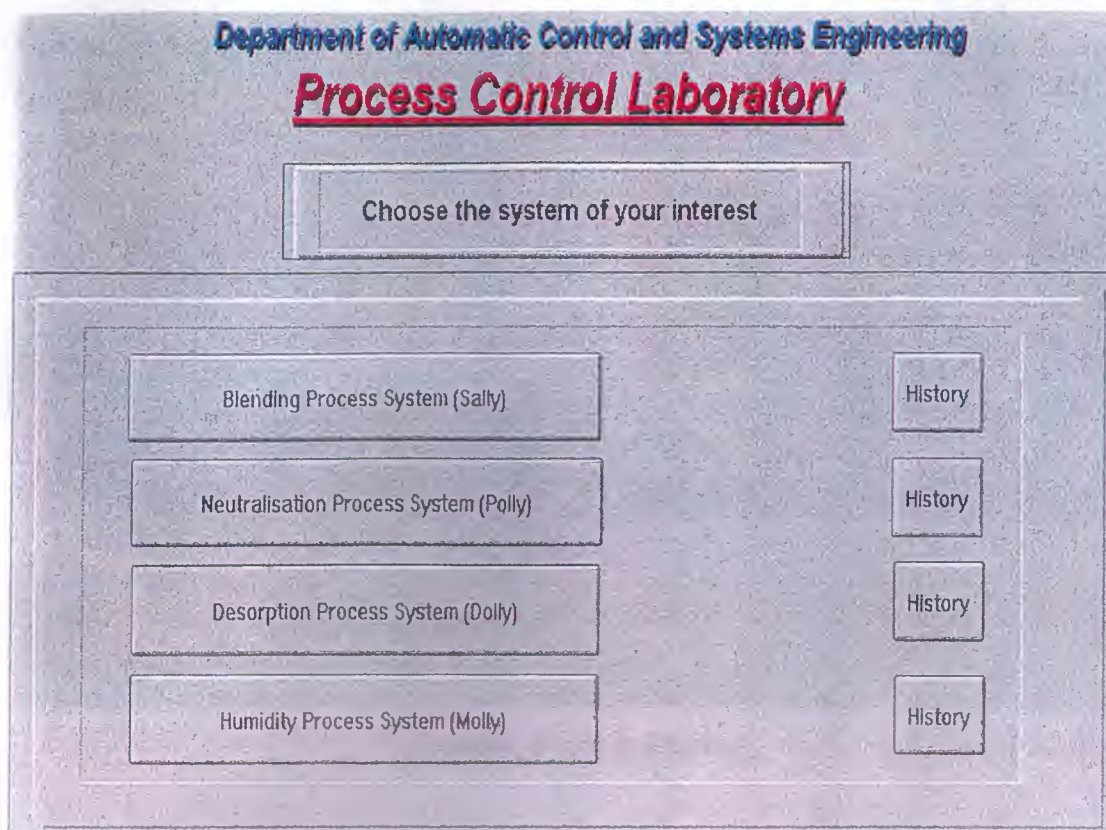


Figure D.1 Overview Display

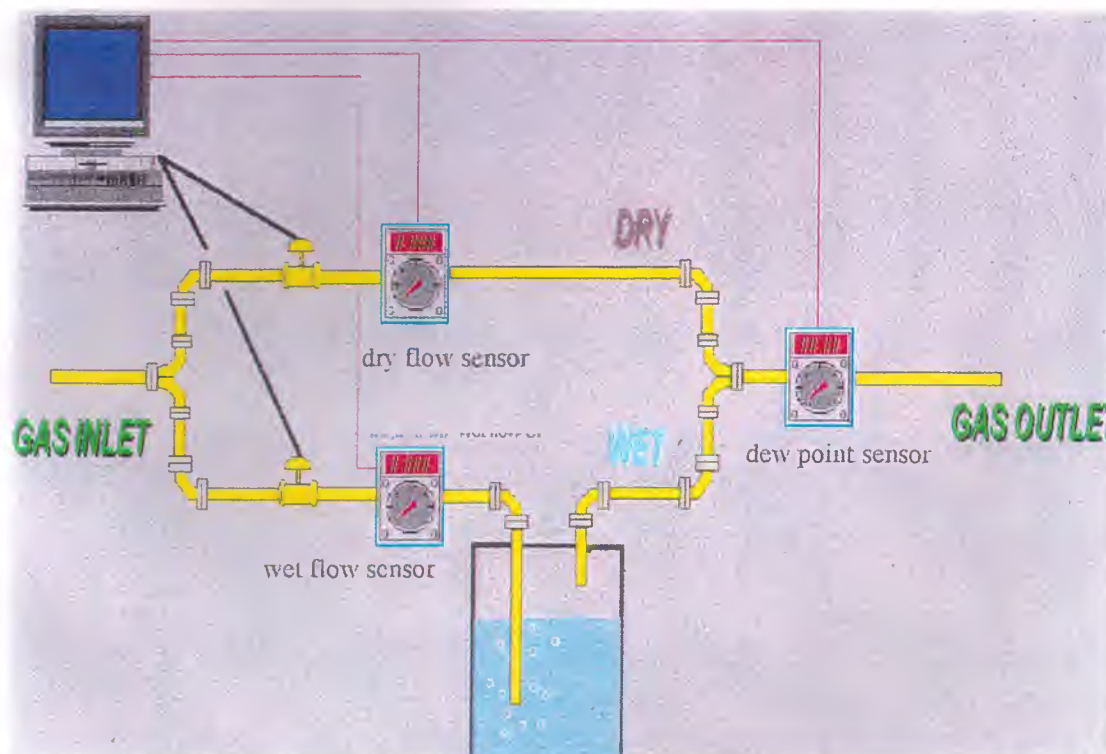


Figure D.2 Mimic Display



Figure D.3 Group Display