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INTELLIGENT OPERATION SUPPORT AND CONTROL SYSTEM FOR HVAC PROCESSES

BY ©

MS. HONG ZHOU

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Abstract

Heating, ventilating, and air conditioning (HVAC) processes provide a comfortable environment in a building. However they consume a great deal of energy. Many efforts have been put into building energy conservation since the energy crisis of 1973. On the other hand, the energy conservation efforts have led a to tight building envelopes and low ventilation rates, which can result in poor indoor air quality (IAQ), or so called "Sick Building Syndrome". Indoor air quality problem had been identified as one of the most serious public health challenges.

Indoor air quality control has not been integrated into current existing HVAC control strategies, therefore a conflict exists between energy saving and indoor air quality improvement. In addition, there exists some problems with indoor temperature setting, supply air control, operation sequencing and selection in conventional HVAC control systems.

The research focuses on investigating an intelligent control strategy to improve energy conservation and IAQ control of HVAC systems simutaneously. By using an intelligence engineering approach to integrate IAQ control, indoor setting, and operation planning into HVAC control systems, the conflict and other problems related to HVAC control systems can be solved.

This work describes the construction of an Intelligent Operation Support System (IOSS) for HVAC processes. The IOSS consists of an expert system for operation planning (ESOP) and an indoor comfort setting system (ICSS) for room temperature setpoint as well as a conflict reasoning system (CRS) for IAQ control and energy conservation. An integrated distributed intelligent system, i.e., meta-system, is introduced to integrate these systems. The ESOP gives a recommendation for selecting an energy saving operating mode for the HVAC processes. The system contains the important personal expertise and public knowledge, provides qualitative reasoning, quantitative computation as well as graphic simulation. By implementing comfort-stat strategy, the ICSS sets indoor temperatures with the advantages of energy saving, thermal comfort and better indoor air quality. The conflict reasoning system obtains a resolution for IAQ control and energy conservation. IOSS can be used to assist or train operators to achieve better operation in HVAC systems.

Finally, an integrated intelligent control framework for HVAC real time process control is presented. This new control strategy integrates indoor air quality control, comfort indoor setting and operation planning into an HVAC control system, which enhances HAVC systems operation, and improves indoor air quality control and energy conservation.

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NOMENCLATURE

Symbols

$CO_2(k)$	Indoor carbon dioxide concentration sampling data
CO_{2}_H	High limit of indoor carbon dioxide concentration
$e(k)$	Error of control system
f_{cl}	The ratio of the surface area of the clothed body to the surface area of the nude body
i	Air enthalpy
I_{cl} (R_{cl})	Total heat transfer resistance from skin to outer surface of the clothed body
i_{ik}	Minimum fresh air mixed enthalpy
i_{in}	Indoor setting enthalpy
i_{is}	Supply air enthalpy
K	Parameter of minimum allowed outside air mixed with return air
Kd	Derivative gain of PID controller
Ki	Integral gain of PID controller
Kp	Proportional gain of PID controller
M	Inflow of mass/energy
$\frac{M}{A_{Du}}$	Human metabolic rate
N	Indoor setting air parameter
N(k)	System noise data
P_a	Partial pressure of water vapor in ambient air
P_s	Saturated water vapor pressure with respect to the dry bulb teperature of the air
P_{ws}	Saturated water vapor pressure with respect to the wet bulb teperature of the air
S	Supply air parameter
t	Air dry bulb temperature

t_a	Comfort temperature
t_{cl}	Clothes Temperature
TN	Indoor setting temperature
to(k)	Outside air temperature sampling data
tr(k)	Return air temperature sampling data
Ts	Supply air temperature setting
ts(k)	Supply air temperature sampling data
tss	Predicted steady state value of supply air temperature
t_w	Washer water temperature
u(k)	Input of control action
U(k)	Control manipulated variable signal
V(k)	Operational variable signal
V	Relative velocity in still air
Vs(k)	Supply air volume sampling data
w	Air absolute humidity
WN	Indoor setting humidity or moisture
wo(k)	Outside air moisture sampling data
wr(k)	Return air moisture sampling data
ws(k)	Supply air moisture sampling data
wss	Predicted steady state value of supply air moisture
Ws	Supply air humidity or moisture setting
Wt	Wet bulb temperature of the air
y(k)	Output of control system
Z	Outflow of mass/energy
Zsp	Steady state of mass/energy outflow
ε	Tuning key
ϕ	Relative humidity
η	Mechanical efficiency
$\xi(k)$	Model noise or disturbance

Abbreviation

AC = Automatic Control

AHU = Air Handling Unit

AI = Artificial Intelligence

CAV = Constant Air Volume

CMV = Control Manipulated Variable

CR = Conflict Reasoning
CRS = Conflict Reasoning System
EMCS = Energy Management and Conservation System
ESOP = Expert System for Operation Planning
HVAC = Heating, Ventilation, and Air Conditioning
IAQ = Indoor Air Quality
ICS = Indoor Comfort Setting
ICSS = Indoor Comfort Setting System
IICF = Integrated Intelligent Control Framework
IOSS = Intelligent Operation Support System
OR = Operation Research
OV = Operational Variable
PID = Proportional, Integral and Derivative
RH = Relative Humidity
THMCC = Temperature-Humidity conditioning, Multi-zone, Constant air volume, and Cooling coil for dehumidifying
THMCD = Temperature-Humidity conditioning, Multi-zone, Constant air volume, and Dehumidifier for dehumidifying
THMCW = Temperature-Humidity conditioning, Multi-zone, Constant air volume, and Washer for dehumidifying
THMVC = Temperature-Humidity conditioning, Multi-zone, Variable air volume, and Cooling coil for dehumidifying
THMVD = Temperature-Humidity conditioning, Multi-zone, Variable air volume, and Dehumidifier for dehumidifying
THMVW = Temperature-Humidity conditioning, Multi-zone, Constant air
THSCC = Temperature-Humidity conditioning, Single zone, Constant air volume, and Cooling coil for dehumidifying
THSCD = Temperature-Humidity conditioning, Single zone, Constant air volume, and Dehumidifier for dehumidifying
THSCW = Temperature-Humidity conditioning, Single zone, Constant air volume, and Washer for dehumidifying
THSVC = Temperature-Humidity conditioning, Single zone, Variable air volume, and Cooling coil for dehumidifying
THSVD = Temperature-Humidity conditioning, Single zone, Variable air volume, and Dehumidifier for dehumidifying
THSVW = Temperature-Humidity conditioning, Single zone, Variable

air volume, and Washer for dehumidifying

TMC = Temperature conditioning, Multi-zone and Constant air volume

TMV = Temperature conditioning, Multi-zone and Variable air volume

TSC = Temperature conditioning, Single zone and Constant air volume

TSV = Temperature conditioning, Single zone and Variable air volume

VAV = Variable Air Volume

CHAPTER 1

INTRODUCTION

Heating, ventilating and air conditioning (HVAC) processes provide a comfortable environment inside buildings, but consumes a great deal of energy. Roughly speaking, buildings account for one-third of the total energy consumed in the world, most of which is used in HVAC processes.

Since the oil embargo of 1973, extensive research and development on energy conservation in buildings has been pursued. Computer technology has played an important role in energy management and control systems (EMCS) during the past 10 to 15 years.

In summary, HVAC energy saving control strategies may be classified as follows:

(1) Time scheduling This is the most effective energy-saving control strategy in the early use of EMCS in HVAC processes. It turns equipment ON or OFF at a preset time. Normally, this strategy turns equipment off when it is not needed or it gives a better match of the loads. For example, scheduling HVAC equipment to run during occupied hours,

'day/night setback' sets low temperature setpoint when heating is used to maintain temperature, and sets high temperature setpoint when cooling is used to maintain temperature at night (Rinehart, 1981). Seven different equations are compared by Seem et al. (1989) to determine the correct time to return from night or weekend setback. It was observed that the return time was linearly related to the outdoor temperature. Linear or quadratic equations with a weighting function provided the best forecast of return time. Time scheduling also allows HVAC equipment to be off-duty to avoid electrical peak time.

(2) Advanced HVAC process control Optimization, adaptive control and predictive control have been applied to HVAC processes (Athienitis, 1988; MacArthur et al., 1989; Maxwell et al., 1989; Nelser, 1986; Mehta, 1983). Since chiller plants consume a very large amount of energy in HVAC systems, chiller plant optimization has been the focus of many research studies. A few important optimal control strategies have been proposed for the chiller (Hachner et al., 1984; Cascia, 1988; Johnson, 1985). Braun et al. (1989) investigated the methodologies for optimal control of chilled water systems without storage, and proposed a component-based nonlinear optimization algorithm and simple system-based near-optimal control. Adaptive control techniques are attractive in HVAC applications because process characteristics change widely due to the variations in weather and building occupancy (Wepfer and Li, 1986; Underwood, 1989). It has been demonstrated by Dexter and Haves (1989) that adaptive control can cope with many problems encountered in HVAC applications, and requires far less commissioning efforts than conventional controllers. The control performance is

superior to that of a manually tuned PID controller. The long term behavior and energy savings achieved by using adaptive control in HVAC processes are still under investigation (Dexter and Haves, 1989). By predicting outdoor and indoor temperatures, as well as building thermal resistance and capacity, it is possible to prevent the loss of energy in preheat or precool cycles, and determine the best recovery time from night setback (Seem et al., 1989) as well as the optimal start/stop sequence. In addition, if an indoor temperature swing is allowed, a large saving can be achieved by the predictive control strategy (Shapiro et al., 1988).

(3) Economic operations There are several alternative air handling processes which can achieve indoor setpoint. The following control methods (Haines, 1984) are developed for energy conservation operations:

(a) *Economy-cycle outside-air control:* This strategy uses outside air for cooling whenever possible, thus minimizing energy use in the refrigeration cycle.

(b) *Enthalpy control:* This strategy is achieved by calculating the enthalpy of the processed air and choosing the minimum enthalpy cost for the desired air handling operation. The enthalpy requirements of the air processing operations can be established by making use of a psychrometric chart in order to select the minimum-enthalpy cost operation.

(c) *Conversion of dual-duct to variable-air-volume (VAV):* Replacing a dual-duct system by a VAV system is a very effective energy conservation technique. Mixing loss and fan horse power savings can be made by adding fan volume control (Johnson, 1984; Teji, 1987).

(d) *Energy-source shutdown:* Depending on the season, shutting down heating or cooling sources also provides energy conservation. However, the shutdown should not cause the loss of environmental control.

(4) Comfort technology Comfort research has provided a number of alternatives for energy conservation (Nelson et al., 1987; Doherty and Arens, 1988). "Comfort" and "energy" could be simultaneously optimized by operation strategies which consider the dynamics of comfort and control system. "Dynamic control" is a recently developed energy conservation control strategy that utilizes comfort technology, having been originally conceived back in the mid-70s. Hartman (1988), Colburn and Harman (1987) investigated this advanced control strategy and pointed out that seven key variables affected on human comfort significantly. These variables are dry bulb temperature, relative humidity, mean radiant temperature, air velocity, clothing, activity (metabolic rate) and exposure time. Compared to other control strategies, dynamic control allows user interaction and uses all seven comfort variables. It combines three concepts: system-free cooling, interior temperature drifting and thermal fly wheeling. This dynamic control strategy introduces two new control concepts into HVAC control. First of all, it integrates all controlled HVAC components into a

coordinated, but continually changing control strategy. Secondly, it continuously anticipates upcoming weather and occupancy conditions in order to develop the control law. A case study by Spratt et al.(1989) illustrated that dynamic control offered less space-temperature control than normal control, and improved the comfort conditions. Thermal comfort dynamic control methodology has been implemented into a commercial product called "Touchstat™". The test results conducted on two residences showed a 55% electricity saving, equivalent to $2.58/m²/yr (Colburn and Harmon, 1987).

Comfort technology has not yet been fully utilized in energy conservation. Many users and designers are still unaware of the opportunities available for energy conservation. Comfort technology education has been suggested for transferring this knowledge to the public (Hayter, 1987).

(5) <u>New energy efficient equipment</u> Heat-pump air conditioners, solar energy heaters, and inverter control systems are the most recently developed energy-efficient HVAC equipment (Nahar and Gupta, 1989). Most of the equipment uses microprocessor-based control and significantly reduce energy consumption (Cooper, 1983). They have often been used in practical applications. Use of heat pumps are used in residential air-conditioning systems with advanced control, i.e. inverter control system, defrost control, setback thermostats, variable-speed fan control, etc., result in a 20-40% energy saving (Colliver et al., 1987; Shimma et al., 1985; Imaiida et al., 1985).

From the system science viewpoint, the current energy management and control strategies used in HVAC processes are a simple collection of remedies or recipes, with neither coordination nor integration. The reduction in energy consumption was easy to achieve in the early stages with only a small capital investment. But these simple remedies have now been exhausted. It is very difficult to model the HVAC processes. Most problem solutions are based on heuristics or experiences. (Jedlicka, 1985; Hartman, 1989).

On the other hand, energy conservation efforts of the last decade have led to reduced infiltration and ventilation in the occupied spaces. concentrations of internally generated contaminants have increased (McNall, 1986). Air sampling in many buildings has indicated that indoor concentrations of known pollutants often exceed the standards set for outdoor and industrial exposures. Complaints by occupants have also drawn attention to indoor pollutant levels, and raise questions as to the adequacy of indoor air quality (IAQ) to protect the health of the building occupants.

Indoor air pollution can impact the health and affect the productivity. Poor indoor air quality causes health problems, such as sensory irritation in eyes, nose, or throat, skin irritation, neurotoxic symptoms, and nonspecific hyper-reactivity reactions, so called "sick building syndrome" (Mølhave, 1987). In recent years, indoor air quality has been identified as a potentially serious health problem, especially in energy responsive buildings (Franta, 1985). The sick building problems have been characterized as "one of the most serious public health challenges in next decade" (Bahnfleth, 1986).

Most production activities and research work are aimed at improving human health and raising living standards. As people spend up to 90 percent of their life time inside residential or commercial buildings, indoor air quality control becomes a very crucial issue in the environmental protection.

The investigations responding to sick building syndrome complaints have been conducted, and a number of problems involving both microbial contamination and inadequate operation of the building's HVAC system have been identified (Morey et al., 1986). The major pollutants of the sick building syndrome include formaldehyde, radon, tobacco smoke, asbestos fibers, carbon monoxide and nitrogen dioxide (Franta, 1985). The sources of the problem are 3-4% from building fabric (such as carpeting), 5% from microbiological contaminants, 11% from contaminants generated from outside the building , 17-19% from inside the building, and 50-52% from inadequate ventilation (Wallingford and Carpenter, 1986; Wallingford, 1988).

The indoor air quality problem is drawing more and more research interest. Progress has been made in the research areas such as IAQ measurement and diagnosis (Thorsen and Molhave, 1987; Sterling et al., 1987; and Levin, 1987) and in modeling and prediction (Yuill and Lovatt, 1986; Druzik et al., 1990; Feustel and Sherman, 1991; Hawthorne and Matthews, 1987; Small and Marshall 1990; Woods, 1986). The successful application of an intelligent environment controller which is an adaptive controller with watchdog software to maintain indoor air quality has been reported (Mesher et al., 1990).

Ventilation system performance deserves a special attention because it is both a mechanism for removing indoor air pollutants, and a potential energy load on the heating and/or cooling system of a building (Sherman and Wilson, 1986). Intelligent ventilation for IAQ control is proposed by Rodahl in 1986. A new philosophy for ventilation is introduced that considers the presence of all pollution sources. It is quantified in a new comfort equation for indoor air quality (Fanger, 1989, 1990). Woods (1986) developed both empirical and rational models to predict the effectiveness of ventilation for acceptable indoor air quality.

As HVAC systems play an important role in indoor environment control (Newman, 1991), the American Society of Heating, Refrigerating, and Air-Conditioning Engineering (ASHRAE) is concerned with indoor air quality control standards (MacNall, 1988). For example, the revision of ASHRAE Standard 62-1981 (Ventilation for Accepted Indoor Air Quality), ASHRAE Standard 62-1989 raised the ventilation rate from 5 cfm (2.5 L/s) to 15 cfm (7.5 L/s), and decreased the allowable CO2 concentration from 2500 ppm to 1000 ppm.

Further research on improving indoor air quality by incorporating energy conservation techniques has been proposed (O'Sullivan, 1989). Energy conservation is important to the national economic and strategic interests, and indoor air quality directly affects our health. A perfect solution should address simultaneously reducing energy consumption and improving indoor air quality. The adequate operation of building HVAC system is one of the key steps to reach the goal of reduced energy consumption coupled with improved indoor air quality (Harrie and Gadsby, 1986). Obviously, there is a conflict between indoor air quality control and energy conservation. So far suitable techniques to resolve this conflict have not been reported. A literature search did not reveal any suitable methods to improve IAQ by coupling energy conservation. Currently, indoor air quality control has not been integrated into HVAC operation and control system, therefore IAQ and EMCS become two conflicting goals. It is realized that we need to investigate new control strategies to improve IAQ and avoid extensive energy consumption. Integration and conflict reasoning are the challenges faced in developing new HVAC control systems.

Artificial intelligence (AI) provides an approach to dealing with ill-structured problems by using heuristics and experience, so it is not surprising that AI techniques have recently been applied to HVAC processes (Haberl and Claridge, 1987; Camejo and Hittle, 1989; Bagby and Cormier, 1989; Bergt, 1989; Brothers, 1988; Hartman, 1989; Haberl et al., 1987; Liu and Kelly, 1988; Tuluca et al. 1989). Many ill-structured engineering problems with non-numeric information and non-algorithmic procedures are suitable for applications of artificial intelligence techniques (Rao et al., 1989). The AI approach provides a programming methodology for solving ill-structured problems and allows the use of heuristics. Intelligence engineering is the subject that applies AI techniques to solve engineering problems and investigates AI theory based on engineering methodology. Integration and conflict reasoning are two important research subjects of intelligence engineering. As most of the IAQ and EMCS problems in the HVAC processes are non-algorithmic and ill-structured, intelligence engineering approach provides a suitable methodology.

This thesis focuses on the research of new methods for HVAC control, which aims at simultaneously reducing energy consumption and improving indoor air quality in buildings. Intelligence engineering approach is our problem solving strategy.

CHAPTER 2

HVAC SYSTEMS AND OPERATIONS

This chapter provides a brief introduction to heating, ventilating, air conditioning (HVAC) systems to assist readers in understanding the HVAC processes before discussing the research project. Therefore, a description concerning HVAC system structures and air handling processes as well as control schemes will be presented first. In addition, problems with the HVAC conventional control strategies are discussed.

2.1 System Structure and Classification

There many different types of HVAC systems and various air handling units exist to meet the requirements for all kinds of buildings and weather. There is a large difference in the control and management between central and distributed HVAC systems. Since central HVAC systems are now used in the most of buildings, in this research project, only central HVAC systems are concerned. The system structure classification for central HVAC systems is demonstrated in Figure 1, which contains decomposition, coupling and taxonomy information. Most residential or office buildings only require temperature conditioning, whereas in some industrial environment both temperature and humidity must be conditioned. A single zone system sets all conditioned rooms at the same temperature and humidity, but a multizone system sets different indoor parameters for the conditioned rooms. An air washer and cooler both are used to cool and dehumidify air, which are chosen by the HVAC system designer depending on the weather and other factors. For a large commercial building, a terminal controller or distributed control system may be required.

The sixteen different types of central HVAC systems shown in Figure 1, which may be classified as follows:

Temperature conditioning, single zone and constant air volume system (TSC).

A TSC system is shown in Figure 2. Outside air is mixed with return air, then filtered, and heated or cooled to meet supply air requirement. A constant air volume fan supplies the processed air to rooms.

Temperature conditioning, single zone and variable air volume system (TSV).

In a TSV system, the volume of air delivered by the supply fan can be changed in order to match the building's heating or cooling load. Therefore a variable air volume (VAV) system usually has better energy conservation performance than a constant air volume (CAV) system does.

Temperature conditioning, multizone and constant air volume system (TMC).

In a multizone CAV system, there is a variable-volume damper, for each zone in order to adjust the supply air volume, operated by a static pressure controller.

Temperature conditioning, multizone and variable air volume system (TMV).

In a multizone VAV system, the amount of air entering each zone is determined by a terminal thermostat, which can also add heat to the supply air if needed.

Temperature-humidity conditioning, single zone, constant air volume, and dehumidifier for air dehumidifying process (THSCD).

A THSCD system is shown in Figure 3. Fresh air is mixed with return air, which passes through a humidifier or dehumidifier, heating or cooling coil. Then the processed air is supplied to rooms by a fan. The differential pressure is usually kept positive by adjusting an exhaust air damper.

Temperature-humidity conditioning, single zone, constant air volume and cooling coil for air dehumidifying process (THSCC).

In this type of the system, the cooling coil is used not only to cool down air temperature, but also to dehumidify air moisture. Further details about this system will be given later.

Temperature-humidity conditioning, single zone, constant air volume, and air washer for air dehumidifying process (THSCW).

Fresh air is mixed with return air, then partially goes through an air washer, and mixes with bypass air. This process is used for both cooling and dehumidifying.

<u>Temperature-humidity conditioning, single zone, variable air volume, and dehumidifier for air dehumidifying process (THSVD).</u>

<u>Temperature-humidity conditioning, single zone, variable air volume, and cooling coil for air dehumidifying process (THSVC).</u>

<u>Temperature-humidity conditioning, single zone, variable air volume, and air washer for air dehumidifying process (THSVW).</u>

<u>Temperature-humidity conditioning, multizone, constant air volume, and dehumidifier for air dehumidifying process (THMCD).</u>

<u>Temperature-humidity conditioning, multizone, constant air volume, and cooling coil for air dehumidifying process (THMCC).</u>

<u>Temperature-humidity conditioning, multi-zone, constant air volume, and air washer for air dehumidifying process (THMCW).</u>

<u>Temperature-humidity conditioning, multizone, variable air volume, and dehumidifier for air dehumidifying process (THMVD).</u>

<u>Temperature-humidity conditioning, multizone, variable air volume, and cooling coil for air dehumidifying process (THMVC).</u>

<u>Temperature-humidity conditioning, multi-zone, variable air volume,</u>

and air washer for air dehumidifying process (THMVW).

2.2 Air Handling Processes

The air handling processes, such as air washing, heating, humidifying, cooling, dehumidifying and mixing are shown in Figure 4, where RH stands for relative humidity.

Mixing: Assuming **a** is fresh air, **N** is return air, then **K** stands for the mixed air status, $\overline{\mathbf{akN}}$ shows a mixing process.

Washing: Assuming **b** is air washer water status, a portion of air goes through an air washer and mixes with the bypass air. $\overline{\mathbf{aLb}}$ shows an air washing process. **L** stands for the processed air status. The process can be used to cool and dehumidify air.

Heating: The heating process increases air temperature or enthalpy, but does not affect absolute humidity. $\overline{\mathbf{ac}}$ demonstrates an air heating process.

Humidifying: Ideally, a humidifying process should change only air dampness, and not affect air enthalpy. In fact, if the temperature of water or steam sprayed is higher or lower than that of the air processed, a humidifying process causes enthalpy to increase or decrease.

Cooling: The process of cooling decreases air temperature or enthalpy. As air temperature decreases to below the saturated water vapor temperature, water condensation occurs. The process is shown as $\overline{\mathbf{ae}}$ in Figure 4, and is used to decrease temperature and/or humidity.

Dehumidifying: As demonstrated by $\overline{\mathbf{af}}$ in Figure 4, when air passes through a dehumidifier, water in the air is absorbed by the dehumidifier.

2.3 Control

Currently, there are several control schemes for HVAC systems, such as 100% outdoor air, 10% outdoor air, economy cycle, and enthalpy control, etc (Haines, 1987).

100% outdoor air: This type of operation is for some special area such as chemistry laboratories and special manufacturing. 100% outdoor air passes through a filter, then enters an air handling unit (AHU), in which a heating/cooling coil is controlled by a room thermostat. This control scheme is simple, and the indoor air quality is high, but it consumes a great deal of energy.

10% outdoor air: By far the simplest method of outdoor air control is to open a "minimum outside air" damper whenever the supply fan is running. 10% outdoor air is mixed with 90% return air, then enters an AHU to be processed and supplied to rooms. Compared to 100% outdoor air, it provides energy saving, but sacrifices indoor air quality. This is early developed control strategy and is still used extensively.

Economy cycle: It is found that with minimum 10% outdoor air control, Cooling coil is operated even when the outdoor air temperature is near or below the freezing mark. This method is called "economy cycle", in which outside, return and relief dampers are controlled by temperature. Economy cycle is the most commonly used control scheme nowadays.

SINGLE-ZONE ECONOMY CYCLE CONTROL SYSTEM: Figure 5 shows a single-zone AHU; economy cycle outside air control system. Outside air and relief dampers are in minimum open position at winter design temperature, and the return air damper is correspondingly in maximum open position. As outside air temperature increases, the mixed air thermostat (T1) gradually opens the outside air damper to maintain a low-limit mixed air temperature. Return and relief dampers modulate correspondingly. As the outside air temperature continues to increase, an outdoor air high-limit thermostat (T2) is used to cut the system back to minimum outside air, thus decrease the cooling load. The room thermostat can be used to reset the low-limit mixed air controller. This will provide greater energy conservation than the system with a fixed low-limit set point. The room thermostat resets the supply air control point. The supply air thermostat controls the hot and chilled water valves in sequence. This system is most commonly used today.

MULTI-ZONE ECONOMY CYCLE CONTROL SYSTEM: Figure 6 demonstrates a typical variable air volume system with discriminator control. It provides multizone control with only a single duct. The supply air is maintained at a constant temperature which varies with seasons. The individual zone thermostat varies with the air supply quantity to the zone to maintain the desired temperature condition. Minimum supply air quantity is usually not less than 40% of the design airflow to provide sufficient ventilation. Supplemental heating is used in all exterior zones. The zone thermostat controls the VAV damper down to its minimum setting then starts to open the heating valve if heating is required.

Enthalpy control: Outside air "economy cycle" control based on dry bulb temperatures is not always most economical. For example, in a very humid climate, the total enthalpy of the outside air may be greater than that of the return air even though the dry bulb temperature is lower. Since the cooling coil must remove the total energy from the air to maintain the desired condition, it is more economical in such a case to hold outside air to a minimum.

2.4 Problems with Conventional Control Strategies

There are several problems with the current existing control strategies, which are summarized as follows:

(1) Lack of indoor air quality monitoring and control

There is no indoor air quality control strategy in the control system, therefore indoor air quality is not guaranteed. If the number of occupants increases, or fresh air mixing decreases, indoor air quality may become poor.

(2) Fixed control strategy vs. variable HVAC operations

The control system has a fixed strategy for all seasons. It is often seen that a cooling coil is in use in winter while the outside air intake is less than 100% for an "economy cycle". Such a problem can be solved by changing the control strategy through seasons/time, selecting different operations or combinations according to weather, heat/damp load and HVAC structure information. In other words, operation planning needs to be integrated into HVAC control system.

(3) Problems with supply air control

In a multizone VAV system, supply air temperature is fixed, supply air volume to each zone is adjusted by a terminal thermostat in responding to the changes of the room heat load. As both supply air volume and temperature directly affect the room temperature, the supply air temperature does not coordinate with supply air volume control which is not a good strategy result in the possibility of both wasted energy and poor indoor air quality.

(4) Disadvantages of thermostat indoor setting

The control systems sets indoor temperature as a constant by thermostat strategy. In addition to temperature, other six variables: mean radiant temperature, relative humidity, air velocity, clothing, activity level (metabolic rate) and exposure time, also have significant effects on comfort. A thermostat strategy does not maintain optimal thermal comfort inside buildings. It possibly results in wasted energy because the indoor temperature could be set unnecessarily high or low. Comfort technology has not been fully utilized in HVAC control to achieve energy conservation and improve comfort. It is suggested that setting indoor temperature by comfort-stat (Fanger, 1970) may give better comfort and energy saving than thermostat setting.

(5) Difficulties of accumulating and utilizing private knowledge

Building operators usually gain valuable knowledge as heuristics and expertise for economic operation from experience. Current existing control strategies have no facilities to update and utilize operators' knowledge.

CHAPTER 3

INTEGRATED DISTRIBUTED INTELLIGENT SYSTEM APPROACH

As discussed in Chapter 2, there are some problems with conventional control strategies. In this chapter, an integrated distributed intelligent system approach to an operation support system (IOSS) for HVAC processes is proposed. The objective of IOSS is to coordinate different operations in HVAC system for better energy saving, comfort and IAQ than that are obtained by a conventional control strategy.

An intelligent system acquires and codifies the knowledge from human experts to solve ill-structured problems. Heuristics play an important role in the problem solving.

An intelligent system provides assistance to operators to optimize the operation environment. It transfers and accumulates the expert knowledge into computer programs so c rators who do not have well-trained operating experience can also control HVAC processes at the level of expert operators.

The knowledge of IOSS covers HVAC control systems, energy conservation management, and comfort technology as well as indoor air quality control. Qualitative and quantitative information processing have to be coordinated. The problem of knowledge integration and management is faced. The implementation of IOSS requires an advanced intelligent system architecture and software environment.

3.1 Meta-System

An integrated distributed intelligent system structure was first proposed in 1987 [Rao, et al., 1987; Rao, 1989]. It is a large knowledge integration environment, which consists of several symbolic reasoning systems, numerical computation packages, neural networks, and computer graphics programs. The integrated distributed intelligent system is illustrated by Figure 7. These software programs may be written in different languages and be used independently. They are under the control of a supervising intelligent system, namely, meta-system. The meta-system manages the selection, operation and communication of these programs.

As shown in Figure 7, a meta-system has its own database, rule base and inference engine, but it decomposes its activities into separated, strictly ordered phases of information gathering and processing. The main functions of a meta-system are:

1. To coordinate all symbolic reasoning systems, neural networks, numerical computation routines as well as computer vision and graphics programs in an integrated distributed intelligent system.

2. To distribute knowledge into separate intelligent systems, computer

vision programs, graphics package, numerical computing routines, as well as neural networks.

3. To acquire new knowledge efficiently and add new programs easily.

4. To find a near optimal solution for the conflict solutions and facts among the different symbolic reasoning systems (i.e., expert systems).

5. To provide the possibility of parallel processing in the integrated distributed intelligent systems.

6. To communicate with the measuring devices and the final control elements in the control systems and transform various input/output signals into the standard communication signals.

Integrated distributed intelligent system is very demanding in the integration for different intelligent systems, neural network, computer vision and graphics programs, as well as numerical computation packages in order to realize the industrial automation in the knowledge intensive stage. This new software integration platform can process different knowledge (analytical and heuristic knowledge), different information (symbolic, numerical and graphic information) as well as different computer languages. The meta-system layout includes the following six main components (Rao, et al., 1991):

1. Interface to external environment

The interface to external environment builds the communications between users and internal software systems as well as the external software systems. The interface includes an icon structured menu that includes windows, data structure, security module, and editor module. The interface will play a key role in an open structured software system in two ways: the first is to codify human expertise into the computer system such that it can adopt the most creative intelligence and knowledge in decision making; the other is to communicate with other intelligent software systems to extend the system into a much larger scale for the more complicated tasks.

2. Meta-knowledge base

The Meta-knowledge base is the intelligence resource of this meta-system. It serves as the foundation for the meta-system to carry out the managerial tasks. The meta-knowledge base consists of a compiler and a structured frame knowledge representation facility. The advantage of an open structured meta-knowledge base allows intelligent functionalities to enter the meta- knowledge to engage more duties in decision-making.

3. Database

The database in the meta-system functions as a global database for the integrated intelligent system, distinguishing with those databases in the subsystems which only attach to the individual subsystems they belong to. The database contains an editor, an interface to the inference engine, a management system and a physical storage structure. The interface converts the external data representation form into an internal form. The control of data flow is provided either by the inference engine, depending on the corresponding module in the meta-knowledge, or by users at certain security classes. The management system will carry out the data processing function.

4. Inference mechanism

Due to the diversity of the meta-knowledge and the variety of its representation forms, the inference mechanism in the meta-system adopts various inference methods, such as forward chaining, backward chaining, exact reasoning, inexact reasoning, and so on. The inference mechanism conducts operation and processing on the meta-knowledge. Additionally, it also carries out various actions according to the results from reasoning, e.g., passing data between any two subsystems, and storing new data in the database. Therefore, there are some functional modules in the mechanism, which further extend the functionality of the inference mechanism.

5. Static blackboard

The static blackboard is an external memory for temporary storage of required information when the system is running. Limited by the on-board memory space, the integrated intelligent system is unable to execute at the same time. In fact, it is unnecessary to run the entire system simultaneously. Very often, the meta-system and all subsystems are run on the external memory for any two subsystems to exchange information. Besides data storage, the conversion of data in heterogeneous languages into exchangeable standard form will also be completed on the static blackboard.

6. Interface to internal subsystems

This component of the meta-system is established based on each specific application. The interface connects any individual subsystems which are used in problem solving and under the control and management by the meta-system. Each module of the interface converts a nonstandard data form in the integrated distributed intelligence environment. The conversion among the standard forms of different languages is carried out by the meta-system.

3.2 Integration of IOSS

In IOSS, expert system for operation planning, indoor comfort setting, and conflict reasoning are integrated and coordinated by a meta-system framework. Symbolic reasoning, computer graphics and numerical computation are integrated to facilitate the functionalities of IOSS. The integrated architecture of IOSS is demonstrated in Figure 8. Several systems, such as operating mode consulting, comfort setting, conflict reasoning and knowledge introduction, including a commercial package, such as DBASE III plus™, Personal Consultant Plus (PC-PLUS™, an expert developing tool), are integrated by the meta-system framework. The software menu screen is shown in Figure 9. The knowledge acquisition, organization and function of each system will be described in the following chapters.

CHAPTER 4

EXPERT SYSTEM: OPERATION PLANNING

Operation planning is a process phase that is concerned with the selecting and sequencing of different operations and combinations to transfer an initial state to a goal state (Tsatsoulis and Kashyap, 1988).

As weather or load changes, an air conditioning system must change air handling equipment. For example, in winter, a heating coil is used to condition temperature, but in summer, a cooling coil is used instead. In some cases, alternative air processing is able to meet the conditioning requirements. Operation planning is needed in HVAC process control. The problem of operation planning is to choose an optimal operating mode for air processing according to information about the weather, HVAC system structure, air handling equipment, heat and wet load, indoor setting, and indoor air quality. Table 1 shows some typical operating modes for the THSCD air conditioning system shown in Figure 3. As many types of HVAC systems exist, operation planning becomes very complicated. It is a non-algorithmic problem, therefore it is difficult to approach by a conventional mathematical modeling method.

An expert system is a computer program containing knowledge, judgment and experiences of an expert in a specialized area. Thus, the expertise of a highly skilled individual can be automated in a computer system, and be utilized by those with less expertise. It is a suitable methodology for solving HVAC operation planning problems.

In this chapter, the development of an expert system for operation planning (ESOP) is described, including knowledge acquisition, representation, organization, and implementation. An example of energy saving operating mode consulting is also illustrated.

4.1 Knowledge Acquisition

The key issue in the operating mode selection is to identify the optimal operational mode subject to the conditions of system structure, weather, indoor setting, air handling equipment, and changing heat/damp load.

Expertise about optimal operation mode identification

The expertise for the operating mode identification can be demonstrated in an air property chart. The following example gives a description about the expertise.

For a constant air volume, single zone, temperature and humidity conditioning (THSCD) system in Figure 3, the operating modes can be divided in an enthalpy-humidity coordinates chart. The operational mode identification expertise is demonstrated in Figure 10.

N is the indoor air setting, which is determined by thermal comfort requirement.

S is the supply air, which is decided by the heat and damp load of a HVAC system.

K is reached by mixing the minimum allowed amount of fresh air (usually 10%) with return air, $\overline{SN}/\overline{KN}$ = 10%

In Figure 10(a), if the fresh air is in area 1, the optimal operation should choose mode 1, i.e. recirculate air at 90%, fresh air at 10%; cooling coil off; heating used to control temperature; humidifier for controlling humidity; dehumidifier off. If the fresh air is in area 2, the air conditioning system should be operated under mode 2, and so on. The status of air handling unit for each operating mode is shown in Table 1.

It can be seen that in each operating mode, some air handling elements are used to control temperature/humidity, some are kept in certain status, and do not participate in the control. Those air handling elements participating in control are defined as control manipulated variables (CMV); others that do not participate in control are defined as operational variables (OV). It should be noted that one air handling element can be a CMV in one operating mode, but an OV in another operating mode.

Air handling processes for various operating modes are described by Figure 11, where

MODE 1 10% outside air is mixed with 90% return air, and heated to the desired supply air temperature, then water or steam is injected to humidify air in order to meet the supply air moisture requirement (1a-1b-1c-S).

Mode 2 Outside air is properly mixed with return air to reach the desired supply air temperature, then water or steam is injected to humidify air to supply moisture (2a-2b-S).

Mode 3 100% outside air is used and cooled to the desired supply temperature, then water or steam is added to reach the supply moisture (3a-3b-S).

Mode 4 10% outside air is mixed with 90% return air, and cooled to the desired supply air temperature, then water or steam is added to reach the supply moisture (4a-4b-4c-S).

Mode 5 Outside air mixed with return air at a ratio of 1:9, then the mixed air is cooled to the desired supply temperature. Afterwards, the air passes through a dehumidifier (5a-5b-5c-S).

Mode 6 100% outside air is heated and then passed through a dehumidifier to satisfy the desired supply temperature and humidity requirement (6a-6b-S).

Mode 7 Outside air is mixed with return air to the supply air temperature, then dehumidified to supply moisture (7a-7b-S).

Mode 8 10% outside air is mixed with 90% return air, then a heating and dehumidifying process is applied (8a-8b-8c-S).

Mode 9 Outside air is mixed with return air to control supply moisture, then the mixed air is heated to the desired supply temperature (9a-9b-S).

Mode 10 Outside air is mixed with return air to control moisture, then the mixed air is cooled to supply temperature (10a-10b-S).

Mode 11 100% outside air is dehumidified and heated to the desired supply temperature and humidity (11a-11b-S).

Mode 12 100% fresh air is humidified and heated to reach the desired supply temperature and moisture (12a-12b-S).

According to Figure 11, the operating modes are identified as:

MODE 1: $i \le iik$ AND $w \le wk$ AND $iin \ge iis$ AND $wn \ge ws$

MODE 2: $i \le iis$ AND $i \ge iik$ AND $\frac{iin - i}{wn - w} \le \frac{iin - iis}{wn - ws}$ AND $iin \ge iis$ AND $wn \ge ws$

. . . . . .

Where **i, iis, iin, iik** are the enthalpies of fresh air, supply air, desired indoor air, and minimum mixed outside air respectively; **w, ws, wn, wk** are the moisture values of outside air, supply air, desired indoor air, and minimum mixed fresh air, respectively.

It should be pointed out that **S** is a dynamic point, and the relative position of **S** and **N** reflects the system heat and moisture load. Considering various load cases, which are demonstrated in Figure 10a-h, **S** moves around **N**, so the integrated conditions to determine the operating modes become Mode 1:

$$i \le iik \text{ AND } w \le wk \text{ AND } iin \ge iis \text{ AND } wn \ge ws$$

OR

$$i \le iin \text{ AND } w \le ws \text{ AND } iin < iis$$

OR

$$i \le iik \text{ AND } w \le ws \text{ AND } iin \ge iis \text{ AND } wn < ws$$

Mode 2:

$$i \le iis \text{ AND } i \ge iik \text{ AND } \frac{iin - i}{wn - w} \le \frac{iin - iis}{wn - ws} \text{ AND } iin \ge iis \text{ AND } wn \ge ws$$

OR

$$i \le iik \text{ AND } i \ge iis \text{ AND } \frac{iin - i}{wn - w} < \frac{iin - iis}{wn - ws} \text{ AND } iin \le iis \text{ AND } wn \le ws$$

OR

$$i \le iis \text{ AND } i \ge iik \text{ AND } \frac{iin - i}{wn - w} > \frac{iin - iis}{wn - ws} \text{ AND } iin \ge iis \text{ AND } wn \le ws$$

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Mode 12:

$$i \le iis \text{ AND } i \ge iin \text{ AND } \frac{iin - i}{wn - w} \le \frac{iin - iis}{wn - ws} \text{ AND } iis \ge iin \text{ AND } ws \ge wn$$

OR

$$i \le iis \text{ AND } i \ge iin \text{ AND } \frac{iin - i}{wn - w} < \frac{iin - iis}{wn - ws} \text{ AND } iin \le iis \text{ AND } ws \le wn$$

These conditions are used to issue IF statements in the knowledge base to identify the operating modes. There exists a total of twelve operating modes that respond to various load cases and weather in the THSCD system. Each rule of the knowledge base identifies one optimal operating mode corresponding to the input information.

For the sixteen different types of HVAC structures shown in Figure 1, over one hundred rules are issued for the operating mode consulting knowledge base. Appendix A shows the energy saving operating mode identification for the all sixteen different types of HVAC systems. The operating mode identification for a multi-zone system is same as for a single zone system except that the indoor setting is the mean value of the temperature/humidity settings of all zones. For VAV systems (Figure A-2, A-6, A-7, A-8), S1, S2 are supply air parameters corresponding to minimum and maximum supply air volume respectively. K1, K2 are the minimum allowed outside air mixing parameters corresponding to minimum and maximum supply air volume respectively. All the operating modes are shown in Appendix B.

4.2 Knowledge Representation

Once the process operation and the related problems had been studied, all the system inputs and outputs were investigated.

Operation Planning Inputs:

HVAC SYSTEM STRUCTURE (Figure 1):

Conditioning-type (temperature-humidity, temperature), zone-type (single zone, multizone), air volume (constant, variable), dehumidifying unit (air washer, cooler, or dehumidifier).

WEATHER: Outdoor air temperature, relative humidity or wet bulb temperature.

INDOOR SETTING: Indoor air temperature, relative humidity.

SUPPLY AIR PARAMETERS: Supply air temperature, humidity, and air volume.

Operation Planning Output:

RECOMMENDED OPERATION MODE: Indication of all air handling units status and combinations.

Qualitative Knowledge Representation

Qualitative knowledge representation for HVAC system structure and symbolic information processing determines the classification of the HVAC system.

A typical rule used to classify HVAC systems may be described as:

IF CONDITIONING-TYPE = TEMPERATURE-HUMIDITY

AND ZONE-TYPE = SINGLE

AND AIR-VOLUME-TYPE = CONSTANT

AND DEHUMIDIFY-AIR-HANDLING-UNIT = AIR-WASHER

THEN HVAC-SYSTEM = THSCW

Quantitative Computation

Weather information, indoor temperature/humidity setpoint and supply air parameters are quantitatively represented. Numerical information processing is applied for operating mode identification, supply air parameters and indoor setting. The quantitative computation is coupled into the symbolic reasoning.

EVALUATION OF AIR ENTHALPY AND HUMIDITY VALUE:

To identify the operating mode, as shown in the above, air enthalpy and humidity need to be evaluated by the input of air temperature and relative humidity. Air enthalpy and humidity are evaluated as follows (Haines, 1987),

in English units:

$$i = 0.24\, t + w\, (1061.2 + 0.444\, t)$$

$$w = \frac{0.6129\, P_s\, \phi}{(14.696 - P_s)}$$

$$\phi = \frac{1}{P_s}\left[P_{ws} - \frac{(14.696 - P_{ws})(t - W_t)}{2831 - 1.43}\right] \qquad (1)$$

while in SI units:

$$i = t + w\, (2501.3 + 1.86\, t)$$

$$w = \frac{0.6129\, P_s\, \phi}{1.0132\times 10^{-5} - P_s}$$

$$\phi = [P_{ws} - 6.748 \times 10^{-8}(t - W_t)] / P_s$$

(2)

Where t is the dry bulb temperature of the air; ϕ is the relative humidity of air; w is the absolute humidity of the air; W_t is the wet bulb temperature of the air; P_s and P_{ws} are the saturated water vapor pressures with respect to the dry bulb temperature and the wet bulb temperature, respectively. In (1) and (2), the atmospheric pressure is assumed to be at standard sea-level pressure. Where atmospheric pressure is not at standard, corrections may be introduced.

SUPPLY AIR PARAMETER ESTIMATION:

Supply air parameters respond to HVAC system heat and humidity load, which behave uncertainly in most situations. Some air conditioning systems have no measurements for supply air. The supply air parameters used in the operating mode identification rules are steady state parameters, so even if they are measured on-line, the signals still need to be processed. Based on these reasons, the following methods for supply air estimation are proposed:

Case 1. On-line data for supply air parameters available and off-line operating mode consulting needed: the mean of the last five samples of data are used as the steady state supply parameters.

Case 2. On-line data for supply air parameters available and on-line operating mode consulting needed: the output and input relationship are modeled for indoor air parameters and supply air parameters by adaptive control techniques (Shi and Zhou, 1985). The steady state supply air parameters can be predicted by the models. More details about this case will be discussed in Chapter 7.

Case 3. On-line data for supply air parameters unavailable and off-line operating mode consulting needed: the steady state supply air parameters are given as:

$$I_{ss} = [(V_i + V_{ss})\, i_{in} + Q_t - i_o \cdot V_i] / V_{ss} \tag{3}$$

$$W_{ss} = [(V_i + V_{ss})\, W_n + Q_w - w_o \cdot V_i] / V_{ss} \tag{4}$$

where I_{ss}, W_{ss}, V_{ss} are the enthalpy, humidity, air volume of steady state supply air, respectively. i_o, w_o are outside air enthalpy and humidity respectively. V_i is infiltration of air volume. Q_t, Q_w are heat and humidity load of the HVAC system, respectively. K is the percentage of outside and return air in the mixed air, i.e.

$$K = \frac{\text{Fresh Air Volume}}{\text{Return Air Volume + Fresh Air Volume}}. \tag{5}$$

As mentioned previously, supply air parameters are estimated based on steady state, the HVAC system design data can be directly applied to Q_t, Q_w, V_i and V_{max}, and these data are usually available to the operators.

4.3 Knowledge Organization and Implementation

This expert system is implemented under PC-PLUS, an expert system developing tool. PC-PLUS provides an external access interface, which allows the execution of the external program and retrieving of an external database.

Knowledge base structure: In PC-PLUS, a knowledge representation mechanism consists of three parts: frames, parameters, and rules. Each frame, parameter, or rule has its properties that define their characteristics. Every frame holds a set of parameters and a rule base.

Frames can be hierarchically structured in PC-PLUS. A parent frame can invoke the rules in a child frame, and a child frame can access the parameters in its parent frame.

Hierarchy of the Frames: The hierarchical structure of the frame in the operating mode consulting is based on the classification of the HVAC systems, which is demonstrated in Figure 12. It consists of two frame levels. The first frame level classifies HVAC systems, which decides the subframe to activate according to the system type. In the second level, consisting of sixteen frames, each frame contains a group of external access rules and a set of rules to choose energy saving operating modes corresponding to the structure of the HVAC systems.

Root Frame: In this frame, the user inputs or confirms the information about the HVAC system structure. Symbolic reasoning decides on the subframe to be activated in responding to the HVAC system structure information.

Subframe: According to the classification of the root frame, there are sixteen types of HVAC systems, and each corresponds to a subframe. As air enthalpy and humidity value are used in the rules to identify the operating mode, numerical calculation programs for evaluating air enthalpy and dampness are written in BASIC and executed by external access rules. Each frame contains a rule base to choose an energy saving operating mode for the corresponding structure of the HVAC system.

A typical rule for the system classification and activating a subframe in root frame is shown as:

IF CONDITIONING-TYPE = TEMPERATURE-HUMIDITY

AND ZONE-TYPE = SINGLE

AND AIR-VOLUME-TYPE = CONSTANT

AND DEHUMIDIFYING-UNIT-TYPE = DEHUMIDIFIER

THEN HVAC-SYSTEM = THSCD AND CONSIDERFRAME THSCD

In the external access, the input data about temperature and humidity are sent to external data files, executing the external computation program, then the enthalpy and damp data are retrieved. Except for air enthalpy and dampness evaluation, the external numeric computation programs also handle the unknown information processing, i.e., the estimation of supply air parameters.

For a constant air volume, single zone or central air conditioning system with a dehumidifier, a typical rule in the subframe THSCD is:

IF **i** ≤ **iik** AND **w** ≤ **wk** AND **iin** ≥ **iis** AND **wn** ≥ **ws**

OR **i** ≤ **iin** AND **w** ≤ **ws** AND **iin** < **iis**

OR **i** ≤ **iik** AND **w** ≤ **ws** AND **iin** ≥ **iis** AND **wn** < **ws**

THEN OPERATION-MODE = MODE-1

AND PRINT "The recommended operating mode is:

OUTSIDE-AIR-DAMPER at 10%; RETURN-AIR-DAMPER

at 90%; DEHUMIDIFIER off; HUMIDIFIER **ON**;

DEHUMIDIFIER **OFF**; HEATING COIL **ON**; COOLING COIL **OFF**."

Since there are twelve operating modes for this type of air conditioning system, there exist twelve such kinds of rules in the knowledge base. For all sixteen types of HVAC systems, the knowledge base is made up of over a hundred such rules to identify energy conservation operating modes.

4.4 An Operation Mode Consulting Example

An illustration of a consulting example (Figure 13) by using ESOP is given below:

Input: HVAC system structure information:

TEMPERATURE

SINGLE-ZONE

CONSTANT AIR VOLUME

Air parameters:

UNIT-SYSTEM = SI-UNIT

WET-MEASUREMENT = RELATIVE-HUMIDITY

T1 = 5 (Outside air temperature is 5 ^{o}C.)

TN = 24 (Desired indoor temperature is 24 ^{o}C.)

TS = 30 (Supply air temperature is 30 ^{o}C.)

Output: OPERATION-MODE = MODE-1

"The recommended operating mode is: OUTSIDE-AIR-DAMPER at 10%; RETURN-AIR-DAMPER at 90%; HEATING COIL **ON**; COOLING COIL **OFF**."

The ESOP recommends an energy saving operating mode for air handling based on the input information about the HVAC structure, weather, load, and indoor setting, thus providing an operating mode consulting.

CHAPTER 5

COMFORT INDOOR SETTING

According to ASHRAE 55-1981, air conditioning system design standard, indoor temperature range is from 65-80°F or 18-27 °C, and relative humidity is 35-62%. Comfort research has provided a number of alternatives for energy conservation (Nelson et al. 1987; Doherty and Arens, 1988). It is realized that there is a relatively wide range of indoor temperature settings that meet thermal comfort requirements. Therefore a suitable indoor temperature setting is an energy conservation strategy in HVAC process control. Currently, indoor temperature is set at one temperature through all season/time, so called thermo-stat setting, so it is not unusual to hear complaints or comments about the room temperature being too warm in winter or too cool in summer. This results in a large amount of wasted energy. Comfort technology has not been fully utilized in HVAC control to achieve energy conservation and improve comfort. Fanger (1970) suggested that setting indoor temperature by comfort-stat may give better comfort and energy saving than thermo-stat setting. And also it has been found out that comfort-stat setting for indoor temperature is beneficial to indoor air quality.

In this chapter, a brief introduction to current indoor setting strategy is given, then the problems with this strategy are discussed.

A comfort indoor setting is proposed to solve the problems. Finally a comfort indoor setting system is developed.

5.1 Thermal-stat Setting

Currently, the indoor temperature of most HVAC systems are set by thermostat strategy, which maintains the indoor temperature at a constant value through all seasons/time. The disadvantages of this strategy are:

1. It does not maintain the optimal thermal comfort. Besides temperature, six other variables: mean radiant temperature, relative humidity, air velocity, clothing, activity level (metabolic rate) and exposure time, also have the significant affection on comfort.

2. It possibly results in energy waste and uncomfortable due to the indoor air temperature being set unnecessarily high or low.

5.2 Comfort-stat Strategy

To overcome these drawbacks, a comfort-stat control strategy is proposed to set indoor air temperature by the thermal comfort equation (Fanger, 1970). The indoor temperature setting changes responding to the all seven variables to maintain comfort. This strategy provides thermal comfort-stat rather than just keeping temperature constant. It optimizes comfort and energy conservation simultaneously. It is also beneficial to the indoor air quality because temperature changes increase the air exchange where air is not well distributed.

The comfort temperature indoor setting can be determined by the following comfort equation, which was developed by Fanger in 1970:

$$t_{cl} = 35.7 - 0.032\frac{M}{A_{Du}}(1-\eta) - 0.18\ I_{cl}\ \{\ \frac{M}{A_{Du}}(1-\eta) - 0.35\ [43 - 0.061\frac{M}{A_{Du}}(1-\eta)-P_a]-0.42[\frac{M}{A_{Du}}(1-\eta)-50]-0.0023\frac{M}{A_{Du}}(44-P_a)-0.0014\frac{M}{A_{Du}}(34-t_a)] \qquad (6)$$

$$\frac{M}{A_{Du}}(1-\eta)-0.35[43-0.061\frac{M}{A_{Du}}(1-\eta)-P_a]-0.42[\frac{M}{A_{Du}}(1-\eta) - 50] -0.0023\frac{M}{A_{Du}}(44-P_a)-0.0014\frac{M}{A_{Du}}(34-t_a) = 3.4 \times 10^{-8} f_{cl}\ [(t_{cl} + 273)^4 - (t_{mrt} + 273)^4] + f_{cl}\ h_c\ (t_{cl} - t_a) \qquad (7)$$

$$h_c = \begin{cases} 2.05\ (t_{cl} - t_a)^{0.25} & \text{for } 2.05\ (t_{cl} - t_a)^{0.25} > 10.4\sqrt{V} \\ 10.4\sqrt{V} & \text{for } 2.05\ (t_{cl} - t_a)^{0.25} < 10.4\sqrt{V} \end{cases} \qquad (8)$$

where the parameters are:

t_{cl}: Clothes temperature(°C)

$\frac{M}{A_{Du}}$: Human metabolic rate(kcal/hr m^2)

η: Mechanical efficiency

v: Relative velocity in still air (m/s)

$I_{cl} = R_{cl}/0.18$ (clo), where R_{cl} is the total heat transfer resistance from skin to outer surface of the clothed body (m^2hr°C/kcal)

f_{cl} : The ratio of the surface area of the clothed body to the surface area of of the nude body.

p_a: The partial pressure of water vapor in inspired air (ambient air) (mmHg)

t_a : Comfort temperature (°C), i.e. the desired indoor temperature setting.

t_{mrt}: Mean radiant temperature(°C).

The data for $\frac{M}{A_{Du}}$, η, v, I_{cl} and f_{cl} are shown in Table 2 and 3 (Fanger, 1970).

The input information for solving the equation is $\frac{M}{A_{Du}}$, η, v, I_{cl} (clo), f_{cl}, P_a, and t_{mrt}. The P_a and t_{mrt} can be obtained through measurement.

The output information is the comfort temperature t_a, which is the desired indoor temperature setting for HVAC control system, and also the input information for the ESOP.

To simplify the computations of solving the comfort equations (6)-(8), and give the practical assessment of thermal environments, a predicted mean vote (PMV) table was provided by Fanger (1970). As a measure for the thermal sensation the commonly used seven point psycho-physical scale is used:

-3 cold

-2 cool

-1 slightly cool

0 neutral

+1 slightly warm

+2 warm

+3 hot

a positive value corresponds to the warm side and a negative value to the cold side of neutral. When the comfort equation is satisfied, a mean vote equal to zero (neutral) is generally expected.

The predicted mean vote under different indoor temperature is presented for any given combination of activity level, clo-value, and relative velocity. The PMV table (Fanger, 1970) presents 8 different activity levels, 7 clo-values, 9 relative air velocities and 8 ambient temperatures (mean radiant temperature = air temperature), as well as about 3500 combinations of the variables. Indoor temperature setting is based on the principle of lowest possible percentage of dissatisfied (LPPD), i.e., the temperature with zero or close to zero predicted mean vote is the optimal comfort temperature or desired indoor temperature setting for HVAC system.

5.3 Implementation of comfort setting system

This indoor comfort setting system (ICSS) is implemented by using DBASE III plus, a commercial database package. It consists of three data bases, namely MRDTA, DCLOTH, and PMV. The MRDTA holds the data for metabolic rate (M/Adu), mechanical efficiency (η) and relative velocity in still air (v) at different typical activities (Table 2). The DCLOTH database contains data for heat transfer resistance (I_{cl}), a ratio of clothed surface (f_{cl}) at different clothing ensembles (Table 11). The PMV database holds for data the comfort temperature with the predicted mean vote close to zero for different combinations of metabolic rate (M/Adu), mechanical efficiency (η), relative velocity in still air (v), and clo-value.

An example of indoor temperature setting is shown below:

Input Information:

ACTIVITY:

Resting

Seated

CLOTHING:

Business suit

Output Information:

COMFORT TEMPERATURE: 23 °C

PREDICTED MEAN VOTE: -0.02

CHAPTER 6

INDOOR AIR QUALITY CONTROL AND CONFLICT REASONING

In recent years, indoor air quality has been identified as a potentially serious health problem. (Franta and Franta, 1985). The sick building problems have been characterized as "one of the most serious public health challenges in next decade." (Bahnfleth, 1986)

The sources of indoor air pollutants are classified into three groups (Hubber and Wanner, 1983): outdoor air pollution; emission products of building materials and indoor human activities. Human activities, such as smoking, cooking, and perspiration, are the major contributions to indoor air pollution.

A HVAC system plays an important role in indoor environment control (Newman, 1991). The indoor air pollution from human activities can be removed by adequate ventilation (Wallingford and Carpenter, 1986; Wallingford, 1988). Ventilation system performance has attracted special research attention because it is both a mechanism for removing indoor air pollutants, and a potential energy load on the heating or cooling system for the building (Sherman and Wilson, 1986). Ventilation models for IAQ control have been investigated (Fanger, 1989, 1990; Woods 1986), but the ventilation control model or algorithm coupling IAQ control has not been reported.

Indoor air pollution caused by occupants can be removed by increasing ventilation rate, but the increase in air exchange rate results in higher energy consumption. Therefore a conflict exists between energy conservation and improving indoor air quality (IAQ).

Investigating the venti[illegible]rol model, algorithm and strategy for indoor air quality [illegible] which couples energy conservation techniques is the objective of this chapter. In this chapter, the field tests for IAQ and ventilation are conducted. Based on the analysis and test, the IAQ ventilation control models are identified and simulated. Then the conflicts of energy conservation operation of HVAC processes and IAQ control are analyzed. Finally the conflict reasoning rules for a compromise solution between energy saving and IAQ improvement are acquired.

6.1 Field Tests

The energy conservation conflict in HVAC operations has been analyzed. The relationship between the IAQ and HVAC operations is further investigated by the field tests.

Indoor air pollution caused by the occupants can be assessed through odors or carbon dioxide in the room [Hubber and Wanner, 1983]. The comparison of the curve for odor intensity with that for carbon dioxide concentration shows correlations between these two parameters. Such a relationship would be of a high practical value because the relatively easy carbon dioxide measurement can be related to a momentary odor situation in a room.

Carbon dioxide (CO2) concentration has been used as an indicator of indoor air quality, and a high carbon dioxide concentration due to human activity was demonstrated being indicative of poor air quality (Hung and Derossis, 1989).

Concentration of carbon dioxide in ambient air lies between 0.03% and 0.04% by volume. The maximum recommended concentration of CO_2 in indoor air of buildings is 1000 ppm (ASHRAE Standard 62-1989).

Field Test Design:

The goal of the field test is to obtain the dynamics about IAQ, supply fan speed and air mixing damper.

The output and input signals are chosen as follows:

Output: CO2 concentration in the return air due to human activity as an indicator of the indoor air quality.

Input 1: Supply fan speed.

Input 2: Air mixing damper opening.

Test Signal: Square waves of various widths as detailed for each test.

Operating condition: Near normal operating conditions.

The operating or starting condition are considered to be the steady state of the input and output signals.

Field Test HVAC System:

The HVAC system of the administration building at the University of

Alberta campus was selected for the tests. The HVAC system is shown in Figure 14. The supply fan speed is variable. The system measurement and control specifications are shown in Appendix C. The carbon dioxide of the return air was measured in response to the square wave changes of supply fan speed and mixing damper opening respectively. The CO_2 concentration in return air was recorded using a CO_2 indicator, R411, made by Gaftech, scale range from -48 to 4884 ppm, the data averaging period is 15 minutes, and the storage capacity is 6512 values.

<u>Field Test 1</u> The results of field test 1, conducted on January 30, 1992 are illustrated in Figure 15.1.

Starting condition:

Output = 500 ppm (CO_2 concentration in return air)

Input 1 = 85% (Supply fan speed)

Input 2 = 60% (Air mixing damper opening)

Test signals:

Input 1: Square waves of different widths shown in Figure 15.1
The supply fan speed was changed by the operator following the square waves.

Input 2: Air mixing damper opening fixed at 60%, i.e., outside air damper opens at 60%, return air damper opens at 40%.

<u>Field Test 2</u> The results of field test 2, conducted on January 31, 1992 are illustrated in Figure 15.2.

Starting condition:

Output = 410 ppm (CO_2 concentration in return air)

Input 1 = 60% (Supply fan speed)

Input 2 = 40% (Air mixing damper opening)

Test signals:

Input 1: Supply fan speed is fixed at 60%, of maximum speed.

Input 2: Square waves of different widths shown in Figure 15.2. The mixing damper opening was changed by the operator following the square waves.

The output data recording started at 9:00 am and finished at 3:30 pm. From the test results, it can be seen that the response of the indoor CO_2 concentration to the step change of the air mixing damper is as expected when the outside air damper opening is increased, the return air CO_2 concentration are decreasing.

Field Test 3 The test condition is the same as the Field Test 1 except the air mixing damper was kept at 30% open. The test was conducted on February 4, 1992 as illustrated in Figure 15.3. From the results of test 1 and 3, it can be seen that the response of the indoor CO_2 concentration does not decrease when fan speed increase as would be expected from the results of test 2. The effect of supply fan speed on the CO_2 concentration of the return air is not so strong as the mixing damper, but increasing the amount of supply air improves the air ventilation and exchange locally, so the indoor air quality improves.

In addition to the HVAC operations, the CO_2 concentration is also affected by the number of the people in the building, which is reflected in the test results, for example, at lunch time, most people left the office, the CO2 concentration decreased as shown in Figure 15.2-3.

Field Test 4 (Figure 15.4) is the recording under the normal operations. The tests started at 8:30 am and finished at 3:30 pm, February 5, 1992.

The four complete field test data are listed in Appendix D.

6.2 IAQ Control Model Identification

Based on the experimental data collected from the field tests, the following control model is identified using the least squares method and Matlab™ software package:

In test 2, starting conditions:

$CO2_o$ = 410 (Indoor CO_2 concentration)

Us_o = 60% (Supply fan speed is 60% of the maximum speed)

Vd_o = 40% (Mixing damper opening is 40%, i.e., outside air damper opening at 30%, return air damper at 60%.)

The model is:

$$CO_2(k+1) = 1.8894\ CO_2(k) - 0.8928\ CO_2(k-1) + 0.0216\ V_d(k) - 0.0901\ V_d(k-1) + \xi(k) \quad (9a)$$

Var = 6.6960

In test 3, starting conditions:

CO_{2_o} = 400 (Indoor CO_2 concentration)

$Us_{\_o}$ = 50% (Supply fan speed is 50% of the maximum speed)

$Vd_{\_o}$ = 30% (Mixing damper opening is 30%)

The model is:

$$CO_2(k+1) = 1.8835\ CO_2(k) - 0.8819\ CO_2(k-1) + 0.0184\ U_s(k) - 0.0446\ U_s(k-1) + \xi(k) \quad (9b)$$

Var = 3.6076

Where Us: Speed (%) of supply fan - $Us_{\_o}$

Vd: Opening (%) of mixing damper - $Ud_{\_o}$

CO_2: Return air CO2 concentration (ppm) - CO_{2_o}

ξ: Disturbance

The sampling time for the models is 5 minutes.

It should be pointed out that the model (9a) and (9b) is time varying, because indoor CO_2 level is strongly affected by the number of occupants inside the building, and it is treated as a disturbance $\xi(k)$ in the models.

6.3 Indoor CO_2 Control Simulation

From the field test results, it is seen that the CO_2 concentration of the return air can be controlled by manipulating the mixing damper opening. The control loop is shown in Figure 16.

Using the mixing damper opening as the manipulated variable as shown in the model (9b),

PID control: $V_d(k) = Kp * e(k) + Ki * \sum e(k) + Kd * [e(k)-e(k-1)]$ (10)

The simulation algorithm:

$e(k) = CO2\_H - CO_2(k)$

$V_d(k) = Kp * e(k) + Ki * \sum e(k) + Kd * [e(k)-e(k-1)]$

$U_s(k) = 0$ (11)

Where Kp, Ki and Kd are the parameters of PID controller. CO2_H is the indoor air carbon dioxide concentration setpoint.

The CO2 concentration control requirement is different from an ordinary control loop. The setpoint can be the high limit of CO2 concentration, and when the output is lower than the setpoint, the control action is not necessary. So for a real time HVAC control system, when the indoor CO2 concentration is lower than the setpoint, the system may be able to switch to an energy saving operation as discussed later.

The simulations were carried out using Matlab™, a commercial software package.

The simulation for the step response by using model (9b) is demonstrated in Figure 17.1.

The tuned PID parameters are:

$Kp = -0.25$

$Ki = -0.01$

$Kd = 0$

Considering the limit of control action in the model 9b, $-40 < V_d < 60$, (i.e., $V_{d\_o} = 40$, V_d = mixing damper opening - V_{d_o}), the simulation result is shown in Figure 17.2

The simulation results show that indoor carbon dioxide concentration can be controlled by a mixing damper.

6.4 Conflict Analysis

In HVAC processes, the ventilation rate or outside air intake is controlled by the air mixing damper position and the VAV supply fan. Conflict analysis for the operations are described in Table 4.

<u>Conflict of air mixing damper operation:</u>

When the outdoor air damper (or air mixing damper) opening **increases**, i.e. outside air intake increases, the IAQ is usually improved under the same indoor pollution load. But there are two cases for the HVAC energy consumption response: (1) if heating or cooling is in use, the energy consumption increases; (2) if the system is in the free cooling or heating operating mode, the energy consumption remains same.

When the outdoor air damper (or air mixing damper) opening **decreases**, the situation is reversed, i.e., there is usually a degradation in IAQ under the same indoor pollution load. And also there are two cases for the HVAC energy consumption response: (1) if heating or cooling is in use, the energy consumption decreases; (2) if the system is in the free cooling or heating operating mode, the energy consumption remains same.

Conflict of VAV supply fan operation:

When the supply fan speed **increases**, the supply air volume increases and the air exchange rate increases. This usually results in improved IAQ, but the energy consumption also **increases** because of the system heating or cooling load increases and the fan motor electricity consumption increases.

6.5 Conflict Reasoning

The field tests, model identification and the conflict analysis provide the knowledge to investigate conflict reasoning for a compromise solution between energy conservation and IAQ control.

To develop the conflict reasoning rules, the following notation is defined for the operating mode:

IAQ Operating Mode: Mixing-damper is used to control indoor CO_2 concentration. Heating or cooling is applied to meet supply temperature requirements. Humidifier or air washer/cooler/dehumidifier is used to meet supply humidity requirements.

Energy Conservation Mode: A operating mode that is recommended by the expert system for operation planning.

Conventional Mode: High and low temperature limit control mixing damper (Economy cycle outside air control). Heating or cooling is applied to meet supply temperature requirements. Humidifier or air washer/cooler/ dehumidifier is used to meet supply humidity requirements.

As discussed in the CO2 control simulation, the high limit of indoor CO2 concentration, i.e., 1000 ppm (ASHRAE Standard 62-1989), can be used as the setpoint of the control loop. If the CO2 level is higher than the setpoint, it has to be switched to the IAQ operating mode, no matter what energy saving operation opportunity exists, The CO2 concentration is under control by manipulating the mixing damper. The indoor air quality is treated as first priority in the HVAC operations. If the indoor CO2 concentration is lower than the high limit, the option of operating the HVAC system under energy conservation mode exists, in which an acceptable indoor air quality and optimal energy conservation can be achieved. In some situations, the IAQ problems may not be solved by increasing outdoor air intake.

Typical conflict reasoning rules are described below:

Rule-1:

IF the CO_2 concentration ≥ **High_Limit**

AND the HVAC process is being operated under the Energy Conservation Mode

or Conventional Mode

THEN Switch HVAC system operation to the IAQ Operation Mode

Rule-2:

IF the CO_2 concentration < **High_Limit**

AND the outdoor-Air intake ≤ 10% for the last period of 30 min.

AND the HVAC process is being operated under

the IAQ Operating Mode

THEN Switch HVAC system operation to the Energy Conservation Mode

Rule-3:

IF the CO_2 concentration ≤ **High_Limit**

AND the outdoor-Air intake < 60% for the last period of 30 min.

AND the HVAC process is being operated under

the IAQ Operating Mode

THEN Check the outside air damper state under

the Energy Conservation Mode

AND **IF** the mixing damper is used to control

Temperature/Humidity

THEN Switch the HVAC system operation to

the Energy Conservation Mode

ELSE Maintain the operating mode

Rule-4:

IF the CO_2 concentration ≤ **High_Limit**

AND the outdoor-Air intake <95% for the last period of 30 min.

AND the HVAC process is being operated under

the <u>IAQ Operation Mode</u>

THEN Check the outside air damper state under

the <u>Energy Conservation Mode</u>

AND **IF** the outside air damper opens at 100%

THEN Switch HVAC system operation to

the <u>Energy Conservation Mode</u>

ELSE Maintain the operating mode

Rule-5:

IF the CO_2 concentration ≤ **High_Limit**

AND the HVAC process is being operated under

the <u>Energy Conservation Mode</u>

THEN Maintain the operating mode

The conflict reasoning system (CRS) was implemented in Turbo-C. The high limit for indoor carbon dioxide concentration is defined as 1000 ppm according to the ASHRAE Standard 62-1989. The system input information is indoor CO_2 concentration data, current operating mode, and outdoor air intake percentage or mixing damper position. The output gives an operating mode change recommendation.

CHAPTER 7

INTEGRATED INTELLIGENT CONTROL FOR HVAC PROCESSES

The intelligent operation support system (IOSS) described in the previous chapters can be used to assist or train operators, and it is an off-line support system. In this chapter, a real time control environment integration with IOSS is described. The integration for indoor air quality control, comfort indoor setting and energy conservation operation planning are presented and comparing with a conventional control strategy.

7.1 Integrated Intelligent Control Framework

An integrated intelligent control framework (IICF) for HVAC processes is proposed as shown in Figure 18. It has an adaptive cascade control loop, and consists of four parts: adaptive control model for supply air, operation planning, intelligent controller and HVAC processes.

The signals in Figure 18 are described below:

<u>Measuring Signals</u>:

ts, ws: Supply temperature and humidity, respectively.

tr, wr: Room temperature and humidity, respectively.

to, wo: Outside air temperature and humidity, respectively.

co2: Concentration of carbon dioxide in room.

Vs: Supply air volume or supply fan speed.

<u>Control Signals:</u>

TN, WN: Indoor temperature and humidity setpoint, respectively (primary loop setpoint, determined by the menu or indoor comfort setting system).

Ts, Ws: Supply temperature and humidity setpoint, respectively (secondary loop setpoint).

U(k): Manipulated variable signals.

V(k): Operational variable signals.

CO_2: High limit of indoor carbon dioxide concentration.

An adaptive control model is applied to determine supply air temperature/humidity setpoint (Tss(k) and Wss(k)) for the second loop, i.e., the setpoint of the intelligent controller. The adaptive control model predicts of the steady state of the supply air (Tss, Wss and Vss) for the operation planning (ESOP) of the IOSS. The IOSS functions as the energy saving operating mode selection (ESOP) and conflict reasoning (CR) as well as indoor comfort setting (ICS). The setpoint of the adaptive control model can be set by menu or the ICS of the IOSS. The ESOP and CR of the IOSS provide the operational variable status (V(k)) directly to the AHU. The control actions of the manipulated variables are decided by the intelligent controller.

The intelligent operation support system (IOSS), including energy conservation operation planning, IAQ control and comfort setting are integrated in this intelligent control framework. Since the IOSS has been described in the previous chapters. Only the adaptive control model for supply air control and intelligent controller for air handling processes will be discussed in the following sections.

7.2 Determination of Supply Temperature/Humidity

To complete operation planning, steady state prediction of supply temperature/humidity must be provided by a primary loop. In addition, the setpoint of supply air control also needs to be determined.

As mentioned before, the heat/humidity load of HVAC system changes widely over the seasons. The model for room temperature/humidity and supply temperature/humidity and volume is time varying and uncertain. In order to determine the prediction of steady state and setpoint of supply air, an adaptive control model, or general predict model to describe the relation between room temperature/humidity, supply temperature/humidity and air volume is considered as follows:

$$tr(k + dt) = a_0\, tr(k)\, vr(k) + a_1\, tr(k-1)\, vr(k-1) + \ldots\ldots + a_{nt}\, tr(k-n_t)\, vr(k-n_t) + b_0\, ts(k)\, vs(k) + b_1\, ts(k-1)\, vs(k-1) + \ldots\ldots + b_{nt}\, ts(k-n_t)\, vs(k-n_t) + \xi_t(k) \qquad (12)$$

$$wr(k + dw) = c_0\, wr(k)\, vr(k) + c_1\, wr(k-1)\, vr(k-1) + \ldots\ldots + c_{nw}\, wr(k-n_w)\, vr(k-n_w) + d_0\, ws(k)\, vs(k) + d_1\, ws(k-1)\, vs(k-1) + \ldots\ldots + d_{nw}\, ws(k-n_w)\, vs(k-n_w) + \xi_w(k) \qquad (13)$$

where

n_t and n_w are the order of models (12) and (13), respectively.

dt and dw are the time delay for temperature and humidity respectively.

ts(k), ws(k) and vs(k) are measured supply air temperature, humidity and volume (or supply fan speed), respectively.

tr(k) and wr(k) are measured return air temperature, humidity, respectively.

$\xi_t(k)$ and $\xi_d(k)$ are the mode disturbances.

$[a_0 \ a_1 \ \ldots\ldots a_{nt}]$, $[b_0 \ b_1 \ \ldots\ldots b_{nt}]$, $[c_0 \ c_1 \ldots\ldots c_{nw}]$, $[d_0 \ d_1 \ldots\ldots d_{nw}]$ are the model parameters.

For a constant air volume system, models (12) and (13) can be written as

$$tr(k + dt) = a_0\, tr(k) + a_1\, tr(k-1) + \ldots\ldots + a_n\, tr(k-n_t) + \\ + b_0\, ts(k) + b_1\, ts(k-1) + \ldots\ldots + b_n\, ts(k-nt) + \xi_t(k) \qquad (12')$$

$$wr(K + dw) = c_0\, wr(k) + c_1\, wr(k-1) + \ldots\ldots + c_n\, wr(k-n_w) + \\ + d_0\, ws(k) + d_1\, ws(k-1) + \ldots\ldots + d_n\, ws(k-n_w) + \xi_w(k) \qquad (13')$$

The model order, delay and parameters can be identified using various model identification techniques. The model parameters can be estimated on line using measured data, therefore the models can be adaptive.

Supply temperature/humidity setpoint are determined as follows:

$$Ts(k) = [TN - (\hat{a}_0\, tr(k)\, vr(k) + \hat{a}_1\, tr(k-1)\, vr(k-1) + \ldots\ldots + \\ \hat{a}_{nt}\, tr(k-nt)\, vr(k-nt) + \hat{b}_1\, ts(k-1)\, vs(k-1) + \ldots\ldots +$$

$\hat{b}_{nt}$ ts(k-nt) vs(k-nt))] $/\hat{b}_o$ /vs(k)

(14)

$$Ws(k) = [WN - (\hat{c}_0\, wr(k)\, vr(k) + \hat{c}_1\, wr(k-1)\, vr(k-1) + \ldots\ldots + \hat{c}_{nt}\, wr(k-nt)\, vr(k-nt) + \hat{d}_1\, ws(k-1)\, vs(k-1) + \ldots\ldots + \hat{d}_{nw}\, ws(k-nw)\, vs(k-nw))] / \hat{d}_o / vs(k)$$

(15)

Steady state prediction of supply temperature/humidity are determined as follows:

$$Tss = \frac{TN\ [\ 1 - \hat{a}_o - \hat{a}_1 - \ldots\ldots - \hat{a}_{nt}\ ]}{\hat{b}_o + \hat{b}_1 + \ldots\ldots + \hat{b}_{nw}}\ \frac{Vrs}{Vss} \quad (16)$$

$$Wss = \frac{WN\ [\ 1 - \hat{c}_o - \hat{c}_1 - \ldots\ldots - \hat{c}_{nt}\ ]}{\hat{d}_o + \hat{d}_1 + \ldots\ldots + \hat{d}_{nw}}\ \frac{Vrs}{Vss} \quad (17)$$

where $\hat{a}_o$ $\hat{a}_1$.....$\hat{a}_{nt}$ ......$\hat{d}_o$ $\hat{d}_1$......$\hat{d}_{nw}$ are the estimated values of the model parameters.

7.3 Intelligent Controller

In IICF (cf Figure 18), with the operating mode changing, the air handling equipment has to be changed correspondingly, therefore the process control is non-linear and non-continuous. The current existing control design methods have some limitations for this type of process control, which mainly arises from a mathematical modeling approach.

A shortfall of the conventional approach is that the control design relies upon subprocess control designed independently. Since independently controlled subsystems are interconnected through internal mass and/or energy flows in the processes, there is no guarantee that the overall system will remain stable. Furthermore, in the sense of optimum, even though all individual subsystems work at optimal status, the overall system may not be optimum due to the interconnection among subsystems.

Compared with a conventional approach, an intelligent control system design shows the following features:

1. Looking at the whole system, integrating industrial process knowledge, operator's empirical knowledge and existing control theory.
2. Using heuristics.
3. Combining numerical computation and symbolic reasoning.

Expert system methodology has been introduced into intelligent controller design (Porter et al., 1987; Astrom and Hagglund, 1984; Astrom et al., 1986, 1989).

As discussed in the previous chapters, to achieve the energy conservation operations and improve IAQ, HVAC processes must change the operating mode according to the recommendations of the online ESOP and CRS. An ordinary PID controller is not suitable to the HVAC operating mode switching because the controller parameters may need to be adjusted due to the changes in the operating mode. The process knowledge and heuristics need to be applied in the control system. Therefore, an intelligent controller with robust and adeptness is considered in the IICF.

NOTATIONS ABOUT DESIGN

In existing control theory, process knowledge is represented as a signal and mathematical model, but some specific physical characteristics of the process cannot be described in control system design. Since any industrial process is actually composed of subprocess interconnected through internal mass/energy flows, the task of a process control is to control the "inflow" or "outflow" of mass/energy of the plant to balance the "outflow" or "inflow" among the subprocess at the setpoint. The conventional control block diagram is modified and some new process knowledge is defined for the control block diagram. A single loop control system is shown in Figure 1S.

The system hardware blocks are:

(1) Plant 1 : controlled process,

(2) Plant 2 : controlling equipment,

(3) Actuator,

(4) Measuring devices, and

(5) Controller.

The system signals are Ysp, e(k), u(k) and y(k), which represent system setpoint, error, input and output,

where

N(k) and **d**(k) are measuring system noise and disturbances.

M is defined as "inflow" of mass and/or energy to the controlled process (plant 1) from the controlling equipment (plant 2).

Z is defined as "outflow" (or "consuming") of mass/energy in the controlled process (plant 1).

The controlled process is classified as overdamped, underdamped, non-minimum phase and non-self-balancing system (i.e., open loop integrator), and the process open loop step response is shown in Figure 20. Most air handling processes are overdamped systems.

DESIGN OF INTELLIGENT CONTROLLER

Combining decision making with control algorithms by integrating process knowledge, operation expertise and control techniques, enables one to handle more complex problems.

Knowledge-base for selecting control law: A key issue in designing a control system is the choice of a suitable control law. This knowledge base provides a decision support to choose a suitable control law for different processes and actuators. The procedure for choosing a suitable control law includes three steps:

(i) Based on the process pattern, select a control algorithm.

(ii) Based on the actuator type and (i), choose a control algorithm which can be executed by the actuator.

(iii) Based on the process dynamic conditions, select the switch point.

The hierarchy of the decision search tree is demonstrated in Figure 21.

When the system error is larger than 3ε (ε is a switching parameter in the decision rule base, namely the tuning key), the decision-maker switches from PID control to bang-bang control. The ε is not only used for switching control algorithms, but also plays an important role in the controller tuning. The starting value of ε may be an acceptable error in a control system.

The effect of the tuning key ε is shown in Figure 22.

Tuning rule base: Tuning rules perform two functions:
(1) provide initial settings for the PID controller parameters, and
(2) on-line tuning of the PID controller parameters

For a PID controller:

$$u(k) = Kp * e(k) + Ki * \sum_{i=k0}^{k} e(i) + Kd * [e(k) - e(k-1)] \qquad (18)$$

Tuning rule for proportional gain Kp: In industrial process design, the demand for accuracy is so governed that the output should be controlled at the set point within an acceptable error, ε, that is, for

$$y(t) = Ysp \pm \varepsilon$$

$$Kp = \frac{(Umax - Umin)\ x\%}{\varepsilon} \qquad 0 < x < 100 \qquad (19)$$

Equation (19) means that when the system output moves across a setpoint with an error $e(k)$ ($|e(k)| \le \varepsilon$), the actuator output signal is x% of the full range. i.e., $\frac{e(k)}{\varepsilon} = \frac{x}{U_{max} - U_{min}}$, x usually is 10%.

Tuning rule for integral gain Ki: The integral term can be considered as the steady-state input. When a control system is at steady-state,

$$Ki = Usp \Big/ \sum_{ko}^{k1} e(k) \tag{20}$$

Where Usp = Ysp/K, K is the static gain of the process. The Usp can be acquired by experiences or estimated.

Tuning rule for derivative gain Kd: The rule to tune derivative gain is to decrease the response rate of the system. For the processes with low gain and large time constant, derivative action is of little use. For other systems, the Ziegler-Nichols tuning rule Td = Ti/4 [Ziegler and Nichols, 1942], therefore

$$Kd = Kp^2 / 4Ki \tag{21}$$

Those tuning rules are easy to apply for the selection of the initial PID parameters . For example, as shown in Figure 22, choosing ko when $|e(k)| = 5\varepsilon$, and choosing k_1 when $|e(k)| = 3\varepsilon$, then the parameters of PID controller are automatically set. The ko is the time of starting the integration of the PID controller, while the k_1 is the time of stopping the integration.

On-line self-adjusting Kp, Ki, Kd : This controller has two features, that is, an automatic switching control algorithm from bang-bang control to PID, and directly tuning PID parameters by adjusting ε. Figure 22 shows the affects of different ε on a step response. K2 is the time when process output first reaches the set point.

Criteria for adjusting ε: Driving the process output y(k) to the setpoint Ysp from an initial state y_0 with maximum speed and no overshoot.

SYSTEM BEHAVIOR AND SIMULATION RESULTS

For convenience, a water-tank control system is selected for the simulation case study, as shown in Figure 23. The output is level-tank-1, the input is valve 1-position. The inflow of tank-1 is from pump-2, and the outflow goes to tank-2. The time delay from the input to the output is 5 seconds. A random noise with a variance of 0.5 is added to simulate the noise in the level measurement. The simulation results obtained from this water-tank control system should be applicable to air handling processes.

Step response The response to the step change of the setpoint tank-level-1 is shown in Figure 24.1, The responses of input (control action), tuning key ε, and controller parameters K_p and K_I are also demonstrated in Figure 24.1. In the starting period, the controller is switched to bang-bang control. When the output is near the new setpoint, the controller is switched back to the PI controller. The integral and proportional parameters are adjusted on-line using these tuning rules. It can be seen that for a negative approach to the step change, though the outflow capacity of the water-tank is quite low, and the system is under saturated state, the intelligent controller drives the output to the new setpoint with maximum speed subject to the system capacity, and no overshoot. It shows that the controller handles the nonlinear saturated control very well. For conventional PID control, overshoot of output would be unavoidable.

Decoupling As shown in Figure 23, the tank-1 level and tank-2 level are coupled. Adding such an intelligent controller to control level-tank-2, the control of the two tank levels is ideally decoupled. Figure 24.2 shows the step response performances of two such intelligent controllers for the water-tank control system. The simulation results are for the ideal conditions, i.e., the ideal tuned controller for conditions of no time delay and measurement noise.

Disturbance rejection The disturbance rejection capability of the intelligent controller is shown in Figure 24.3. A step disturbance is introduced into the control system by turning off pump-2. The controller shows a good rejection to the step disturbance in inlet flow to the tank.

Non-minimum-phase system control

Changing the knowledge base of the water-tank to behave like a non-minimum-phase system, the open loop test is similar to the non-minimum-phase pattern shown in Figure 20. Applying the controller to this non-minimum phase system, a series of step responses is demonstrated in Figure 24.4. The tuning process no longer resulted in overdamped system behavior, but the performance is still satisfactory.

In summary, the simulations of the water-tank control system shown in Figure 24.1-4 indicate the excellent performance of this intelligent controller. Further discussions about this controller are given as follows:

(1) *the output of control system never diverges out of a shell.*

The controller is configured as a bang-bang self-adjusting PID con' 'hen a large magnitude error appears, the bang-bang controller ' drives the output to the set-point. In the case of the out, close to the set-point, the self-adjusting PID controller gently drives the system to the set-point. As bang-bang control is applied, the system output is constrained. Under any circumstances, the output y(t) is governed by

$$Y_{sp} - (3\varepsilon + \Delta) < y < Y_{sp} + (3\varepsilon + \Delta) \quad (22)$$

where Δ = (time delay) × (error rate). $Y_{sp} \pm (3\ \varepsilon + \Delta)$ can be considered as a shell, and the output does not diverge out of the shell.

For a first order system

$$\frac{y(s)}{u(s)} = \frac{k\, e^{-\tau s}}{1+T_1 s} \quad (23)$$

$$Y_{sp} - 3\varepsilon - \tau \cdot k/T_1 < y < Y_{sp} + 3\varepsilon + \tau \cdot k/T_1 \quad (24)$$

For a second order system

$$\frac{y(s)}{u(s)} = \frac{k\, e^{-\tau s}}{(1+T_1 s)(1+T_2 s)} \tag{25}$$

$$Y_{sp} - 3\varepsilon - \tau \cdot k/(T_1-T_2) < y < Y_{sp} + 3\varepsilon + \tau \cdot k/(T_1-T_2) \tag{26}$$

In industrial process, equation (22) is very significant, which guarantees that the output is within a certain range under any circumstances. The limit for minimum and maximum value of ε may determine the shell size.

(2) *the system behaves robustness and adaptability.*

As shown by the simulation results presented in Figure 24.1 to 24.4, when the system structure or parameters changed, such as disconnecting tank-2, turning off or on the pump, and changing the pump outflow, the control system keeps good performance. The controller is quite robust. As the controller combines both the bang-bang control and the PID control, the switch point and PID parameters are tuned on-line by the expertise rules. The controller is adaptable to process changes.

(3) *little a prior information is needed for the controller design.*

The only prior information needed is process pattern, actuator type and "outflow" Zsp or steady input Usp, which are easy to obtain. Furthermore, any time delay mismatch, does not affect the control performance.

(4) *satisfactory performance for controlling non-minimum-phase system*

For a non-minimum-phase system, neither a conventional PID controller nor a self-tuning regulator can deal with it well, but the intelligent controller shows quite satisfactory results.

Air handling processes are overdamped, and the actuators consisting of switch, motor and valve. Conventional PID control algorithm with one time tuning often gives unsatisfactory performance because the air handling process characteristics change over seasons, especially when operation planning is integrated, each operating mode has its suitable PID parameters. The intelligent controller contains process knowledge, operation expertise and control techniques, and is composed of a decision-making rule base, a tuning rule base and special situation handling rule base. It combines bang-bang and PID control with adaptive strategies and on-line self-adjusted PID parameters. The simulation results show that the controller exhibits both safety robustness and adaptability, and very little a priori information is needed for the controller design. Therefore, this intelligent controller is very suitable for application to HVAC control.

7.4 Advantages of the Integrated Intelligent Control Strategy

Compared with the conventional HVAC control strategy, the proposed integrated intelligent control framework has the following advantages:

1. Indoor air quality monitoring and control are integrated in the HVAC control system. If indoor CO_2 concentration is higher than the high-limit, more fresh air is supplied to control the IAQ and a compromise solution for the conflict between energy saving and IAQ

improvement is obtained.

2. Flexible control strategy versus variable HVAC operations. Since operation planning is integrated into real time control environment, energy conservation is achieved by changing operating modes with maximum use of outside air energy over seasons.

3. Variable supply air temperature/humidity control in VAV system. The adaptive control model for supply air provides coordination for the supply temperature/humidity setpoint with the supply air volume. This coordination can be beneficial to both energy conservation and IAQ improvement in IAQ.

4. Comfort technology is integrated in the control system so unnecessary high or low temperatures can be avoided compared with the thermal-stat setting of of indoor temperature using a conventional control strategy.

5. Operator's valuable knowledge from their operating experience can be updated and accumulated through the IOSS.

CHAPTER 8

SUMMARY AND CONCLUSIONS

An intelligent operation support system (IOSS) and an integrated intelligent control frame (IICF) for HVAC processes have been studied. The IOSS consists of operation planning, comfort indoor setting, conflict reasoning and system introduction. An integrated distributed intelligent system is used to integrate the subsystems. The expert system for operating mode consulting (ESOP) chooses optimal energy saving operation for air handling. Comfort setting system (ICS) provides the desired room temperature setpoint. The conflict reasoning system (CRS) provides a compromise solution to the conflict between energy conservation and IAQ improvement. The system introduction provides a foundation to train HVAC operators. The IOSS functions as an off-line operation decision support or operator training system.

The integrated intelligent control framework (IICF) presents a new control strategy which integrates IOSS into a real time control environment. The IICF has an adaptive cascade control loop. In the primary loop, the adaptive control or general predict model determines the setpoint of supply air temperature/ humidity for the secondary loop, and predicts the steady state temperature and humidity of supply air for operation planning. The indoor comfort setting (ICS) provides optimal comfort temperature for the primary loop setpoint. In the secondary loop, the air handling processes are controlled by the intelligent controller to reach the supply setpoint. The intelligent controller with self-adjusting parameters enhances air handling control quality and incorporates operating mode changes recommended by the IOSS. Comparing with the conventional HVAC control systems, the IICF has advantages in improving both energy conservation and indoor air quality simultaneously.

This study paves the way for a new direction for future process operation, energy management and control in the HVAC industry. The following conclusions about IOSS and IICF are drawn:

(1) The development of the IOSS for a real world application requires knowledge from different disciplines. The meta-system provides a framework for the integration and management of this knowledge. In IOSS, four subsystems: operating mode consulting (ESOP), indoor comfort setting (ICS), conflict reasoning (CSS) and knowledge introduction, are integrated in the meta-system framework.

(2) The ESOP codifies the important expertise about the operation planning, which for the first time considers supply air parameters with complete dynamics. So it provides a real time integrated operation planning method for the HVAC process. It overcomes the disadvantages from some currently used methods, and offers better energy conservation, thermal comfort and indoor air quality than the operations based on a conventional control strategy.

(3) The indoor comfort setting system provides comfort-stat instead of temperature-stat, which offers comfort and energy saving simultaneously.

(4) Conflict reasoning gives the conflict resolution for energy conservation and indoor air quality control in HVAC processes. The IAQ operating mode is recommended when indoor CO_2 concentration is over the limit, which increases outdoor air intake If indoor CO_2 concentration is under the limit, an energy saving operating mode is in use. The mode utilizes the energy of fresh air as much as possible.

(5) The IICF proposes a strategy to integrate IOSS in a real time HVAC control system, therefore the problems related to the conventional control strategy are overcome, and IQA control are coupled energy conservation techniques. Since adaptive control techniques are used to [illegible]e supply air set point and air handling control, IICF can also [illegible]e [illegible]ter control performance compared to the conventional control strategy.

Further research on the implementation of IICF into a real HVAC plant is suggested.

Table 1 ENERGY SAVING OPERATION MODES FOR THSCD SYSTEM

actuator / mode	return air damper U1	outside air damper U2	cocling coil U3	dehumidifier U4	humidifier U5	heater U6
1	90%	10%	off	off	(D)	(T)
2	(T)	1-U1	off	off	(D)	off
3	0%	100%	(T)	off	(D)	off
4	90%	10%	(T)	off	(D)	off
5	90%	10%	(T)	(D)	off	off
6	0%	100%	(T)	(D)	off	off
7	(T)	1-U1	off	(D)	off	off
8	90%	10%	off	(D)	off	(T)
9	(D)	1-U1	off	off	off	(T)
10	(D)	1-U1	(T)	off	off	off
11	0%	100%	off	(D)	off	(T)
12	0%	100%	off	off	(D)	(T)

* (T): The equipment used to control temperature
* (D): The equipment used to control humidity

Table 2 Metabolic Rate at Different Typical Activities (Fanger, 1970)

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Table 3 Data for Different Clothing Ensembles (Fanger, 1970)

Page 85 inclusive have been removed due to copyright rest   ions.

Table 4 Conflict Analysis

HVAC Operation	Cooling/Heating STATUS	Energy Consumption	Indoor Air Quality
Outside Air Intake DECREASE	ON	DECREASE	DECREASE
	OFF	Unchange	
Outside Air Intake INCREASE	ON	INCREASE	INCREASE
	OFF	Unchange	
Ventilation Rate DECREASE		DECREASE	DECREASE
Ventilation Rate INCREASE		INCREASE	INCREASE

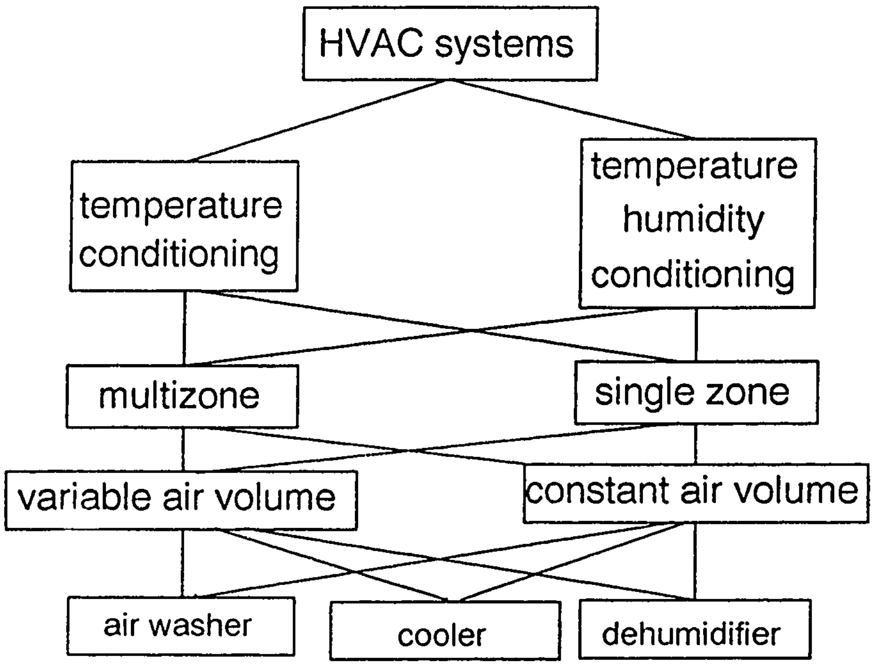


Figure 1 Structure classsification for HVAC systems

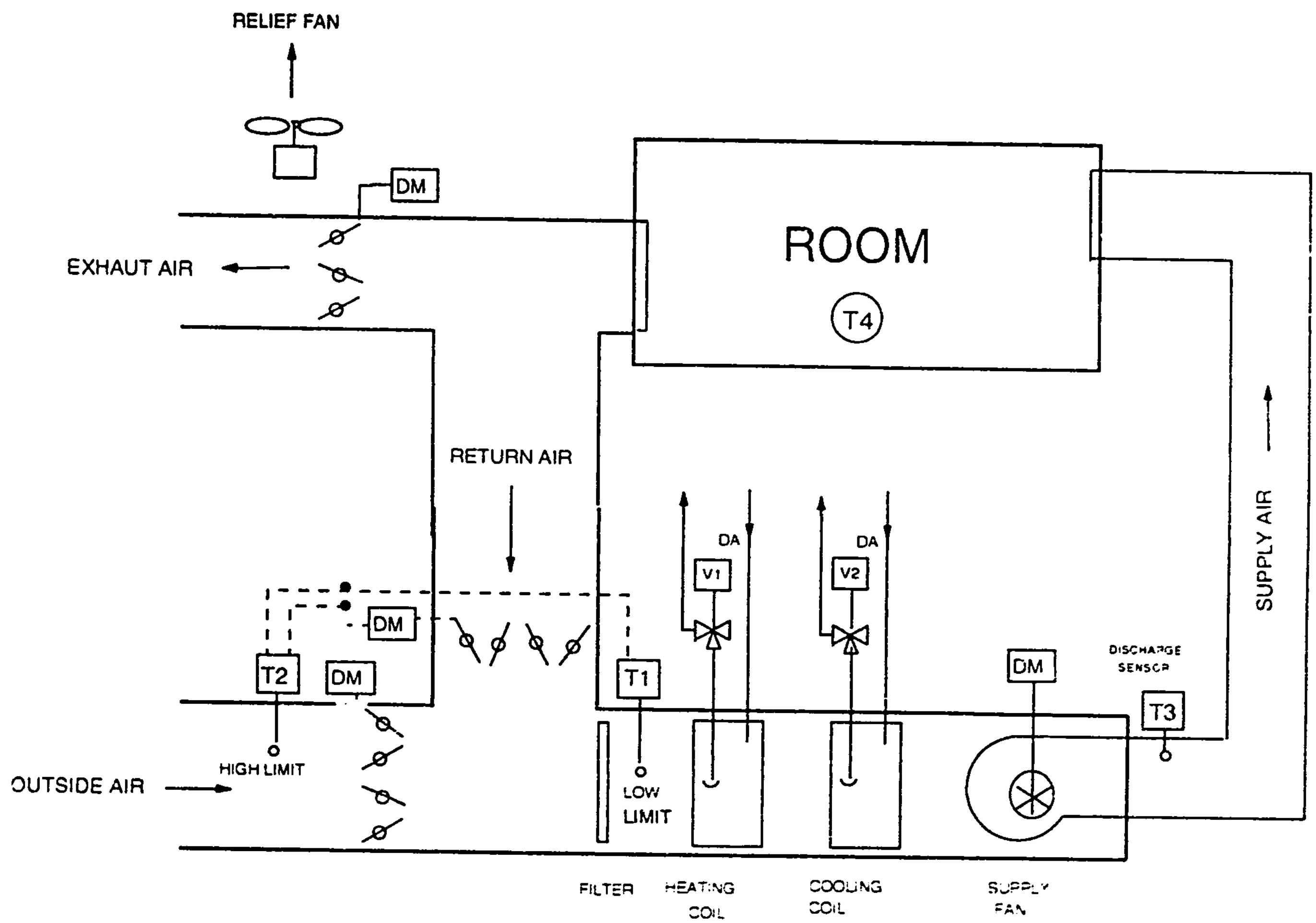


Figure 2 A scheme of a temperature-conditioning, single zone, and constant volume (TSC) system

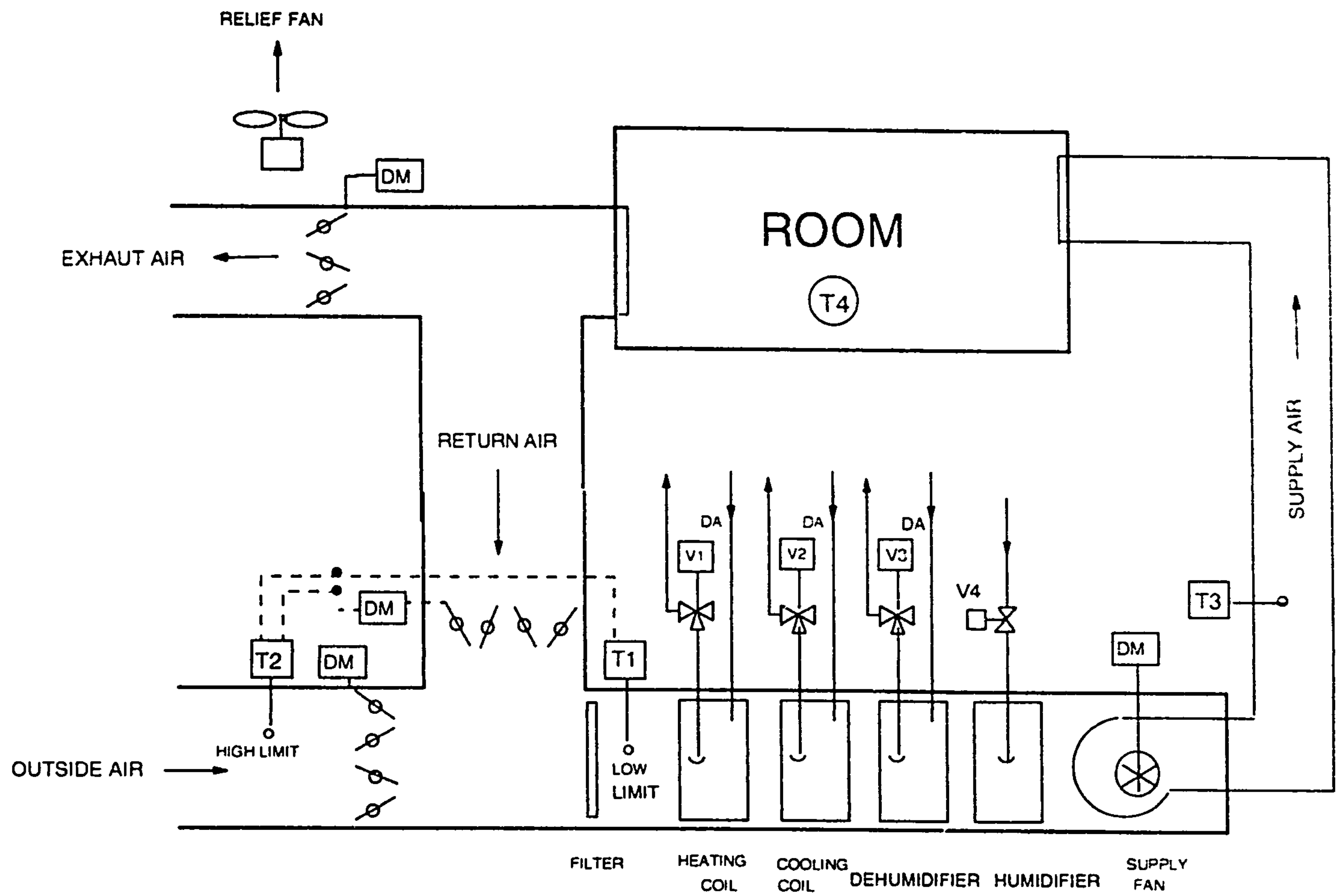


Figure 3 A scheme of temperature and humidity conditioning, single zone, and constant volume (THSCD) system

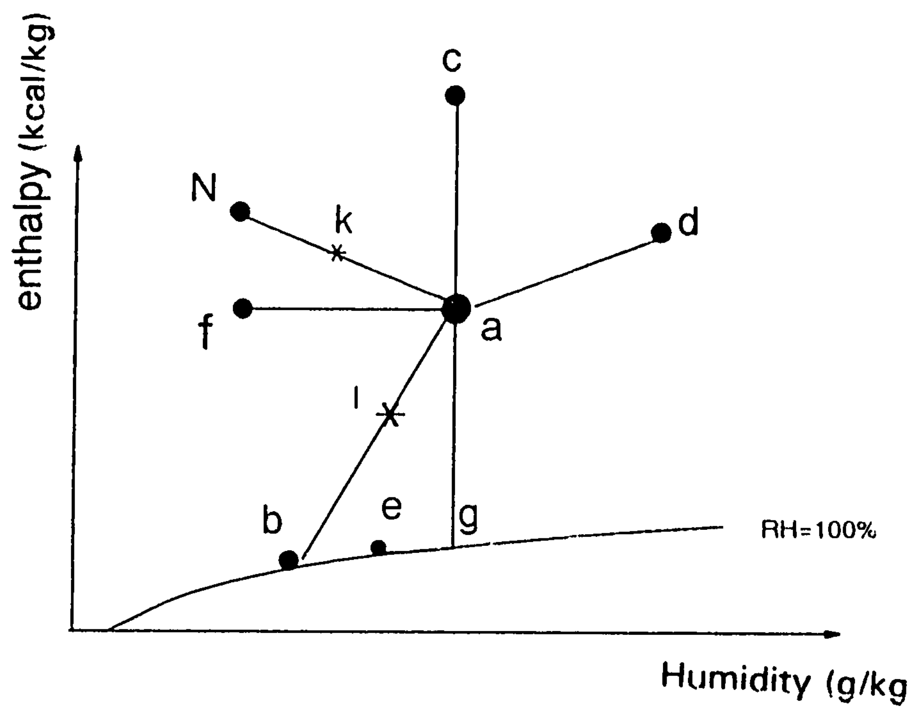


Figure 4 Air handling processes

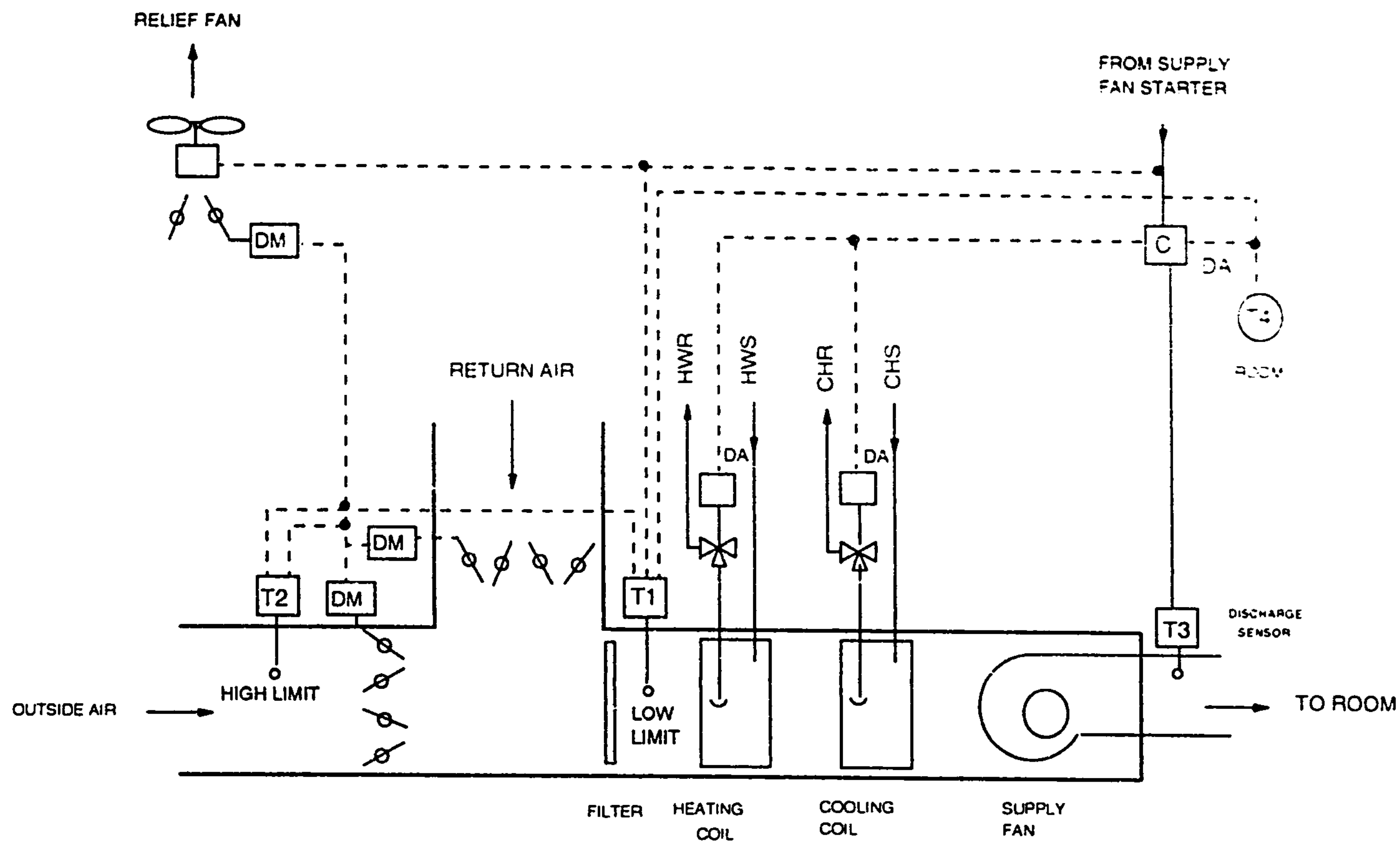


Figure 5 Control system for single zone, constant volume and temperature conditioning (TSC) AHU

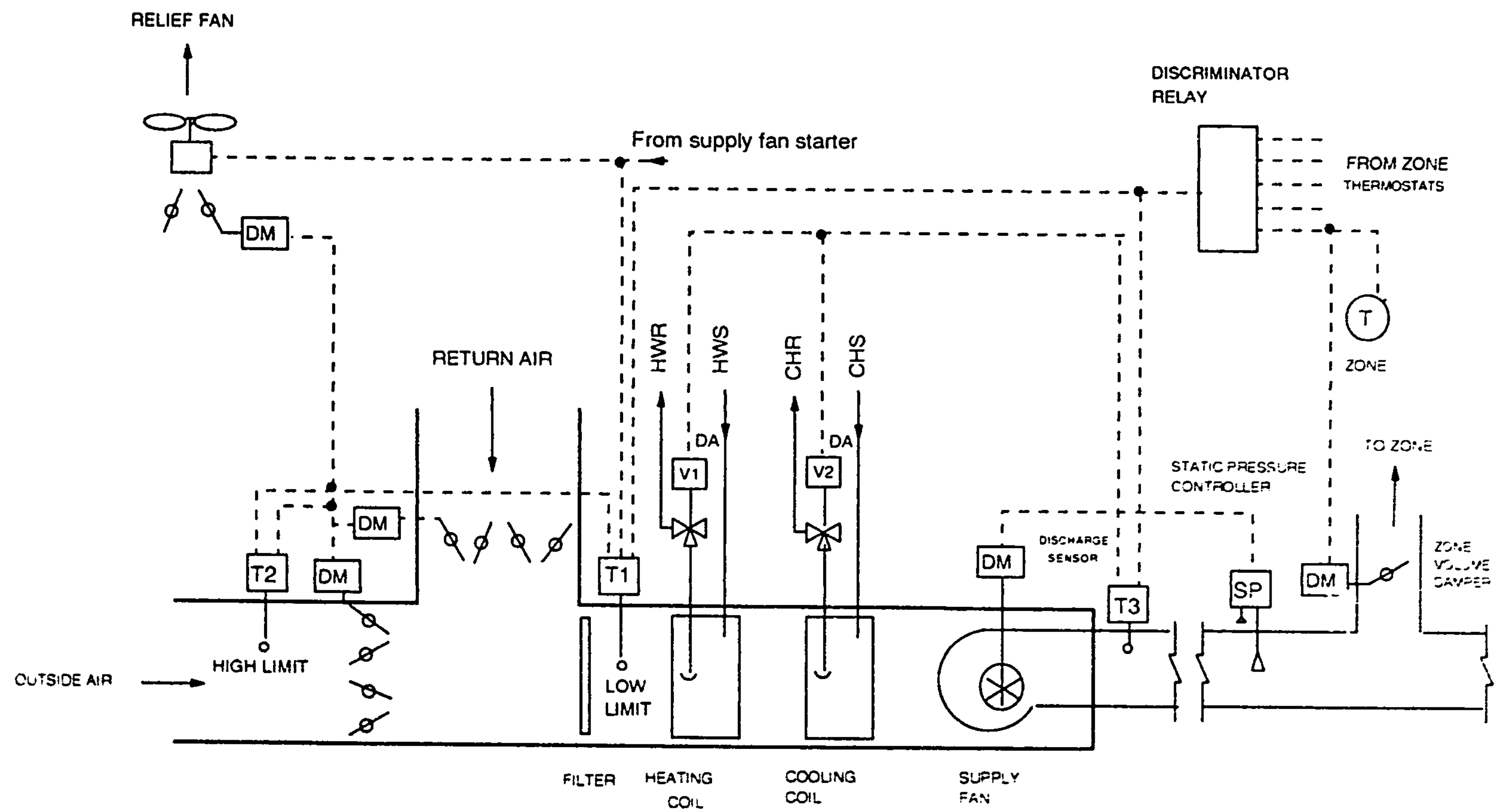


Figure 6 Control system for multizone, VAV, and temperature conditioning (TMV) AHU

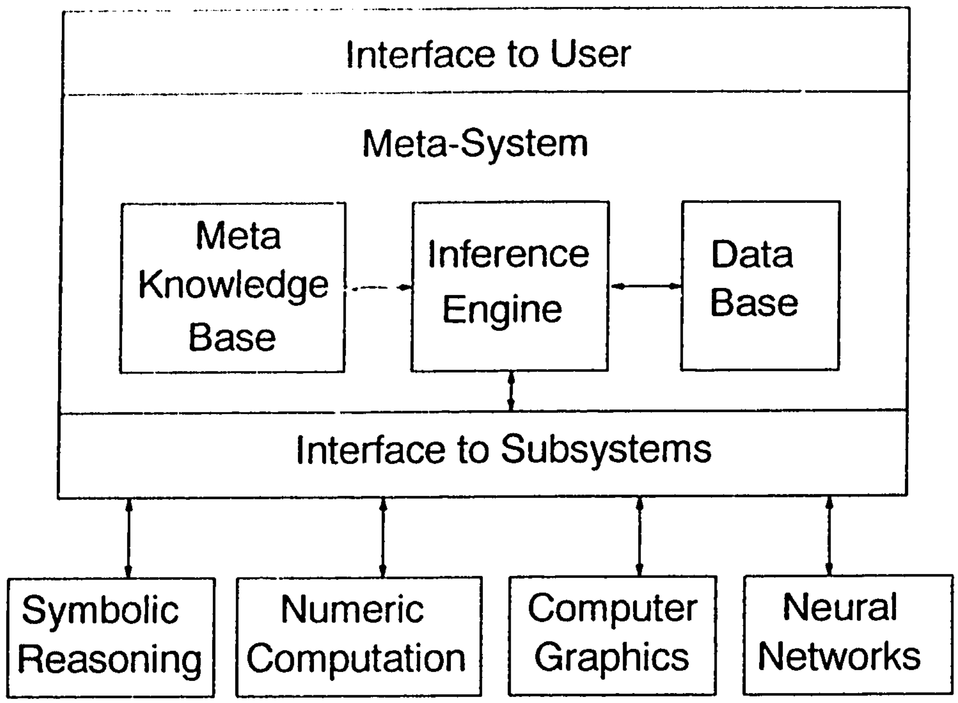


Figure 7 Integrated distributed intelligent system

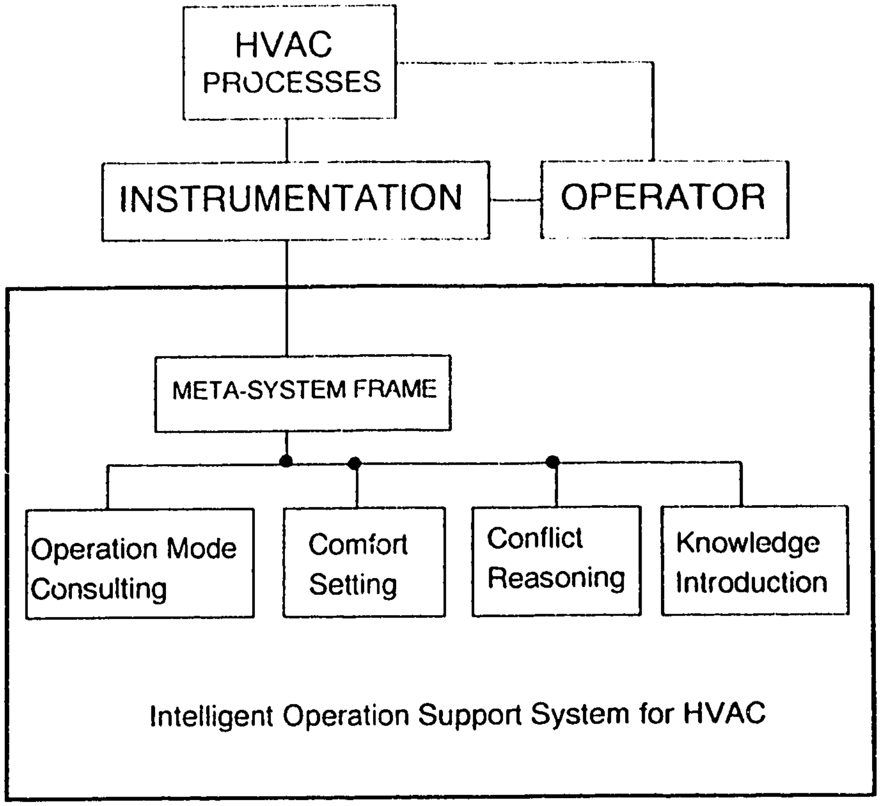


Figure 8 Integrated architechture of IOSS

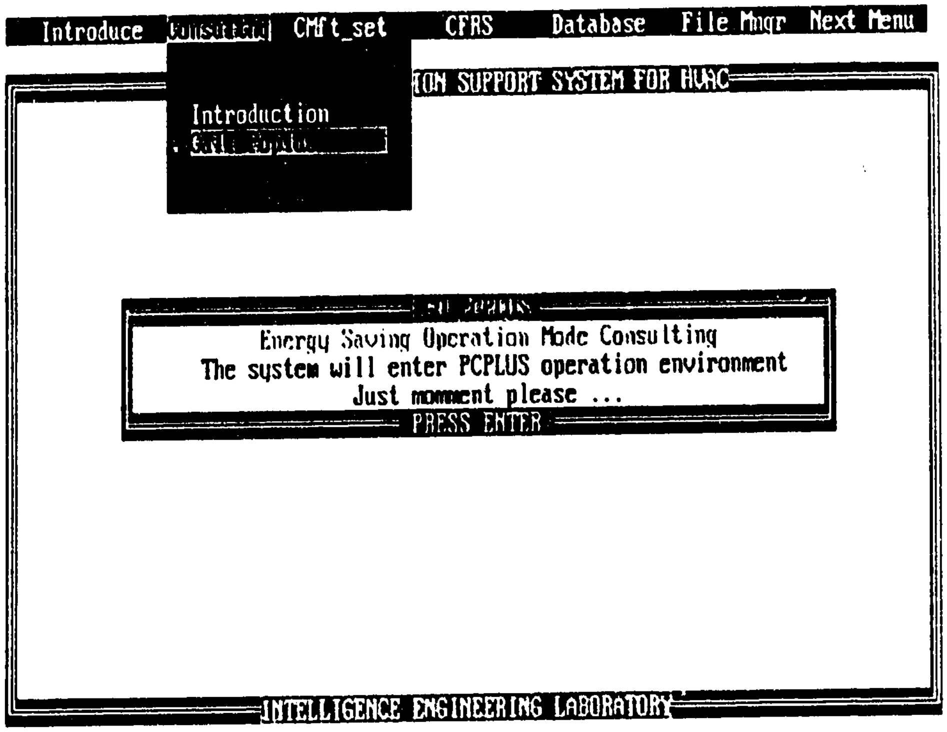


Figure 9 Software menu screen

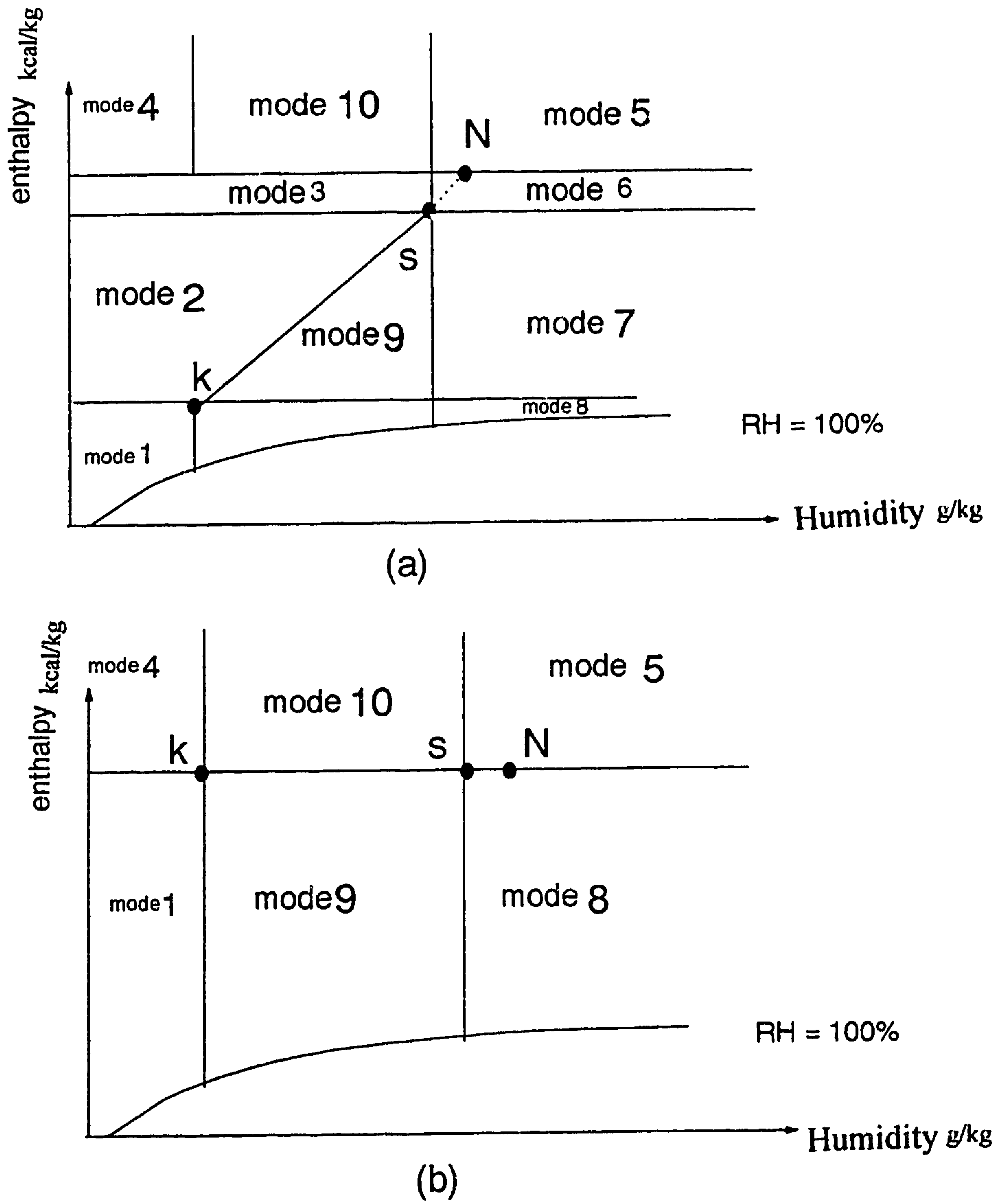
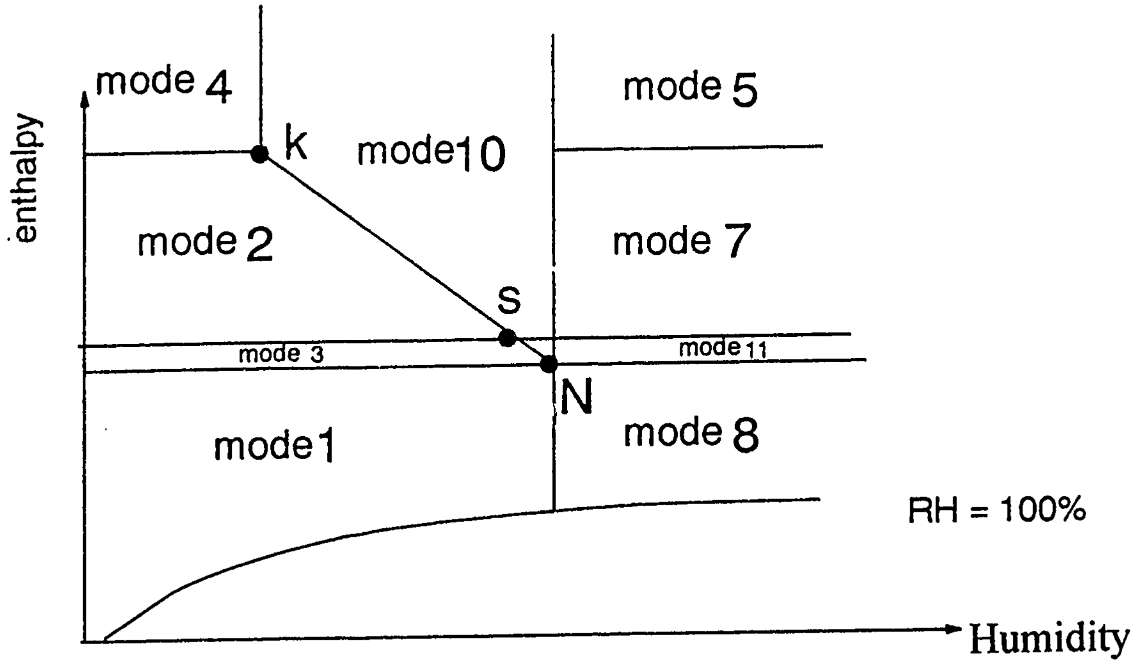
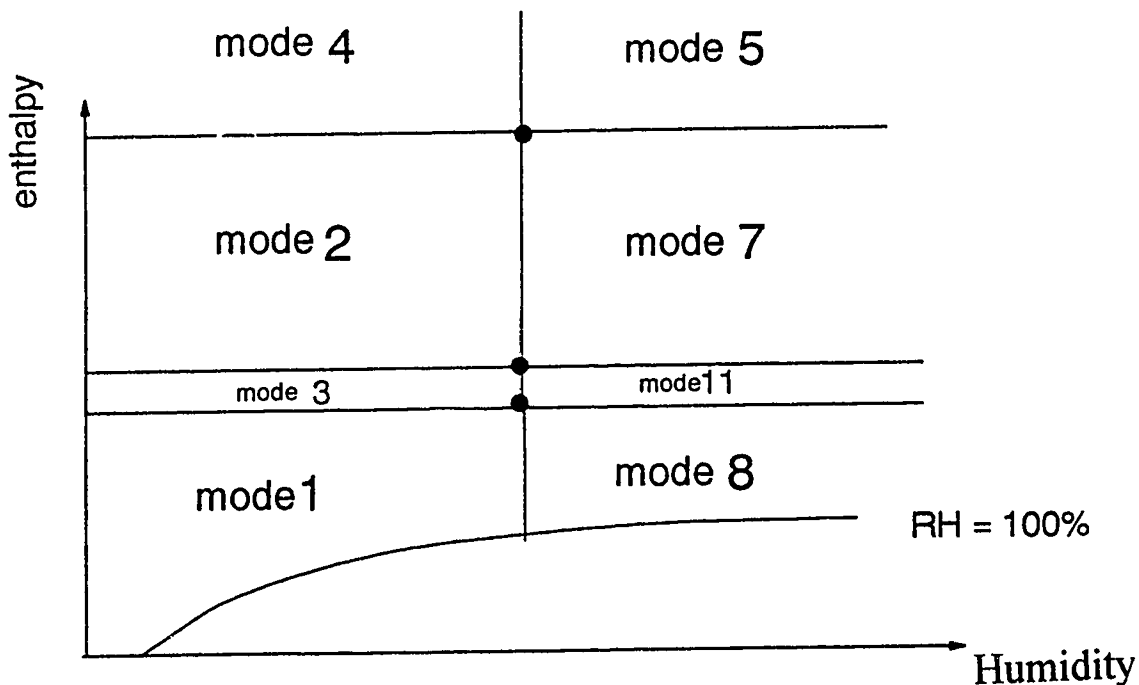


Figure 10 Energy Saving Operating Mode Identification

THSCD system



(c)



(d)

Figure 10 Energy Saving Operating Mode Identification THSCD system

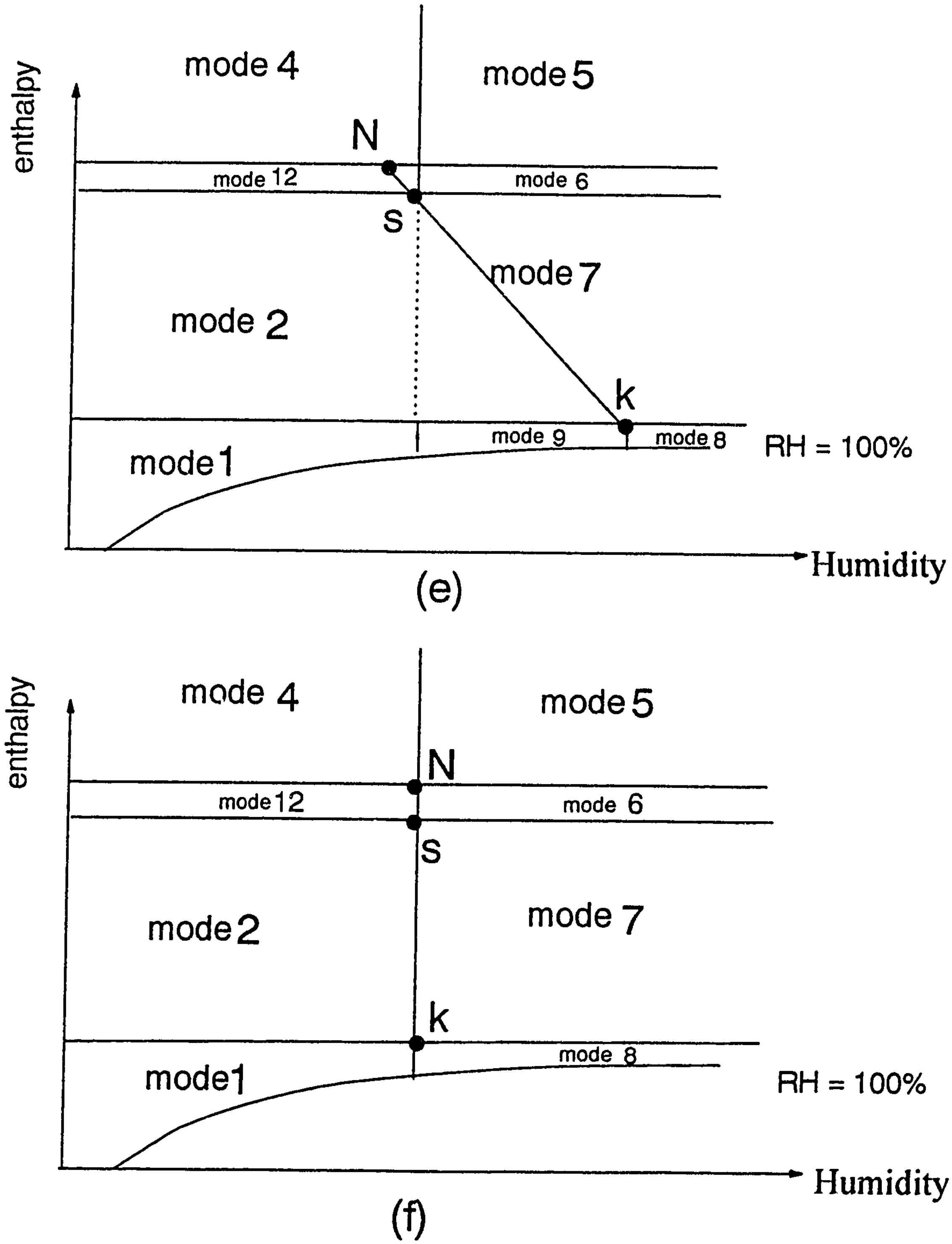
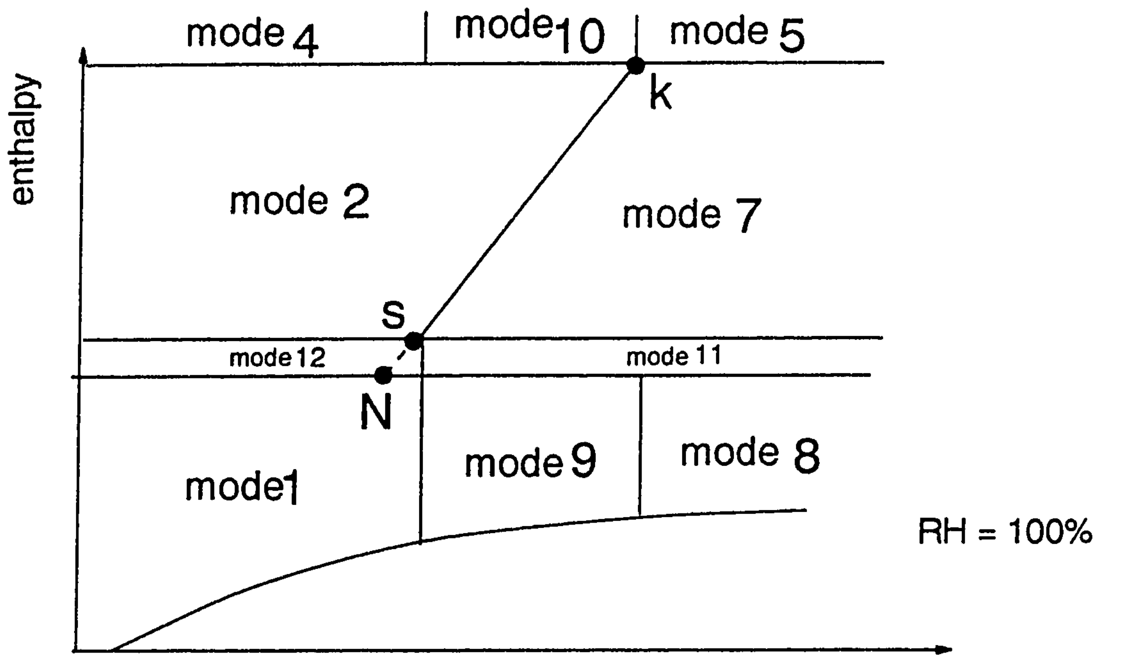
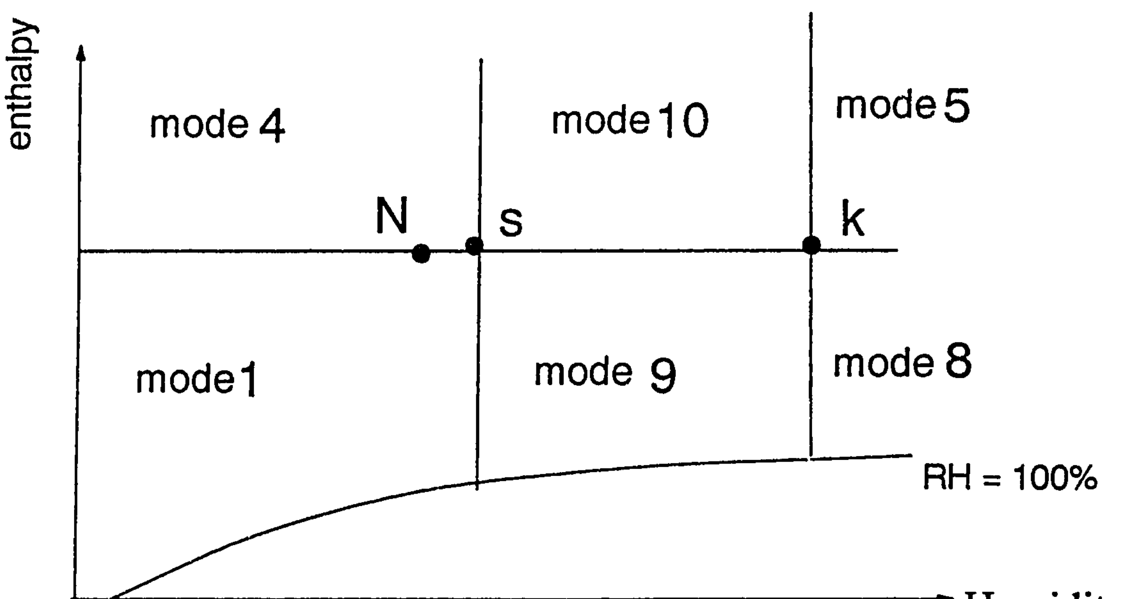


Figure 10 Energy Saving Operating Mode Identification for THSCD system



(g)



(h)

Figure 10 Energy Saving Operating Mode Identification for THSCD system

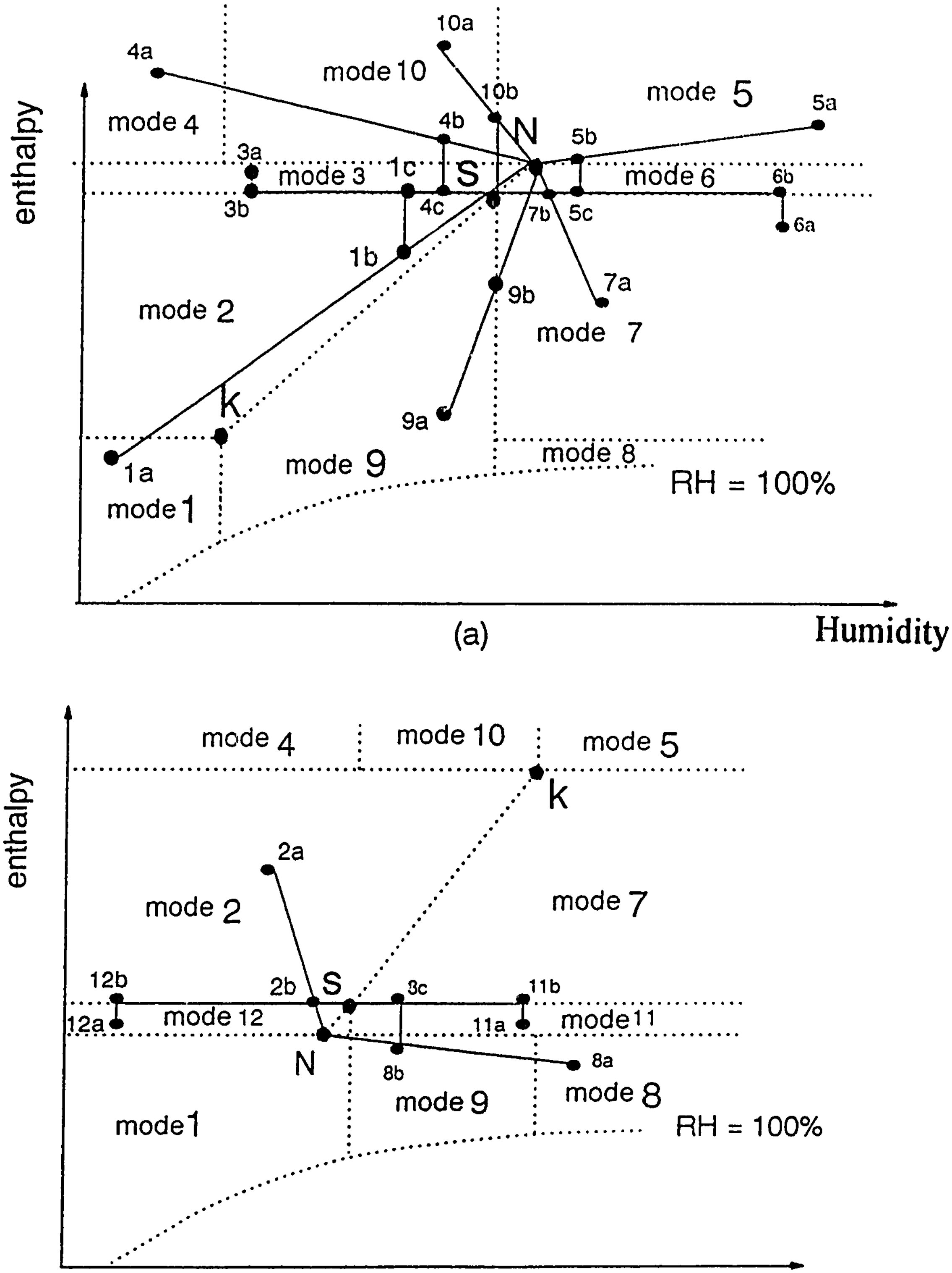


Figure 11 Air handling processes illustrations for THSCD system

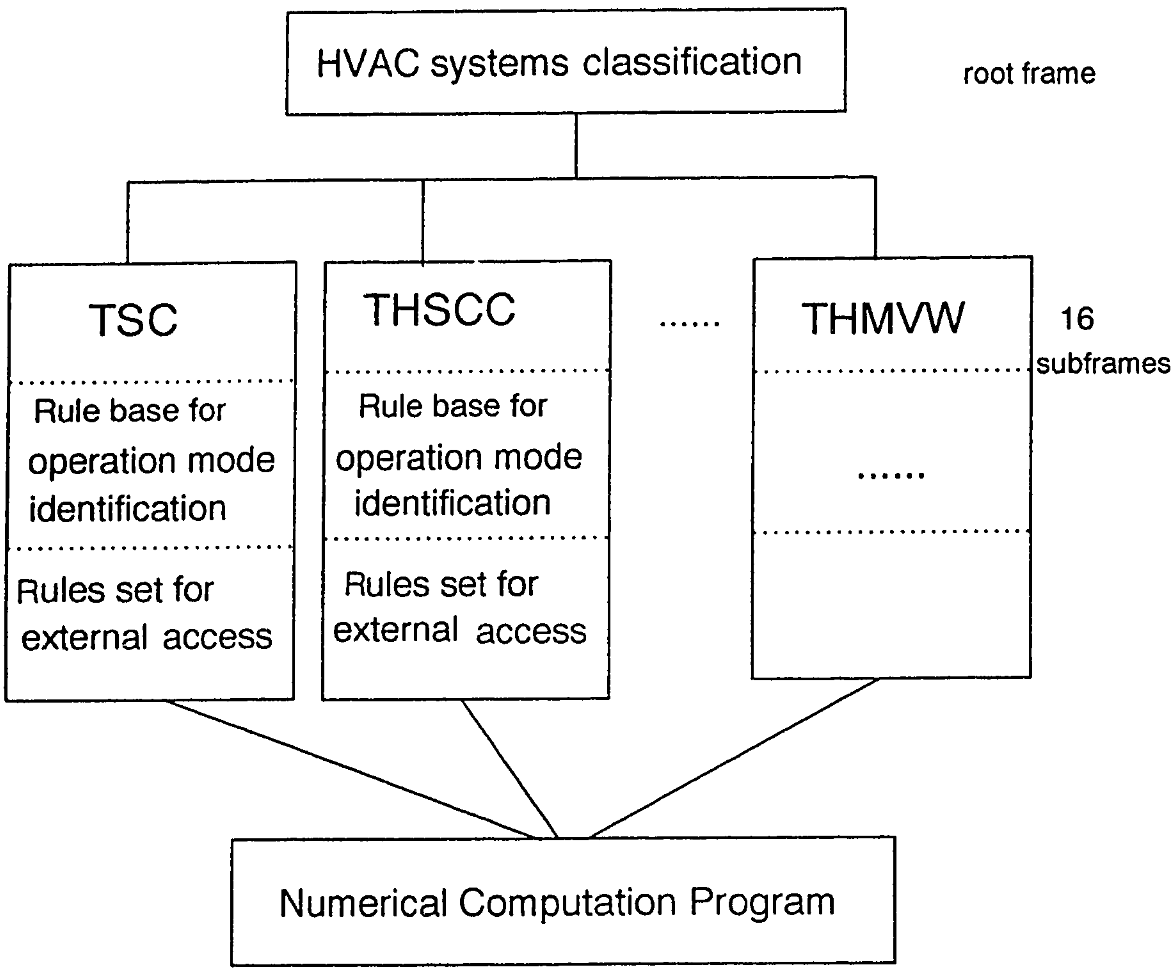


Figure 12 Frame structure of ESOP

HVAC operation planning

```
The recommended operation mode is: RETURN-AIR DOOR open 90%; FRESH-AIR DOOR
open 10%; COOLER off; HEATER used to control TEMPERATURE.
 Review:
      Yes
 ↔     ·  air conditioning type                     :: TEMPERATURE
 ↔     ·  The zone type matched your system.        :: SINGLE-ZONE
 ↔     ·  The type of air volume matched your ...   :: CONSTANT
 ↔     ·  unit system: English units and SI units   :: SI-UNITS
 ↔     ·  outdoor fresh air temperature             :: 2
 ↔     ·  expected or desired temperature in room   :: 20
 ↔     ·  two types of measurement for humidit...   :: NO
 ↔     ·  *IMPORT* :: TK1 (7.677787) TK (1.448332E-3) TS2 (23.676...

 1. Use arrow key or first letter of item to position the cursor.
 2. Select all applicable responses.
 3. After making selections, press ENTER to continue.

** End - press ENTER to continue.
```

Figure 13 A consulting example

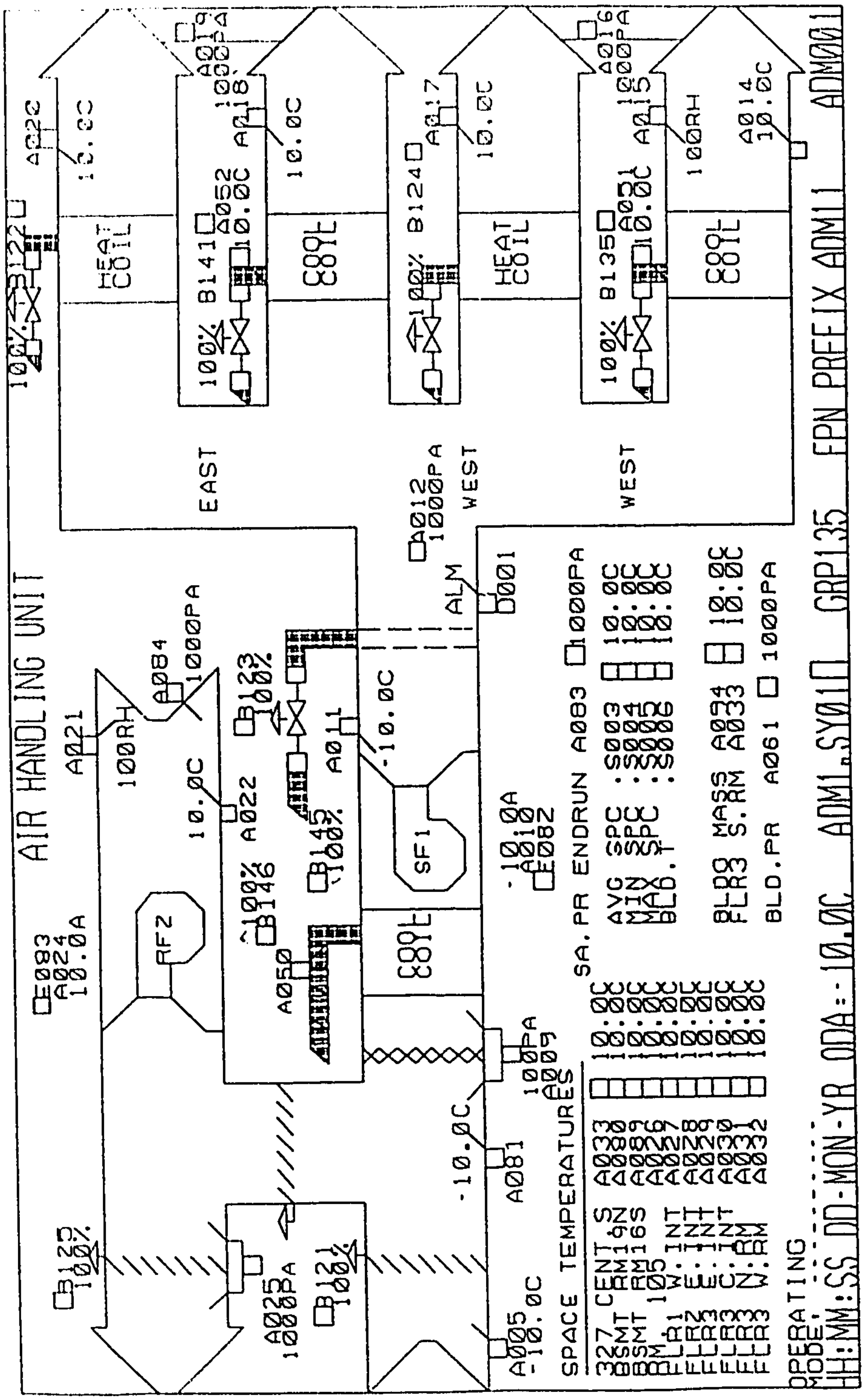


Figure 14 HVAC system of the administration building at University of Alberta

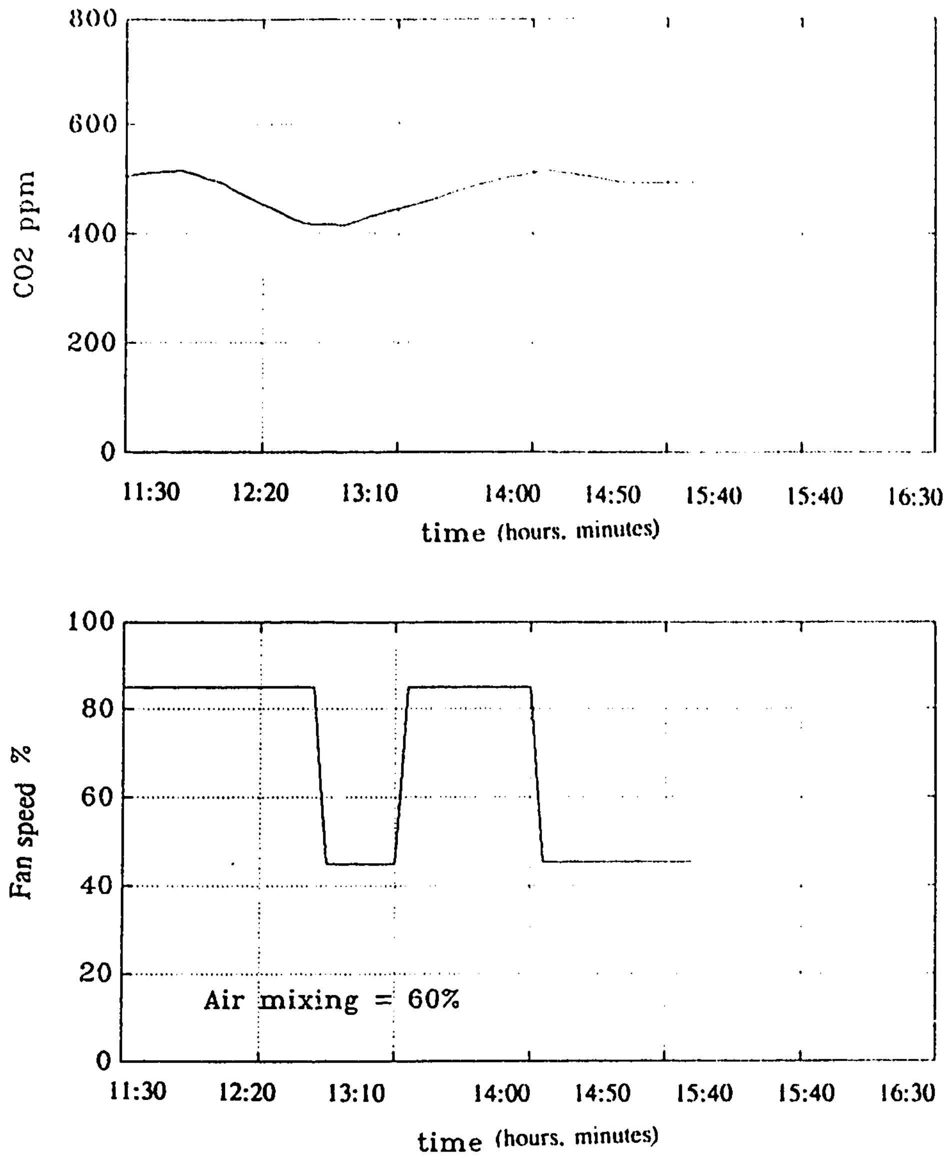


Figure 15.1 Field test 1

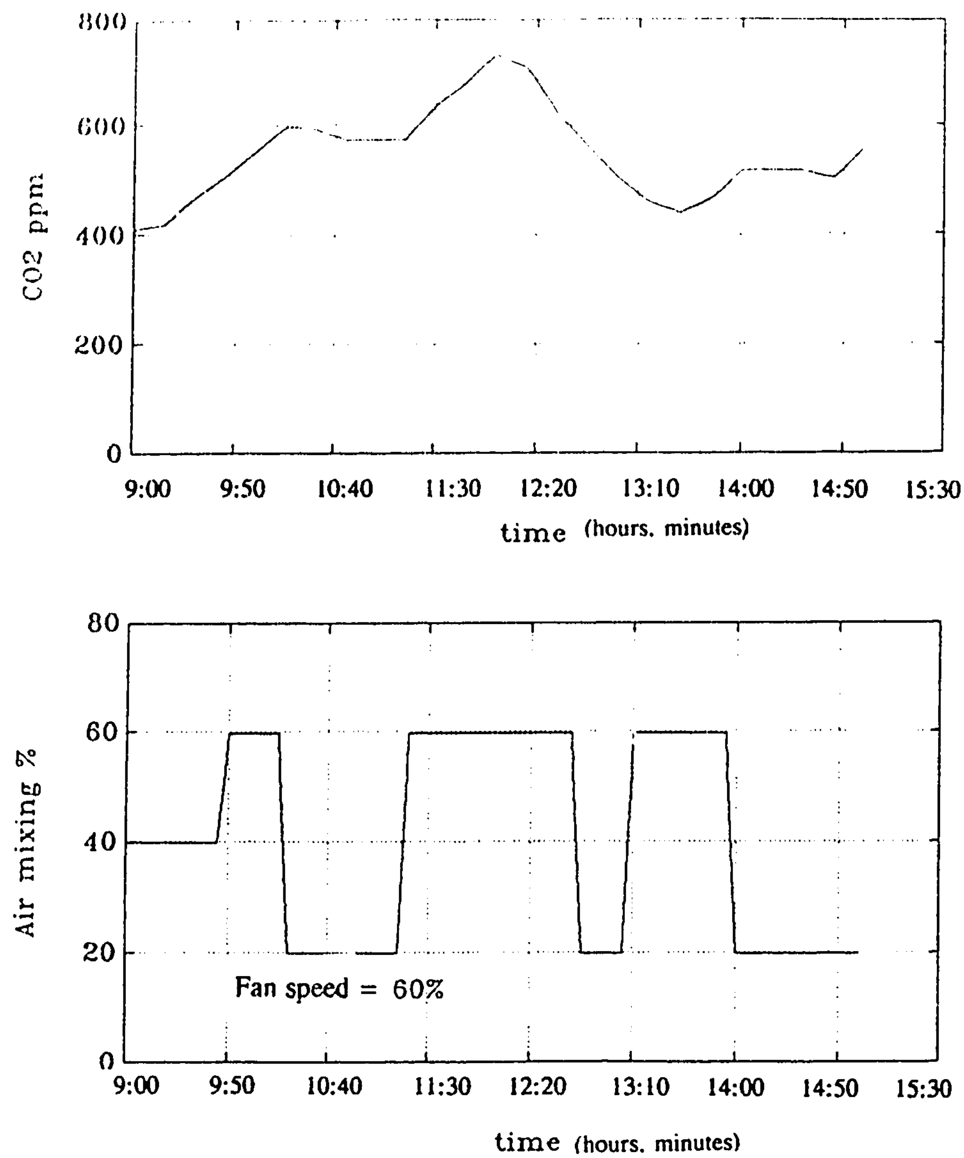


Figure 15.2 Field test 2

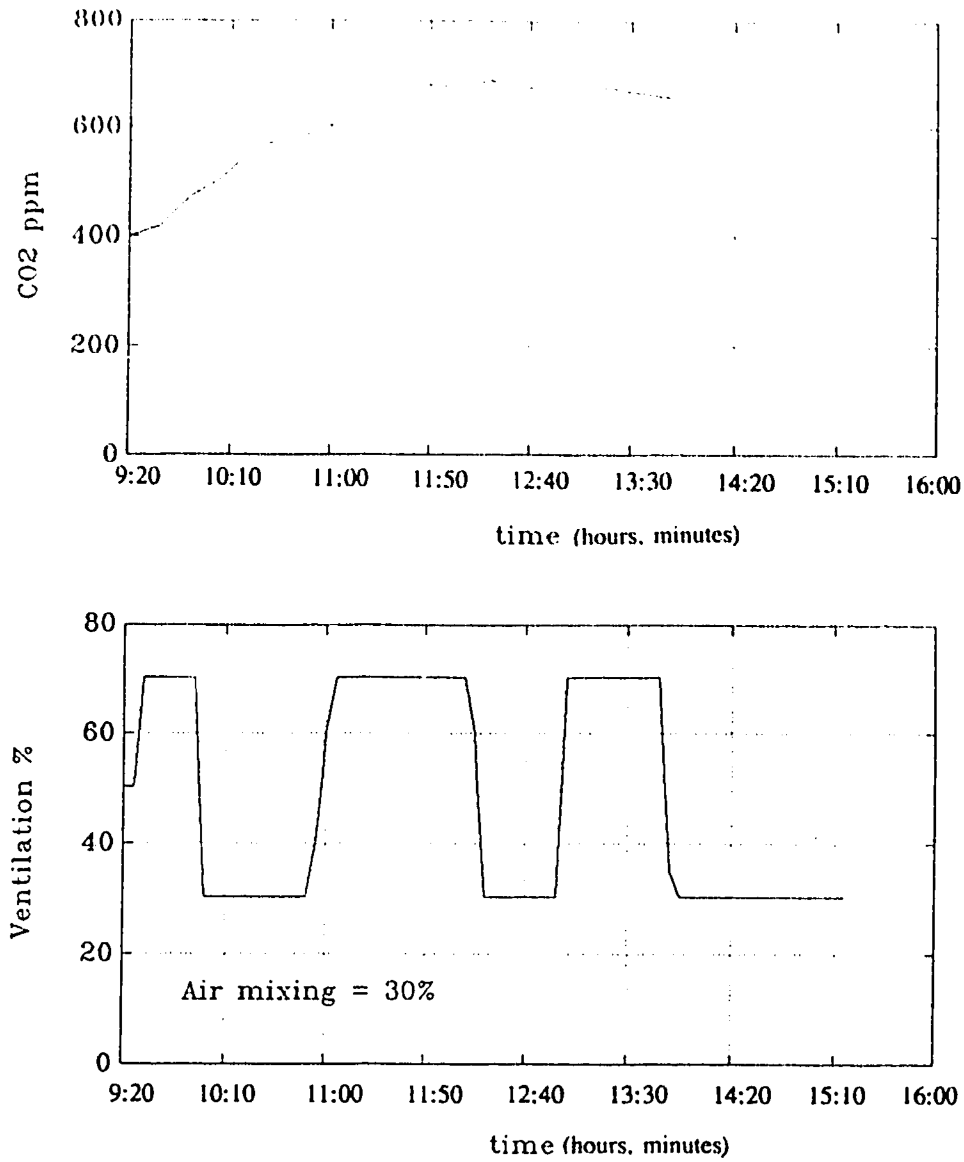


Figure 15.3 Field test 3

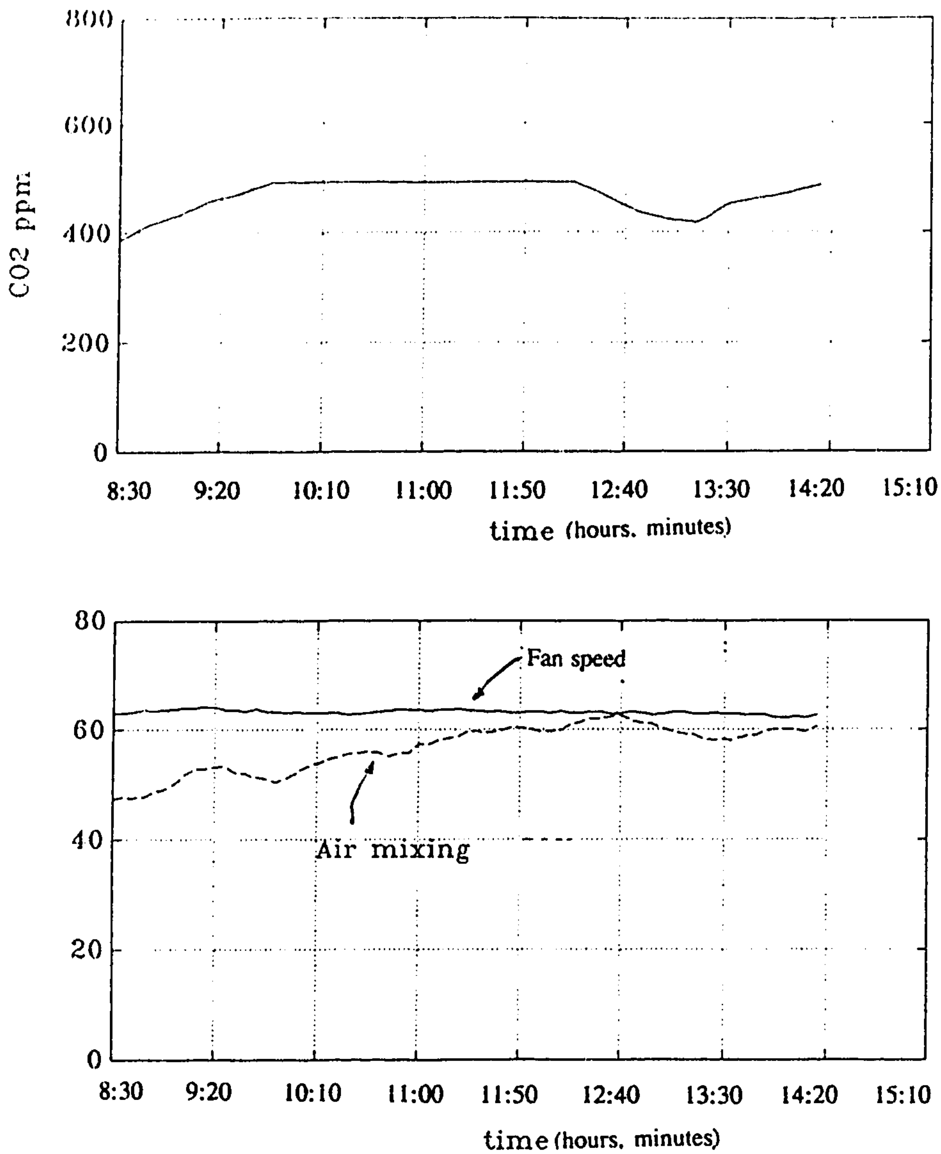


Figure 15.4 Field test 4

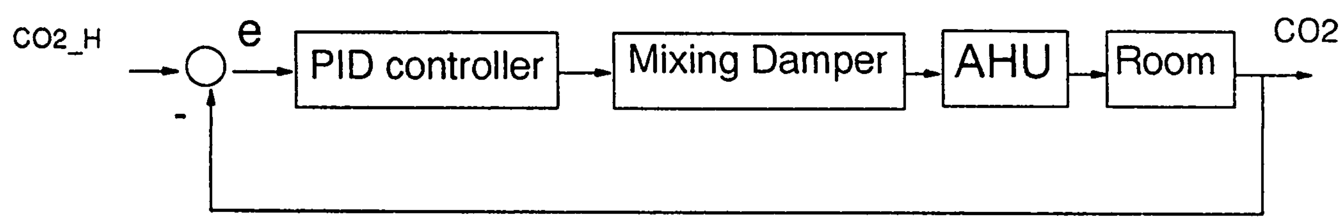


Figure 16 Indoor CO2 control loop

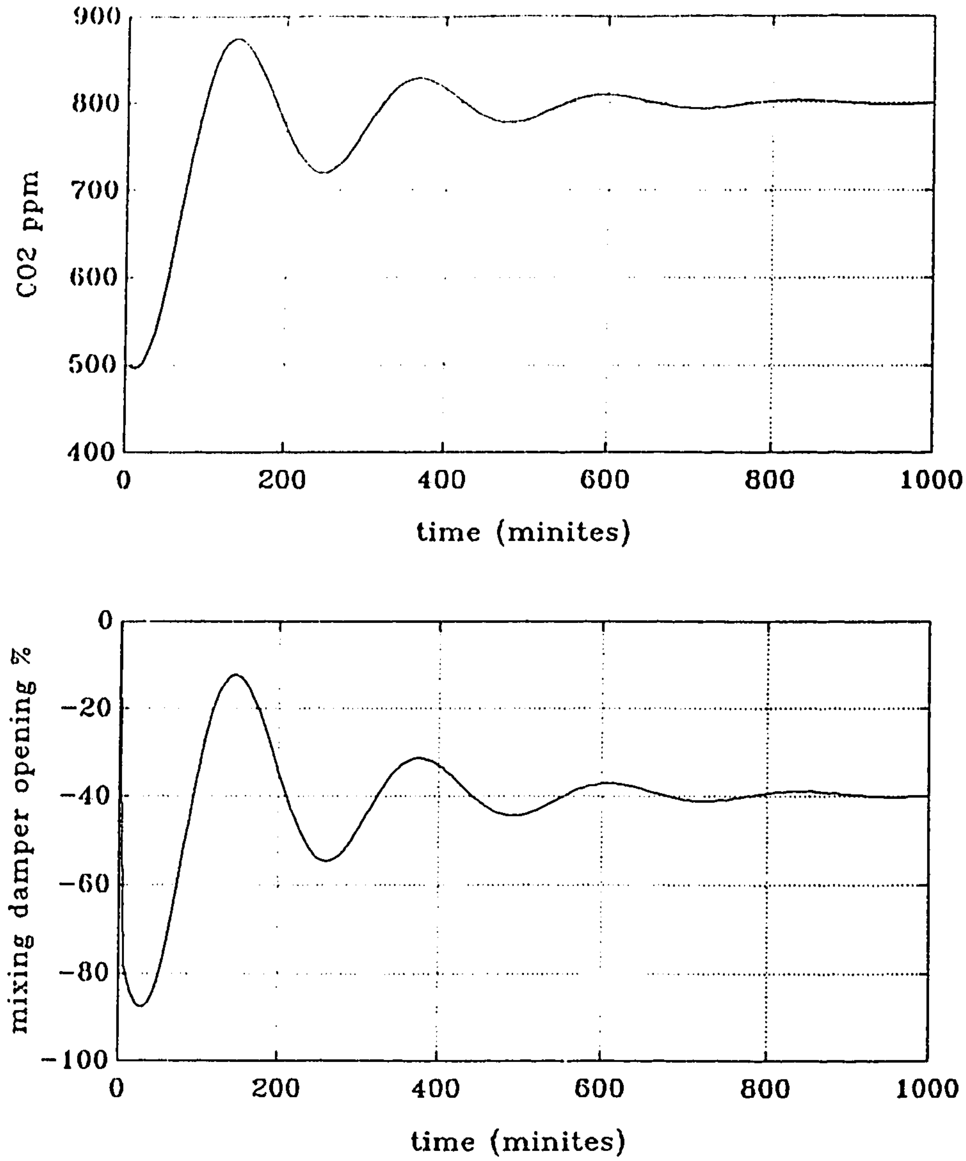


Figure 17.1 Simulation of indoor CO2 control without control action limit

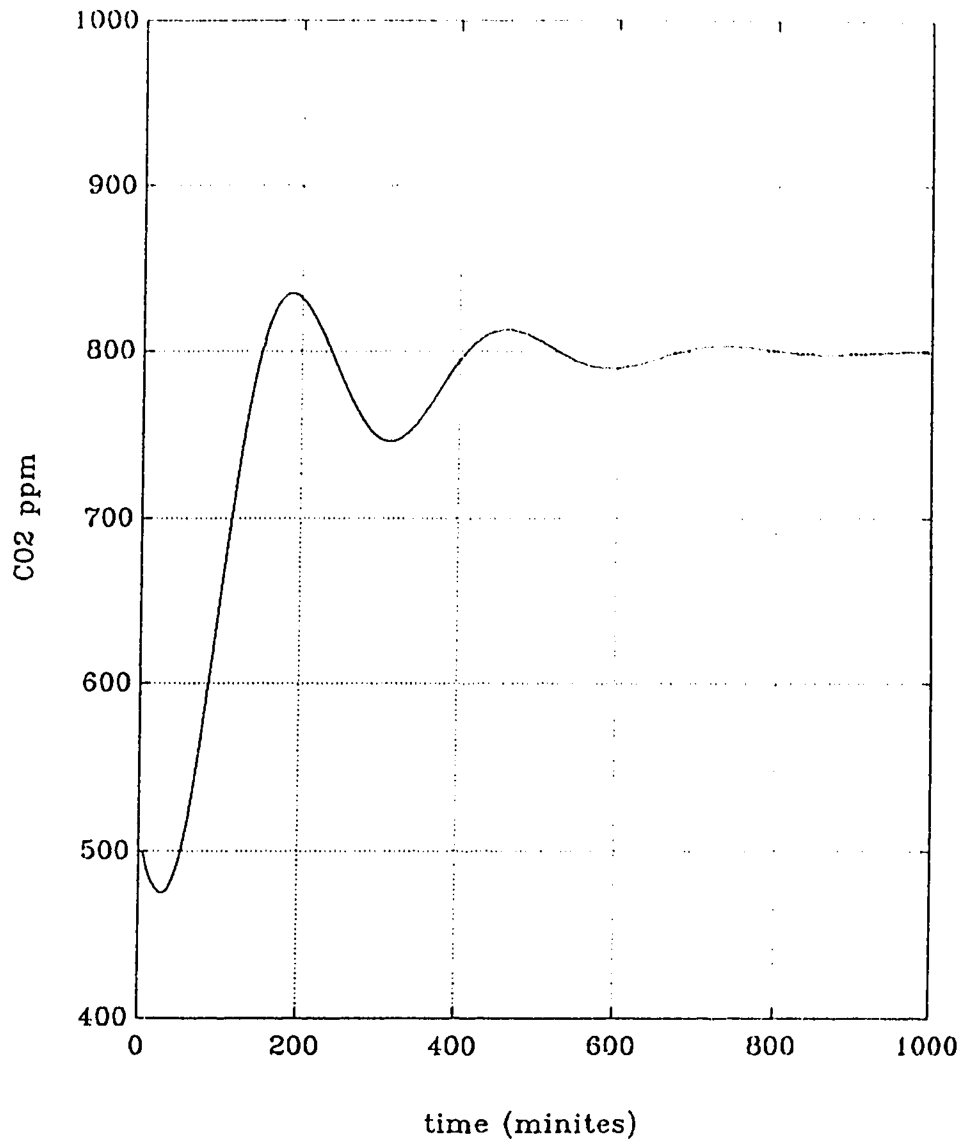


Figure 17.2 Simulation of indoor CO2 control with control action limit

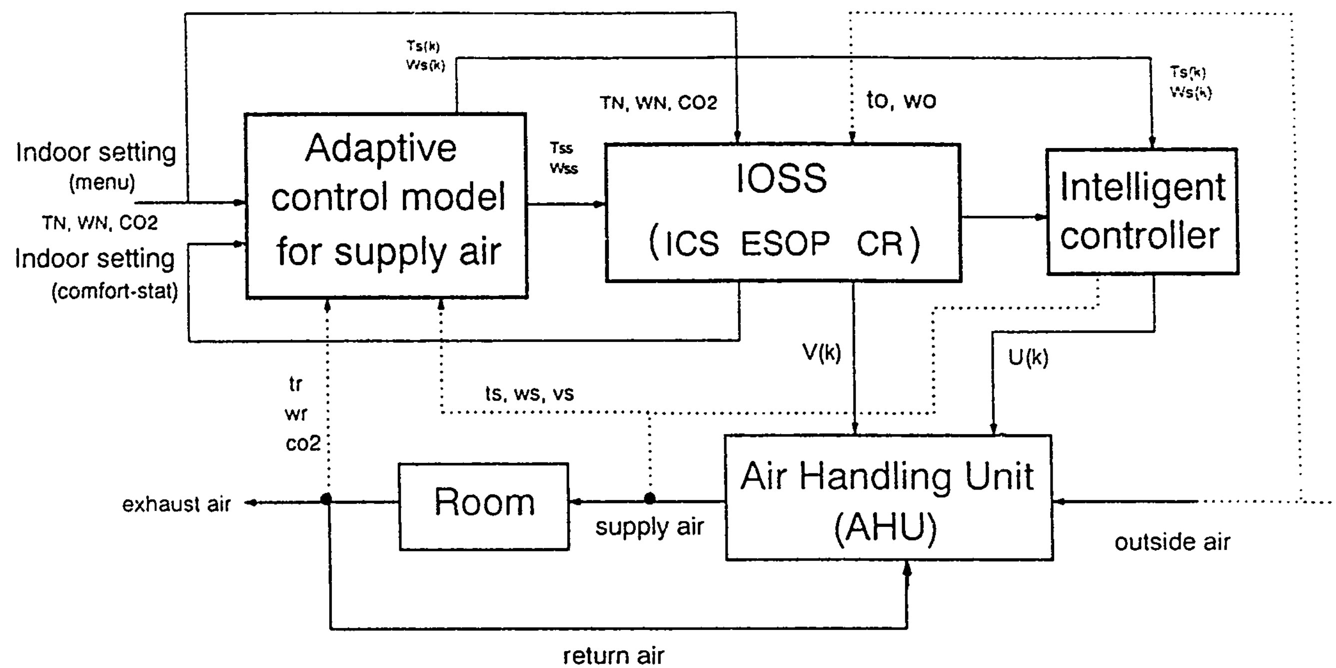


Figure 18 Integrated Intelligent control framework for HVAC processes

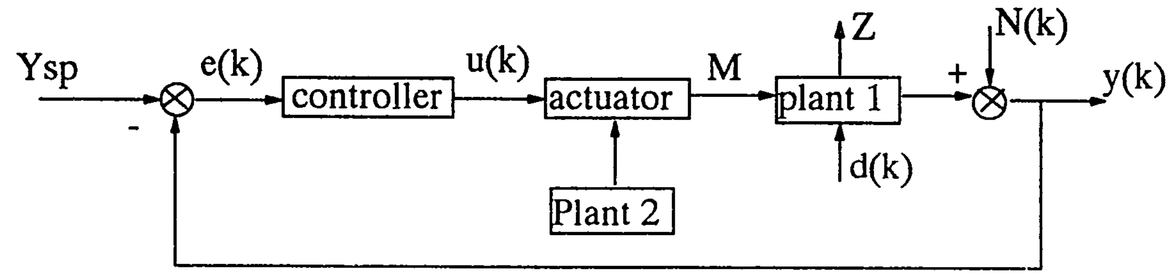


Figure 19 A single loop control system

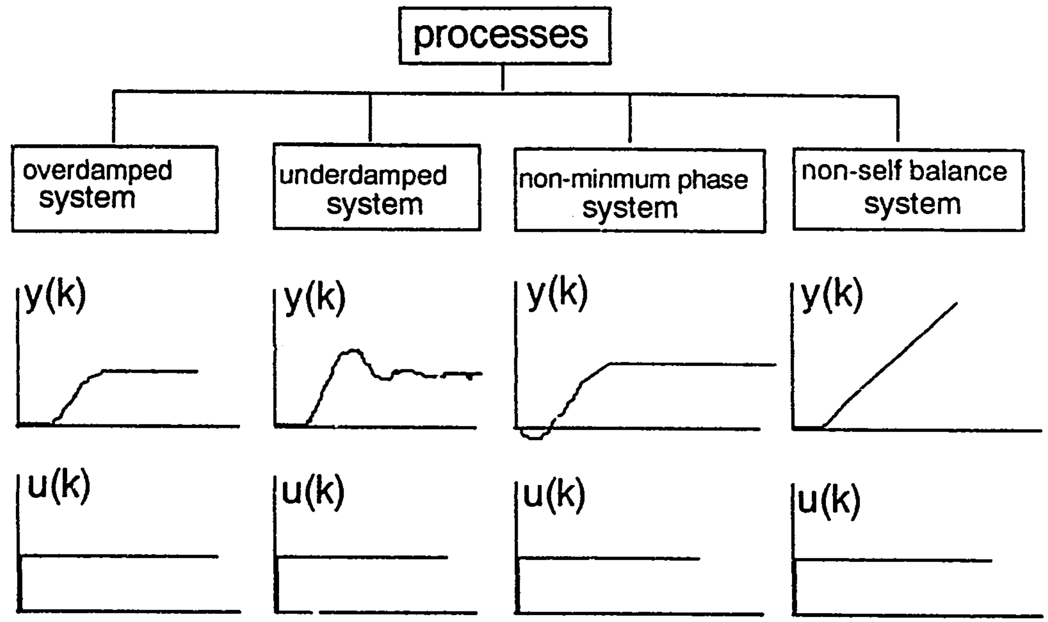


Figure 20 Process patterns (Open loop test response patterns)

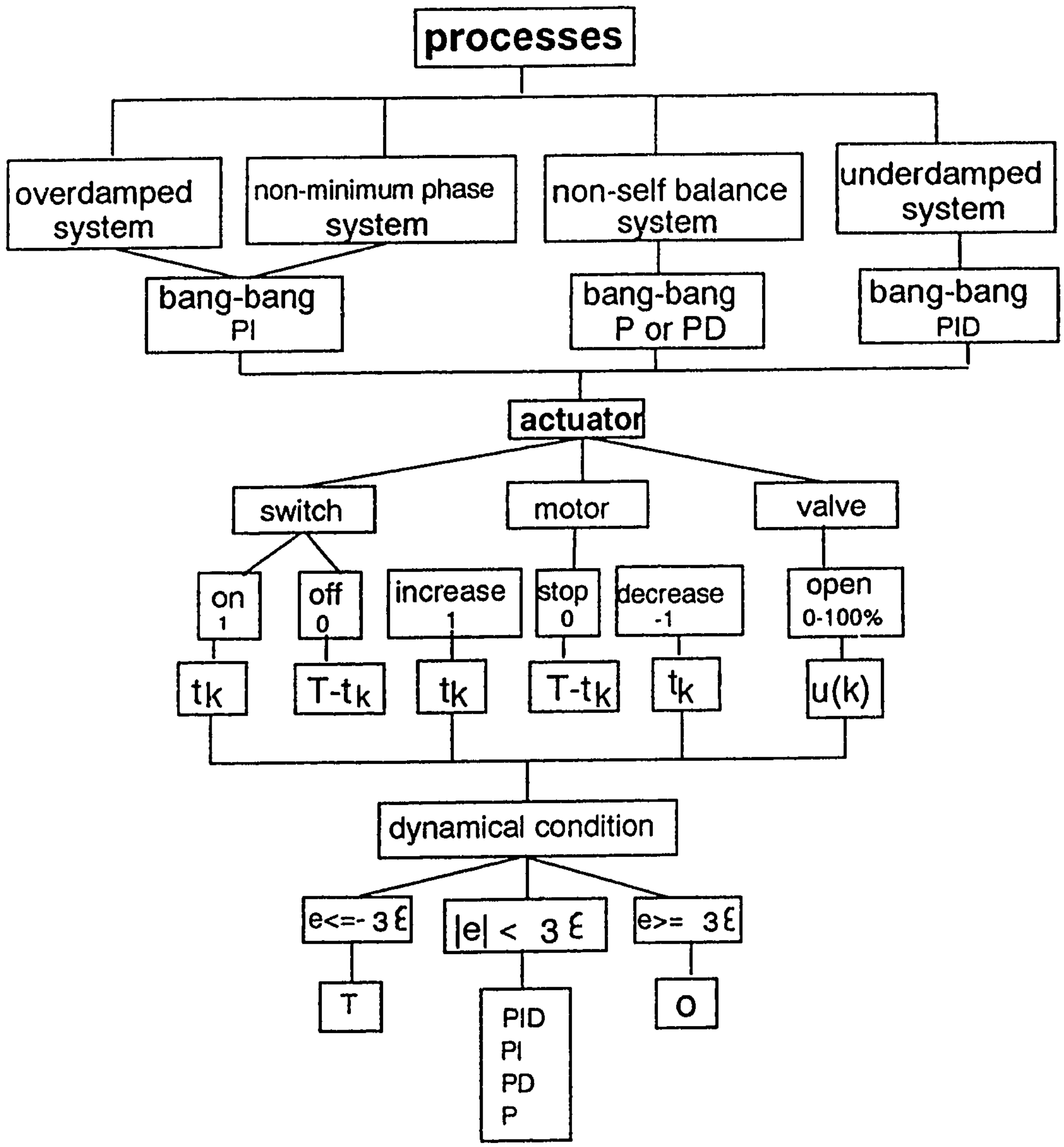
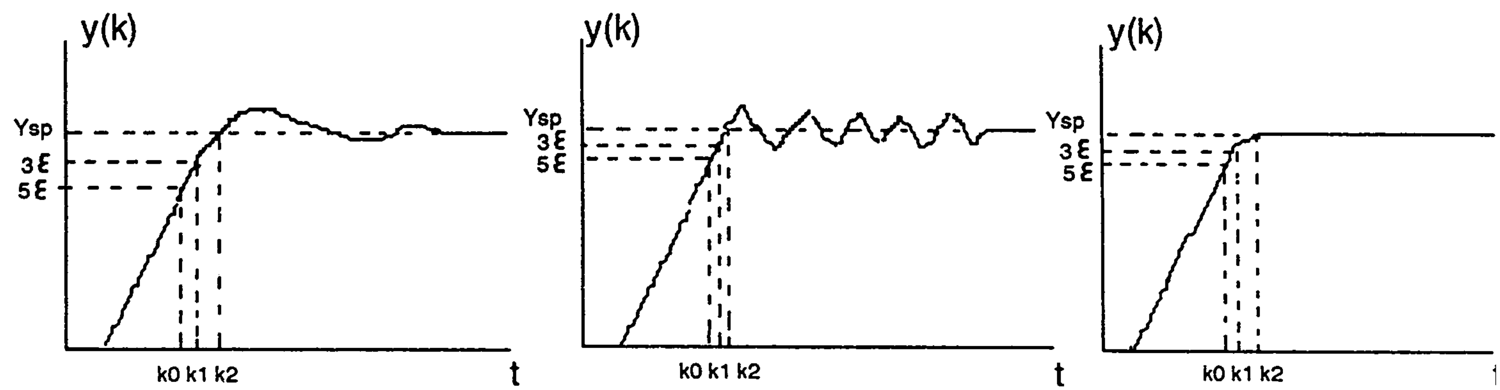


Figure 21 Hierarchy of decision search tree



(a) ε too large (b) ε too small (c) ε match

Figure 22 Effect of tuning key

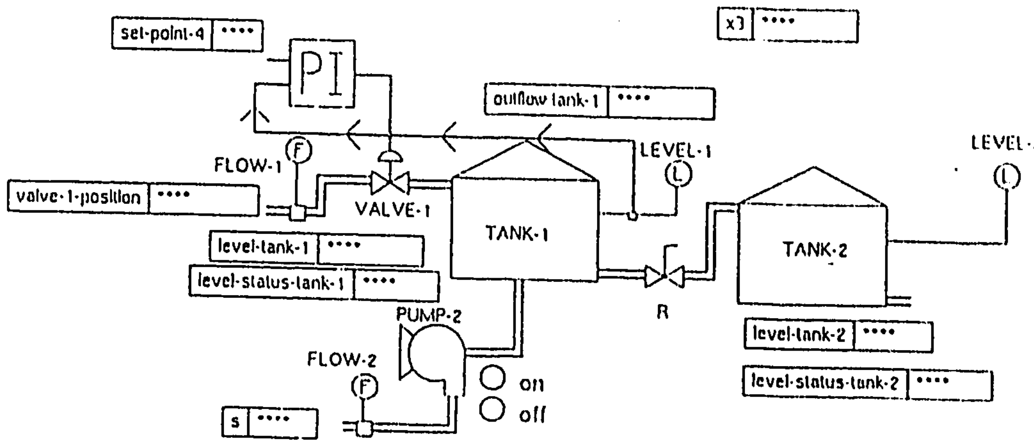


Figure 23 A water-tank control system using the intelligent controller

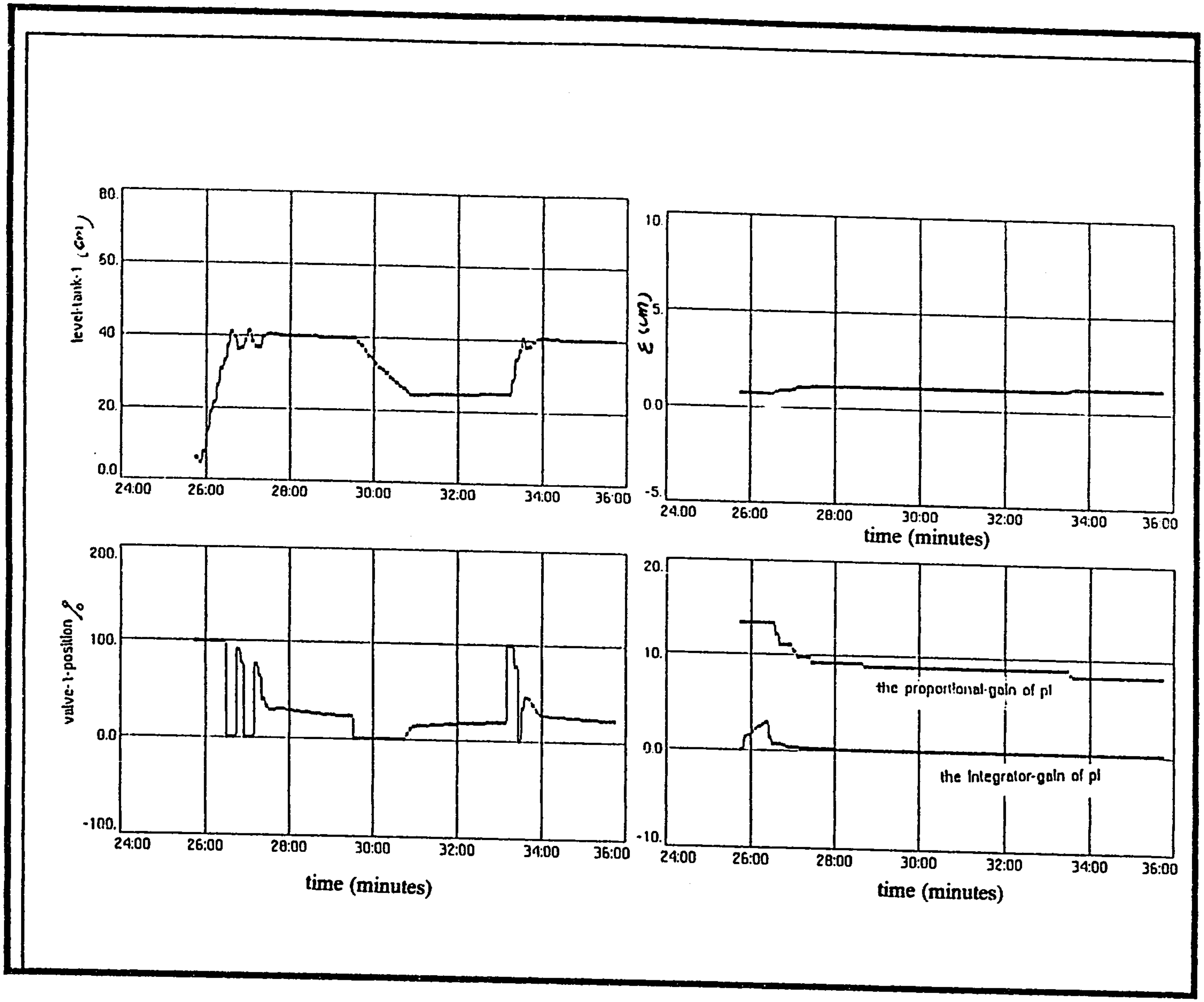


Figure 24.1 Step response of the level of tank-1 (time delay = 5 sec.)

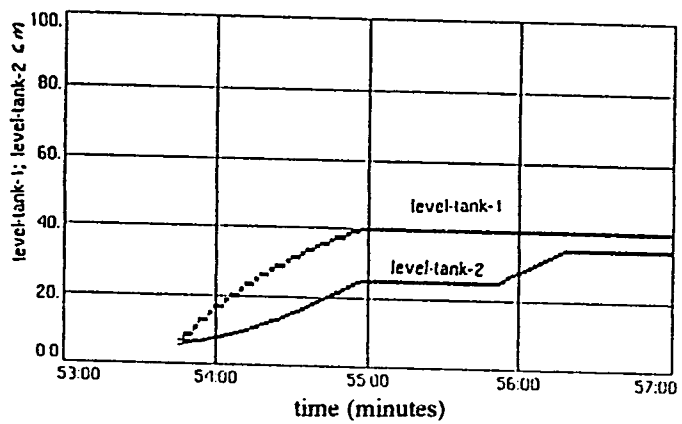


Figure 24.2 Step response of the levels of tank-1 and tank-2 (no time delay)

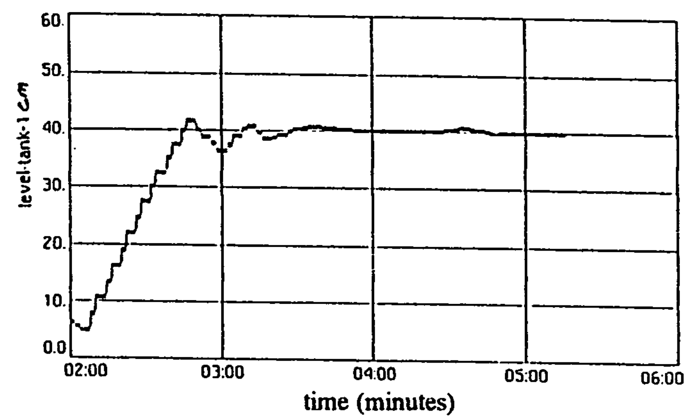


Figure 24.3 Step response of load disturbance

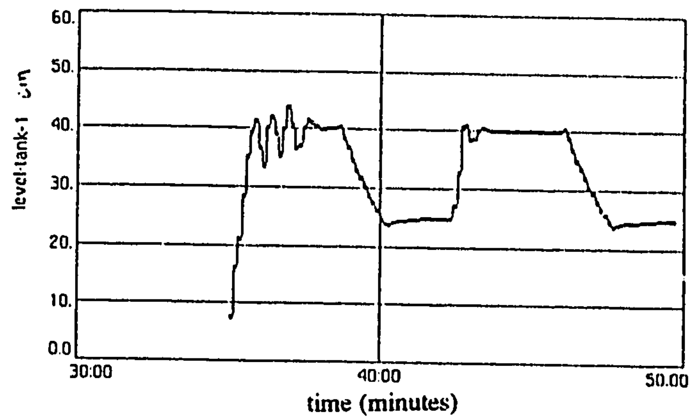


Figure 24.4 Step response of non-minimum phase system using the intelligent controller

References

ASHRAE Standard 62-1989: Ventilation for acceptable indoor air quality, by ASHRAE, Atlanta, Ga: 1989

Athienitis, A.K. 1988. A predictive control algorithm for massive buildings. ASHRAE Transactions, **94**(2), 1050-1067.

Astrom, K.J., Anton, J. J. and Arzen, K.-E. 1986. Expert control. Automatica, **22**, 277-286

Astrom, K. J. 1989. Toward Intelligent control. IEEE Control System Magazine, 9(4), 60-64

Astrom, K. J. and Hagglund, T. 1984. Automatic tuning of simple regulators with specifications on phase and amplitude margins. Automatica, **20**, 645-651

Awbi, H.B. and Allwinkle, S.J., 1986. Domestic ventilation with heat recovery to improve indoor air quality. Energy and Buildings, **9**(4), 305-312

Bagby, D.G. and Cormier, R.A. 1989, A heat exchanger expert system. ASHRAE Transactions, **95**(2), 927-933.

Bahnfleth, D.R., 1986, Problems of the 80's. ASHRAE Journal, **28**(7), 30-40.

Bergt, C. 1989, Creating a PROLOG Knowledge-based system using an existing air-to-refrigerant computer model. ASHRAE Transactions, **95**(1), 1237-1244.

Boonyatilkarn, S., Arch, D. and Jones, J.R. 1989. Smart building controls strategies: research and application. ASHRAE Transactions, **95**(1), 557-562.

Borrazzo, J.E.; Osborn, J.F.; Fortmann, R.C.; Keefer, R.L.; and Davidson, C.I. 1987, Modeling and Monitoring of CO, NO and NO2 in a modern townhouse. Journal of Non-Newtonian Fluid Mechanics, **22**(3), 299-311

Braun, J.E.; Klein, S.A.; Beckman, .A.; and Mitchell, J.W. 1989. Methodologies for optimal control c chilled water systems without storage. ASHRAE Transactions, **95**(1), 652-662.

Braun, J.E.; Klein, S.A.; Beckman, W.A.; and Mitchell, J.W. 1989. Applications of optimal control to chilled water system without storage. ASHRAE Transactions, **95**(1), 663-675.

Brothers, P.W. 1988. Knowledge engineering for HVAC expert systems. ASHRAE Transactions, **94**(1), 1063-1073.

Caffrey, R.J. 1988 The intelligent building -- an ASHRAE opportunity. ASHRAE Transactions, **94**(1), 925-932.

Camejo, P.J. and Hittle, D.C. 1989. An expert system for the design of heating, ventilation, and air-conditioning systems. ASHRAE Transactions, **95**(1), 379-386.

Cascia, M.A. 1988. Optimizing chiller plant energy savings using adaptive DDC Algorithms. ASHRAE Transactions, **94**(2), 1937-1946.

Colburn, B.K. and Harmon, K.S., JR., 1987. Thermal comfort dynamics--an advanced control strategy. Energy Engineering, **84**(4), 30-52.

Colliver, D.G., White, G.M. and Turner, L.W. 1987. Electrical energy consumption and demand reduction using heat pump controls. ASHRAE Transactions, **93**(1), 578-587.

Cooper, K.W. 1983. Microcomputers in an energy saving residential heat pump. IEEE Transactions on Industry Applications, IA-**19**(4), 486-490.

Dexter, A.L. and Haves, P. 1989. A robust self-tuning predictive controller for HVAC applications. ASHRAE Transactions, **95**(2), 431-438.

Doherty, T.J. and Arens, E. 1988. Evaluation of the physiological bases of thermal comfort models. ASHRAE Transactions, **94**(1), 1371-1378.

Druzik, J.R.; Adams, M.S.; Tiller, C.; and Case, G.R. 1990, Measurement and model predictions of indoor ozone concentrations in museums. Atmospheric Environment V. **24A**(7), 1813-1823.

Fanger, P.O., 1970. Thermal Comfort Analysis and Application in Environmental Engineering, McGraw-Hill Book Company, New York.

Fanger, P.O., 1989. New comfort equation for indoor air quality. ASHRAE Journal, **31**(10)

Fanger, P.O., 1990. Air Quality, Australian Refrigeration, Air Conditioning and Heating, **44**(8), 28-31.

Feustel, H.E. and Sherman, M.H., 1991. COMIS infiltration model - a tool for multizone applications. Proceedings of the International Centre for Heat and Mass Transfer, 771-779.

Fleming, W.S., 1986. Indoor air quality, infiltration, and ventilation in residential buildings. Proceedings of the ASHRAE Conference IAQ' 86: Managing Indoor Air for Health and Energy Conservation, 192-207.

Franta, S. and Franta, G., 1985. Energy in architecture and the sick building syndrome: A public health perspective. Proceedings of the 10th National Solar Conference, 359.

Fu, K.S. 1971. Learning control system and intelligent control systems: an intersection of artificial intelligence and automatic control, IEEE Transaction on Automatic control, **16**, 70-72

Haberl, J.S., Smith, L.K., Cooney, K.P. and Stern, F.D. 1988. An expert system for building energy consumption analysis: applications at a university campus. ASHRAE Transactions, **94**(1), 1037-1051.

Haberl, J.S. and Claridge, D.E. 1987. An expert system for building energy consumption analysis: prototype results. ASHRAE Transactions, **93**(1), 979-987.

Hachner, R.J.; Mitchell, J.W.; and Beckman, W.A. 1984. HVAC System and energy use in existing buildings--part1. ASHRAE Transactions, **90**(2B), 523-535.

Haines, R.W., 1984. Retrofitting reheat-type HVAC system for energy conservation. ASHRAE Transactions, **90**(2B), 185-191.

Haines, R.W. Control Systems for Heating, Ventilating, and Air Conditioning, by Van Nostrand Reinhold Company (1987).

Harrie, D.T. and Gadsby, K.J., 1986. Practical engineering solutions for optimizing energy conservation and indoor air quality in residential buildings. Proceedings of the ASHRAE Conference IAQ '86: Managing Indoor Air for Health and Energy Conservation, 333-341.

Hartman, T.B. 1989. An operator's control language to improve EMS successes. Energy Engineering, **86**(2), 6-11.

Hartman, T.B. 1988. Dynamic control: Fundamentals and considerations ASHRAE Transactions, **94**(1), 599-609.

Hawthorne, A.R. and Matthews, T.G., 1987. Models for estimating organic emissions from building materials: formaldehyde example. Atmospheric Environment, **21**(2), 419-424.

Hayter, R.B. 1987. Comfort education for energy conservation. ASHRAE Transactions, **93**(1), 1080-1083.

Hubber, G. and Wanner, H.U. Indoor air quality and minimum ventilation rate. Environment International, **9**, 153-156 (1983)

Hung, I-Fu and Derossis, P., 1989. Carbon dioxide concentration as an indicator of indoor air quality. Journal of Environmental Science and Health, part A, **24**(4), 379-388.

Imaiida, T., Kojima, S., Aoi, F. and Ohta, M. 1985. Development of demand defrost control system for residential heat pumps. ASHRAE Transactions, **91**(2B), 1527-1535.

Janssen, J.E., 1989. Ventilation for acceptable in indoor air quality. ASHRAE **31**(10)

Jedlicka, A.D. 1985. Improving conservation behavior. Energy Engineering, **82**(5) 29-34.

Johnson, G.A. 1984. Retrofit of a constant volume air system for variable speed fan control. ASHRAE Transactions, **90**(2B), 201-211.

Johnson, G.A. 1985. Optimization techniques for a centrifugal chiller plant using a programmable controller. ASHRAE Transactions, **91**(1B), 835-847.

Klim, M.S. 1986. Seek air quality answers. ASHRAE Journal, **28**(5), 35-36.

Lee, J. 1989. On-line PID controller tuning from a single, closed-loop test, AIChE Journal, **35**, pp.329-331

Liu, S.T. and Kelly, G.E. 1988. Knowledge-based front-end input generating program for building system simulation. ASHRAE Transactions, **94**(1), 1074-1084.

Lu, Y.Z. 1986. Applications of modern control techniques to industrial control- with working examples. Proc. of the Twelfth Annual Advanced Control Conference, 1-17

MacArthur, J.W.; Grald, E.W.; and Konar, A.F. 1989. An effective approach for dynamically compensated adaptive control. ASHRAE Transactions, **95**(2), 415-423.

Martin, A. 1988. Integration of building management functions. Measurement and Control, **21**(Sept.) 211-212.

Maxwell, G.M.; Shapiro, H.N.; and Westra, D.G. 1989. Dynamics and control of a chilled water coil. ASHRAE Transactions, **95**(1), 1243-1255.

McNall, P.E., 1986. Control of indoor air quality by means of HVAC systems. Proceedings of the ASHRAE Conference IAQ '86: Managing Indoor Air for Health and Energy Conservation, 541-547.

McNall, P.E., 1988. ASHRAE's response to the indoor air quality issue. Repowering America: Proceedings of the Energy Technology Conference, **15**, 429-435

Mehta, D.P. 1983. Effects of control dynamics on energy consumption in residential heating systems. Energy Engineering, **80**(3), 7-24.

Mesher, D. and Poehlman, W.F.S., 1990. Intelligent environmental controller for R2000 residential homes. Canadian Journal of Electrical and Computer Engineering, **15**(2), 73-82.

Mølhave, L. 1989. The sick building and other buildings with indoor climate problems. Environment International, **15**, 65-74

Morey, P.R.; Jones, W.G.; Clere, J.L.; and Sorenson, W.G., 1986. Studies on sources of airborne microorganisms and on indoor air quality in a large office building. Proceedings of the ASHRAE Conference IAQ '86: Managing Indoor Air for Health and Energy Conservation, 500-509.

Morre, T. 1986. Artificial intelligence and power production. Energy Engineering, **83**(3), 4-16.

Morris, R and Wiggin M. 1985 Indoor air pollution. Heating/Piping/Air Conditioning. **57**(2) 73-86.

Nahar, N.M. and Gupta, J.P. 1989.Energy conservation and pay back periods of collector-cum-storage type solar water-heaters. Applied Energy, **34**(2), 155-163.

Nelson, T.M., Nilsson, T.H. and Hopkin, G.W. 1987. Thermal comfort: advantages and deviations. ASHRAE Transactions, **93**(1), 1039-1047.

Nelser, C.G. 1986. Adaptive control of thermal processes in buildings. IEEE Control System Magazine, **6**(4), 9-13.

Newman, J.L., 1991, HVAC system performance and indoor air quality. Energy Engineering: Journal of the Association of Energy, **88**(3), 61-78.

O'Sullivan, P., 1989. Energy and IAQ can be complementary, Heating, Piping & Air Conditioning, **61**(2), 37-42.

Payne, P.P. 1988. What distributed controllers bring to the building management system. ASHRAE Transactions, **94**(1), 1503-1513.

Petze, J.D. and Reed, D.R. 1988. Artificial intelligence in building control systems. ASHRAE Transactions, **94**(1), 960-969.

Porter, B., Jones, A.H. and Mckeown, C.B. 1987. 'Real-time expert tuners for PI controllers', IEE Proceedings-D, **134**, pp.260-263

Rao, M., Jiang, T.S. and Tsai, J.P. 1989. Combining symbolic and numerical processing for real time intelligent control. Engineering Application of AI, **2** (March), 19-27.

Rao, M., Jiang, T.S. and Tsai, J.P. 1987. A frame work of integrated intelligent system. Proc. 1987 IEEE International Conference on System, Man, and Cybernetics, 1133-1137

Rinehart, R.D., 1981. Energy savings with large set-backs. Energy Engineering, **78**(6), 21-38.

Rodahl, E., 1986. Comfort by intelligent ventilation. Proceedings of the ASHRAE Conference IAQ' 86: Managing Indoor Air for Health and Energy Conservation, 101-105.

Rouse, K. 1988. BEMS energy management systems -- an overview. Measurement and Control, **21**(Sept.) 1988.

Seem, J.E.; Armstrong, P.R.; and Hancock, C.E. 1989. Algorithms for predicting recovery time from night setback. ASHRAE Transactions, **95**(2), 439-446.

Shapiro, M.M.; Yager, A.J.; and Ngan, T.H. 1988. Test hut validation of a microcomputer predictive HVAC control. ASHRAE Transactions, **94**(1), 644-659.

Sherman, M.H. and Wilson, D.J., 1986. Relating actual and effective ventilation in determining indoor air quality, Building and Environment, **21** (3-4), 135-144

Shi, J. and Zhou, H., 1985. Air conditioning control system with microcoputer using an adaptive regulator. Proceeding of CLIMA 2000 World Congress on Heating, Ventilating, and Air Conditioning, Copenhagen 85

Shimma, Y., Tateuchi, T. and Sugiura, H. 1985. Inverter control systems in the residential heat pump air conditioner. ASHRAE Transactions, **91**(2), 1541-1553.

Shirley, R.S. 1987. 'Some lessons learned using expert systems for process control', IEEE control system magazine, **12**, 11-15.

Small, M.J.; Wilkes, C.R.; Andelman, J.B.; Giardino, N.J.; and Marshall J., 1990. Inhalation exposure from contaminated water uses. A behavioral model for people and pollutants. Proceedings of the 1990 Specialty Conference, 764-771.

Spratt, D.K., Sadler, G.W. and Moodie, K.R. 1989. Dynamic control -- A case study. ASHRAE Transactions, **95**(2), 193-200.

Teji, D.S. 1987. Controlling air supply for energy conservation. Energy Engineering, **84**(3), 4-14.

Thorsen, M.A. and Molhave, L., 1987. Elements of a standard protocol for measurements in the indoor atmospheric environment. Atmospheric Environment, **21**(6), 1411-1416.

Tsatsoulis, C. and Kashyap, R.L., A case-based system for process planning. Robotics & Computer-Integrated Manufacturing, **4**(3), 557-570 (1988)

Tuluca, A.N., Turner, G.E., Krarti, M. and Antipa, V. 1989. Expert system for selection of standardized research greenhouses. ASHRAE Transactions, **95**(2), 938-953.

Underwood, D.M. 1989. Response of self-tuning single-loop digital controllers to a computer-simulated heating coil. ASHRAE Transactions, **95**(2), 424-429.

Wallingford, K.M. and Carpenter, J. 1986. Field experience overview: Investigating sources of indoor air quality problems in office buildings. Proceedings of the ASHRAE Conference IAQ '86: Managing Indoor Air for Health and Energy Conservation, 448-453.

Wallingford, K.M., 1988. Indoor air quality investigation in office buildings. Energy Technology: Proceedings of the Energy Technology Conference, **15**, 436-444.

Wepfer, W.J. and Li, X. 1986. Implementation of adaptive control to building HVAC systems. Proceedings of the 18th World Energy Engineering Congress, 143-150.

Williams, V.A. 1988. Intelligent Buildings -- smarter with DDC. ASHRAE Transactions, **94**(1), 1314-1317.

Woods, J.E.Jr., 1986. Status - Ventilation models for indoor air quality. Chemical Engineering Monographs, **24**, 33-52.

Yuill, G.K. and Lovatt, J.E., 1986. Prediction of pollutant concentration in houses. Proceedings of the ASHRAE Conference IAQ' 86: Managing Indoor Air for Health and Energy Conservation, 383-391.

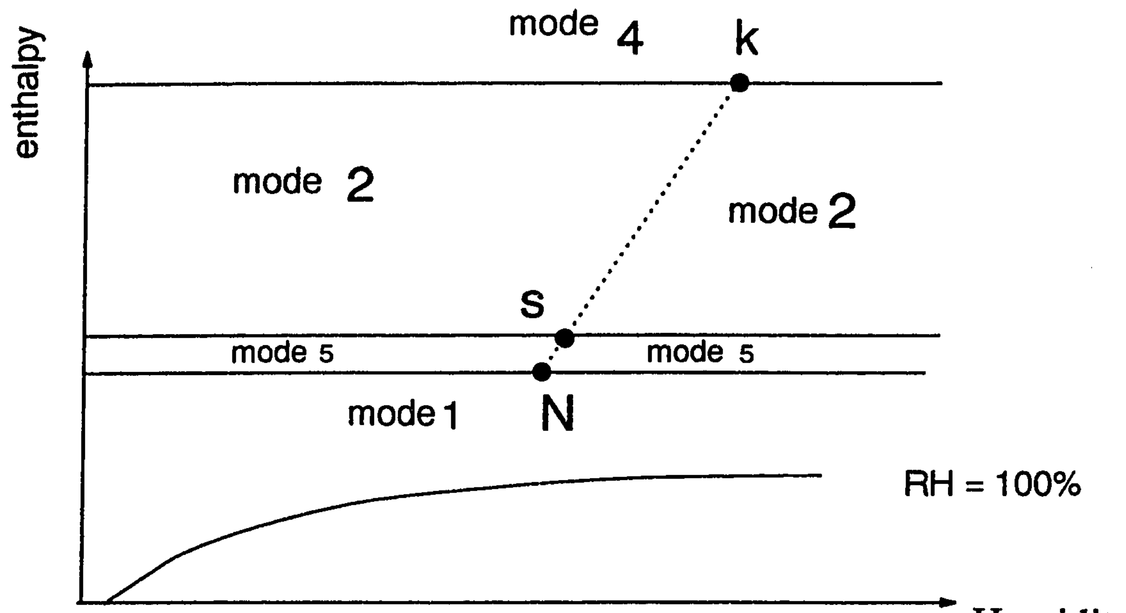
Zhou, H., M. Rao, and Chuang, K.T. Artificial Intelligence Approach to Energy Management and Control in HVAC process: An Evaluation, Development, and Discussion. (in press), Developments in Chemical and Metallurgical Engineering (1993)

Zhou, H., M. Rao, and Chuang, K.T. Integrated operation planning: Intelligent system approach for HVAC process. (in press), Journal of Intelligent and Robotic Systems (1993)

Zhou, H., M. Rao, and Chuang, K.T. 1993, Knowledge-based Automation for Energy Conservation and Indoor Air Quality Control in HVAC Proceses. Special Issue, Engineering Applications of Artificial Intelligence, **6**(2), 131-144

Ziegler, J.G. and Nichols, N.B. 1942, Optimum settings for automatic controllers, Transactions of the ASME, **64**, pp.759-768

Appendix A



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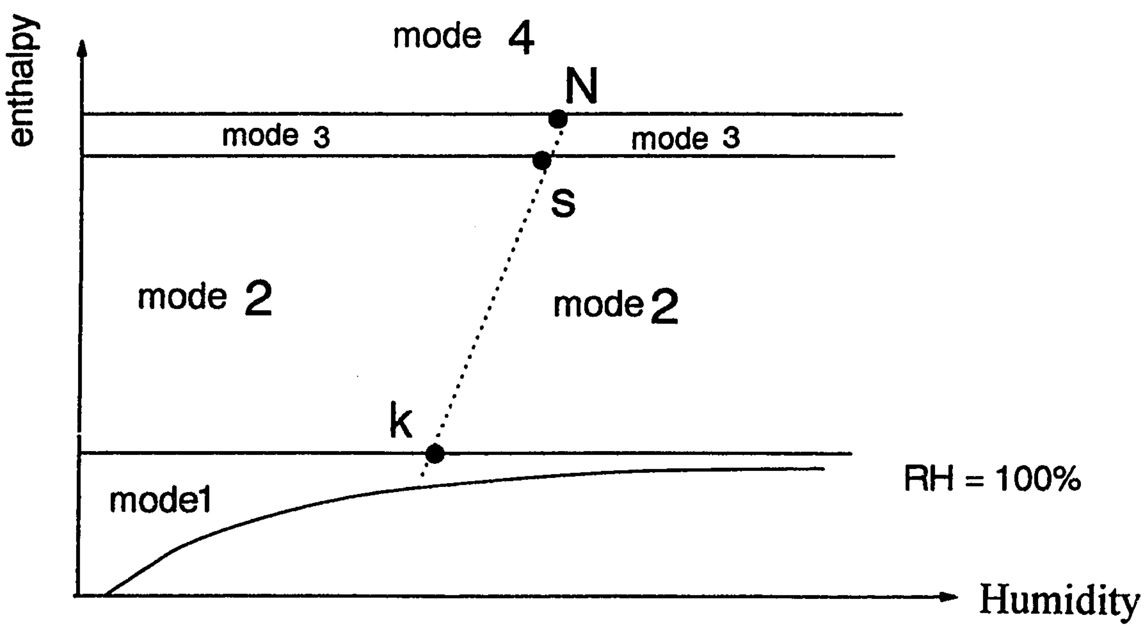


(b)

Figure A-1 Energy Saving Operation Mode Identification

TSC System

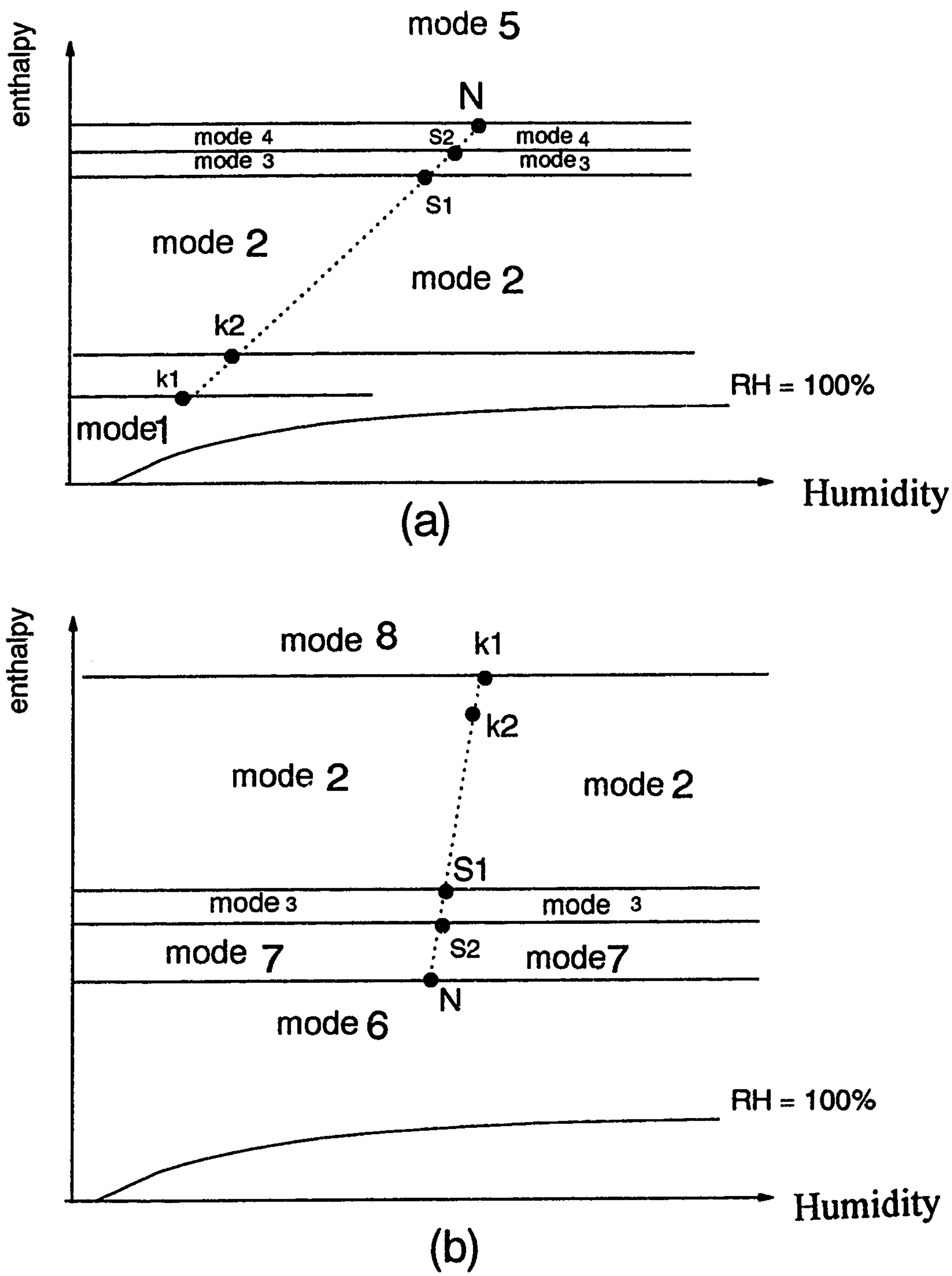


Figure A-2 Energy Saving Operation Mode Identification for TSV System

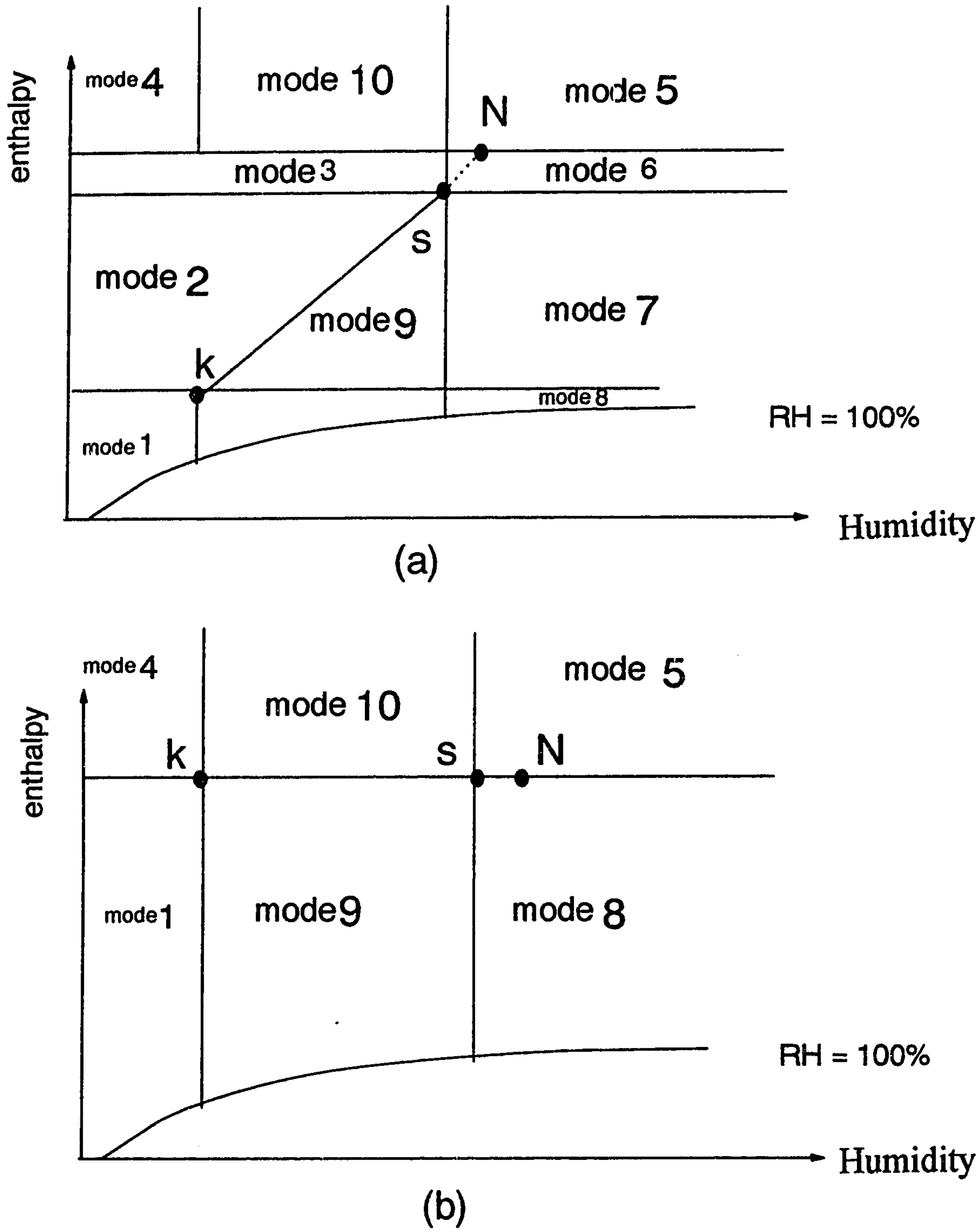
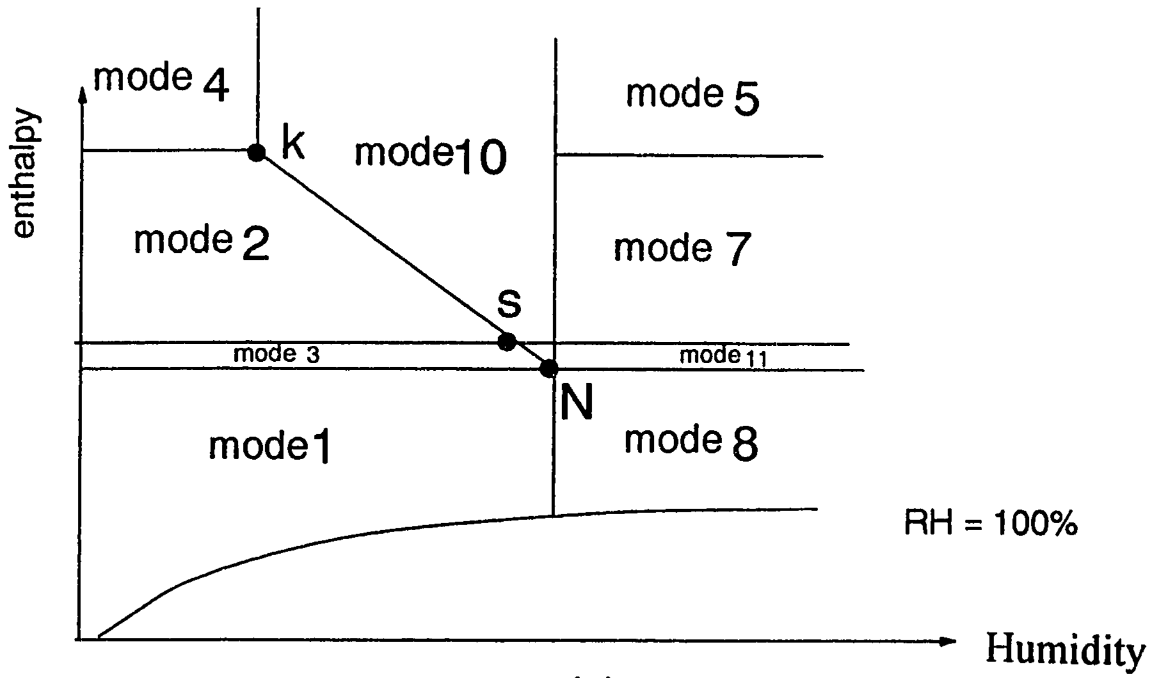


Figure A-3 Energy Saving Operation Mode Identification

THSCD system



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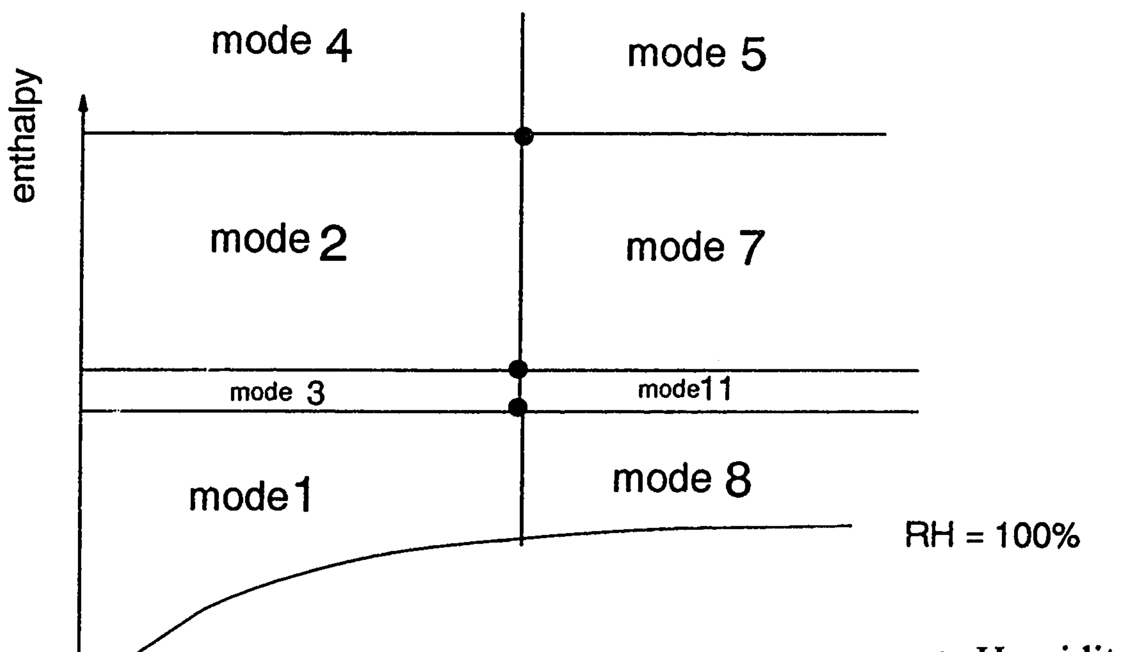

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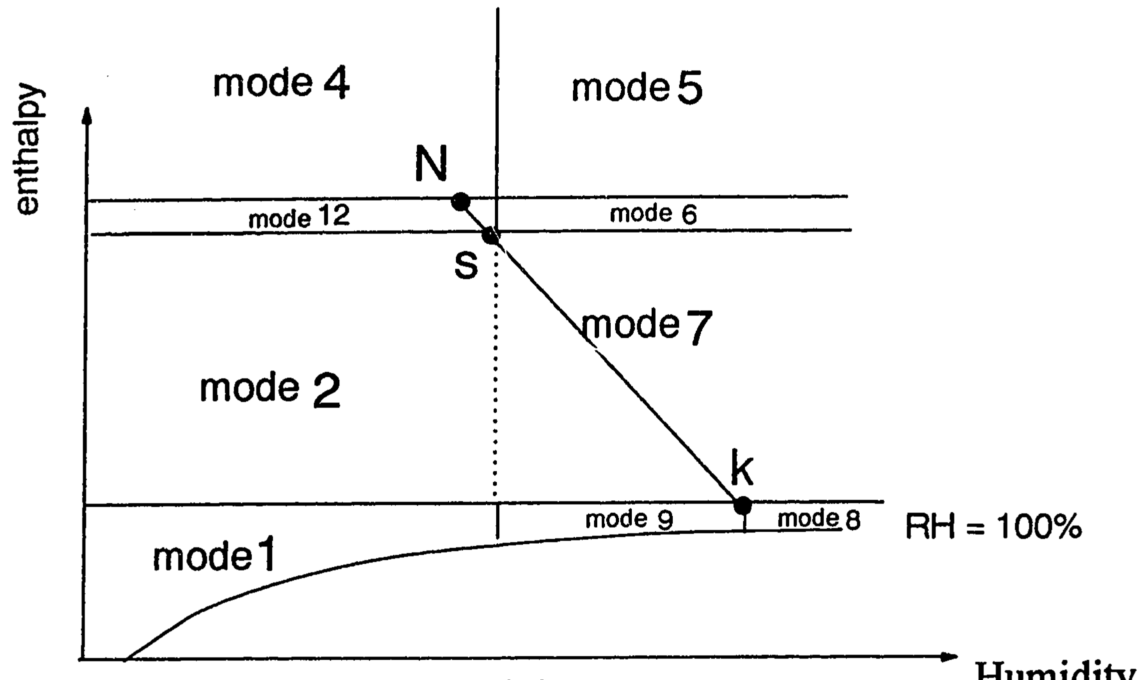
Figure A-3 Energy Saving Operation Mode Identification
THSCD system



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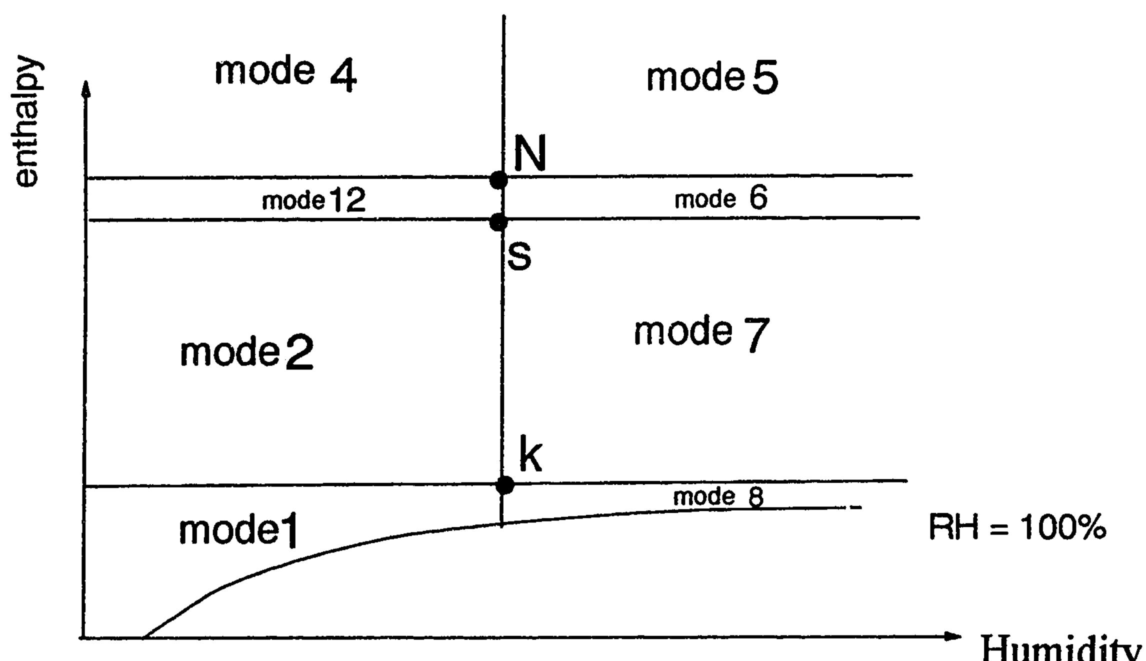

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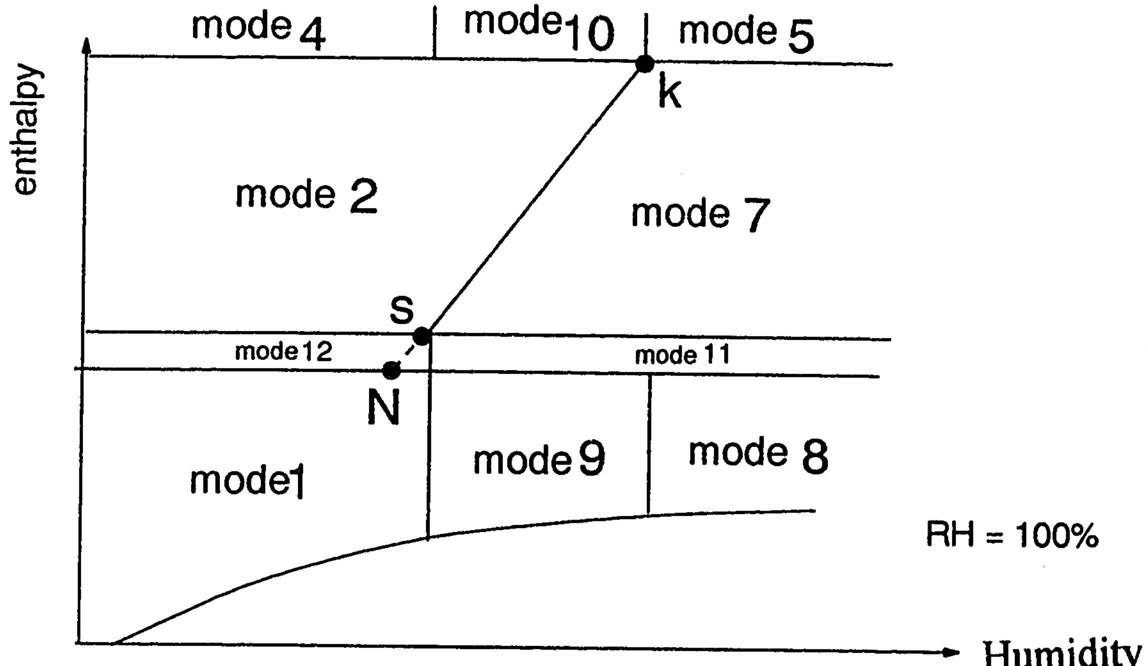

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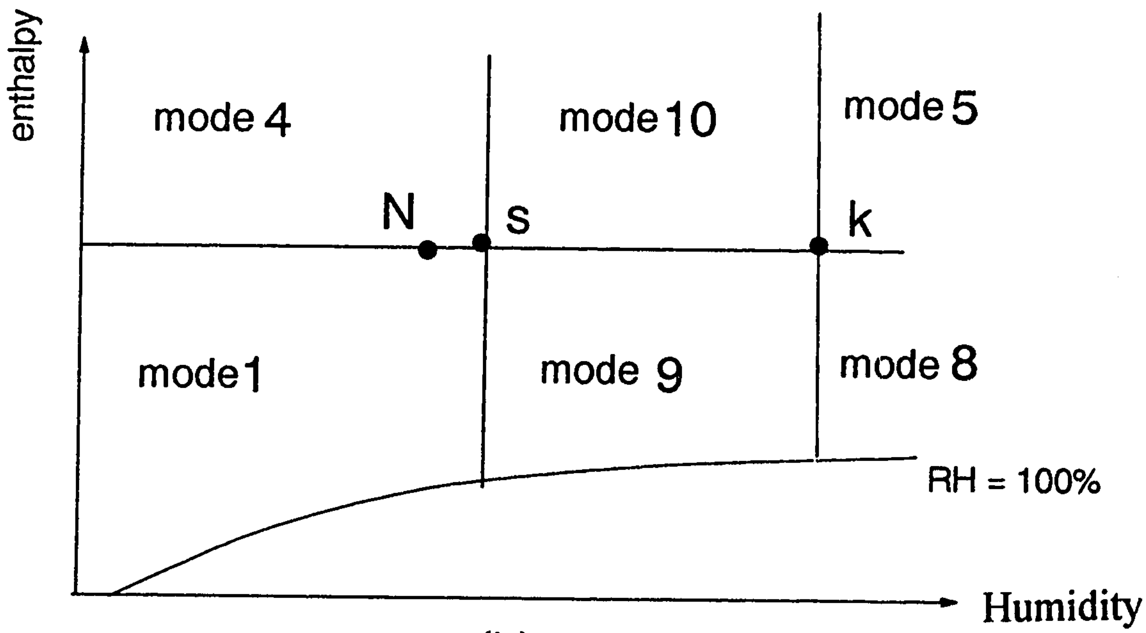

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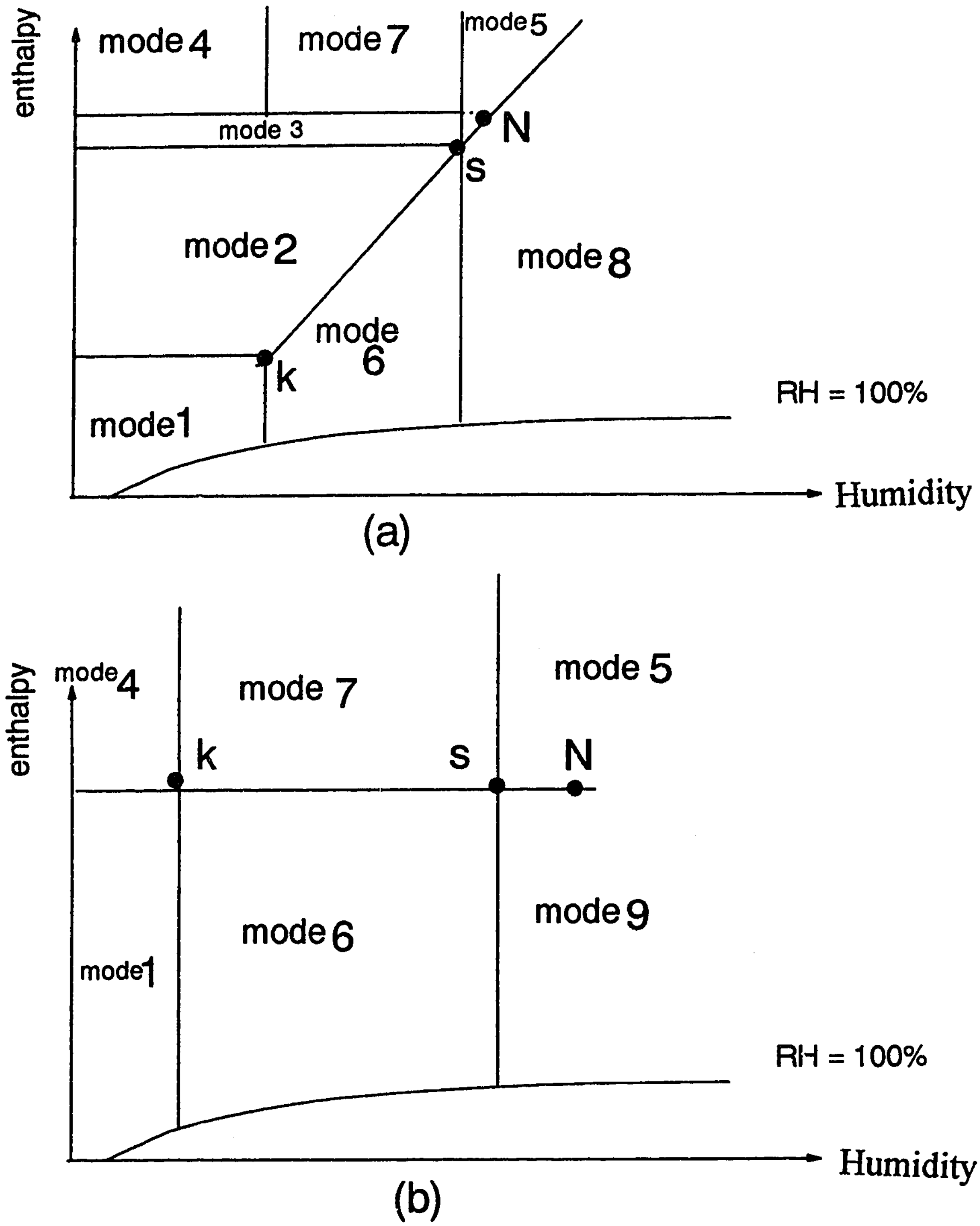


Figure A-4 Energy Saving Operation Mode Identification for THSCC System

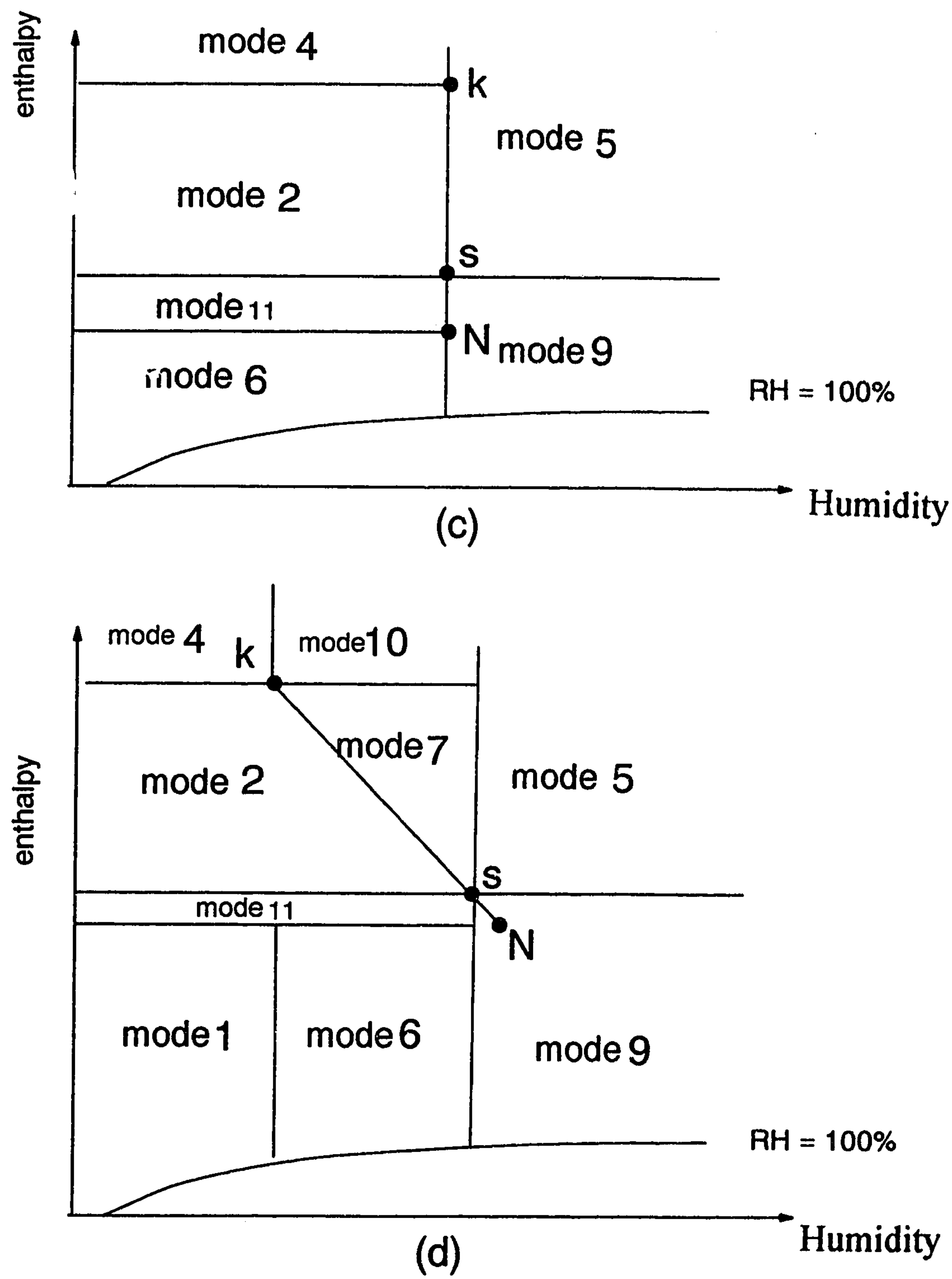
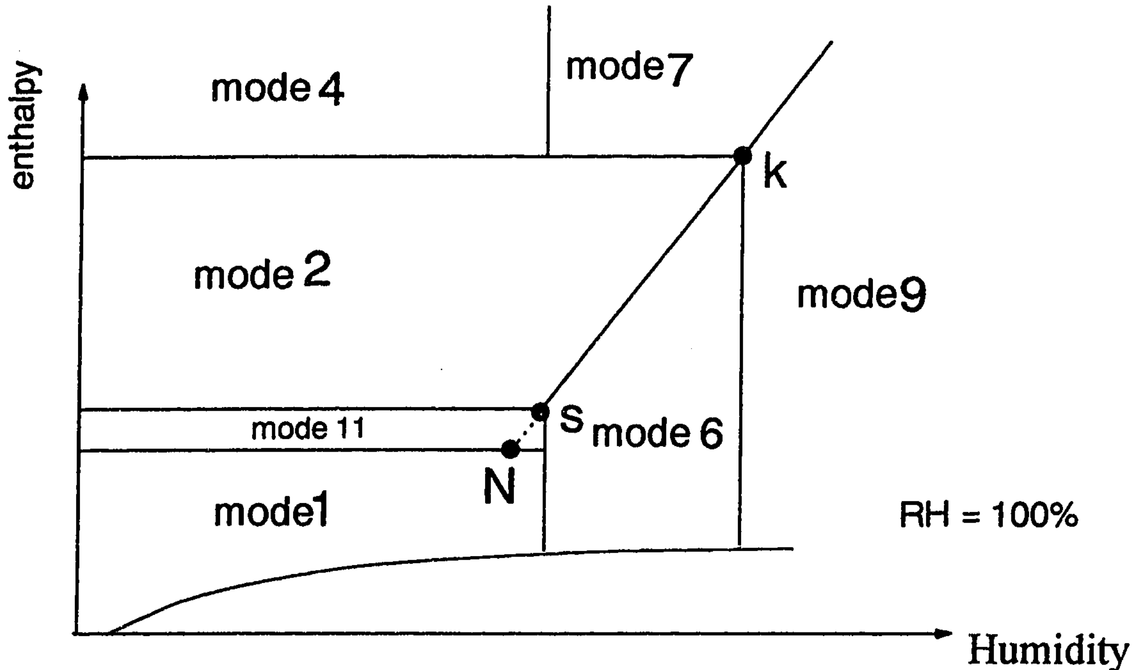


Figure A- 4 Energy Saving Operation Mode Identification for THSCC System



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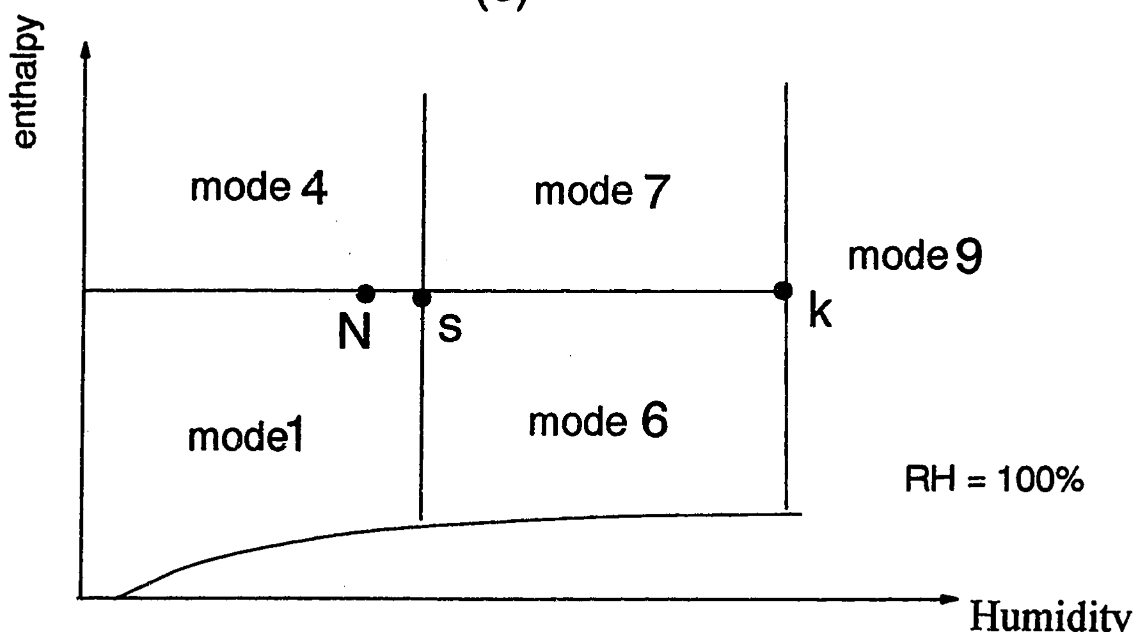

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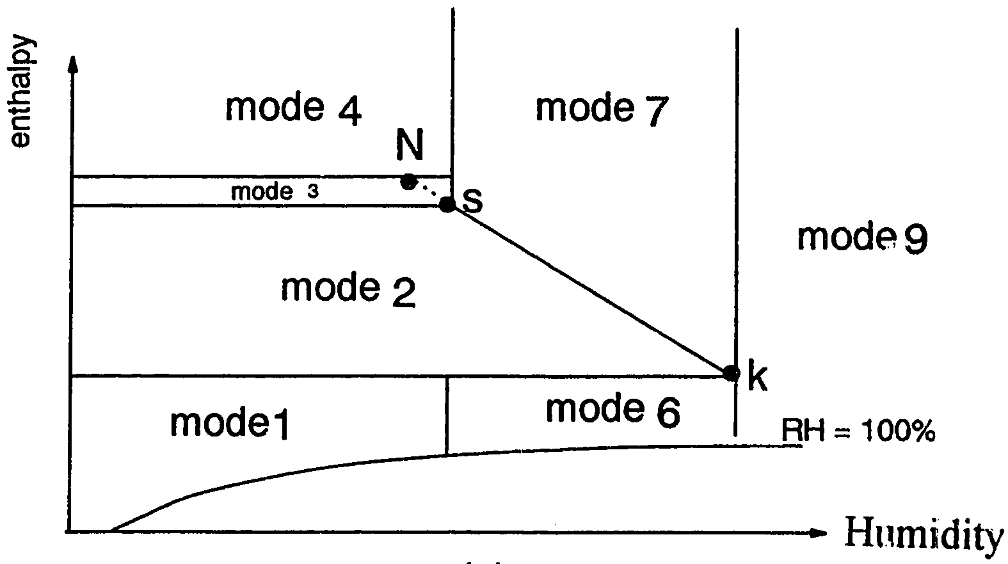
Figure A- 4 Energy Saving Operation Mode Identification for THSCC System



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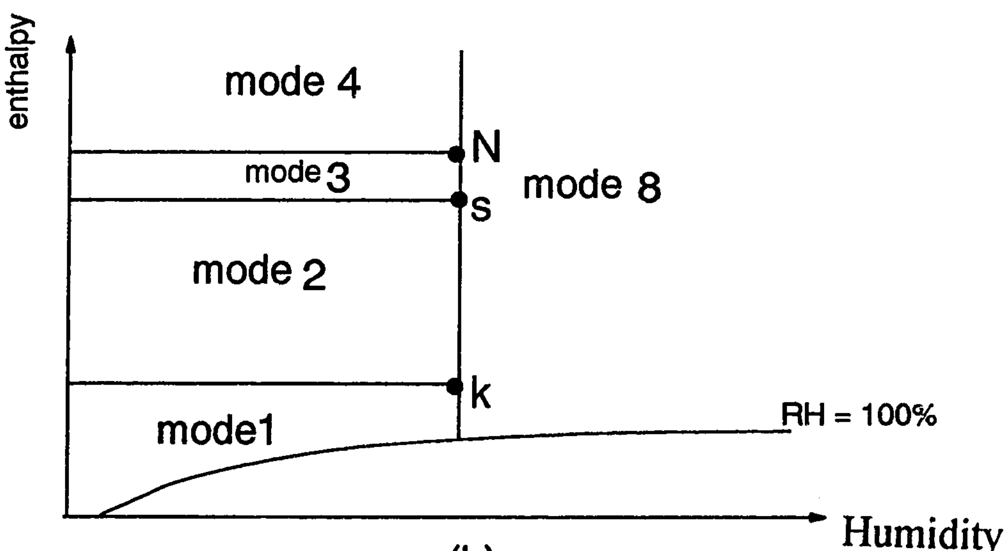

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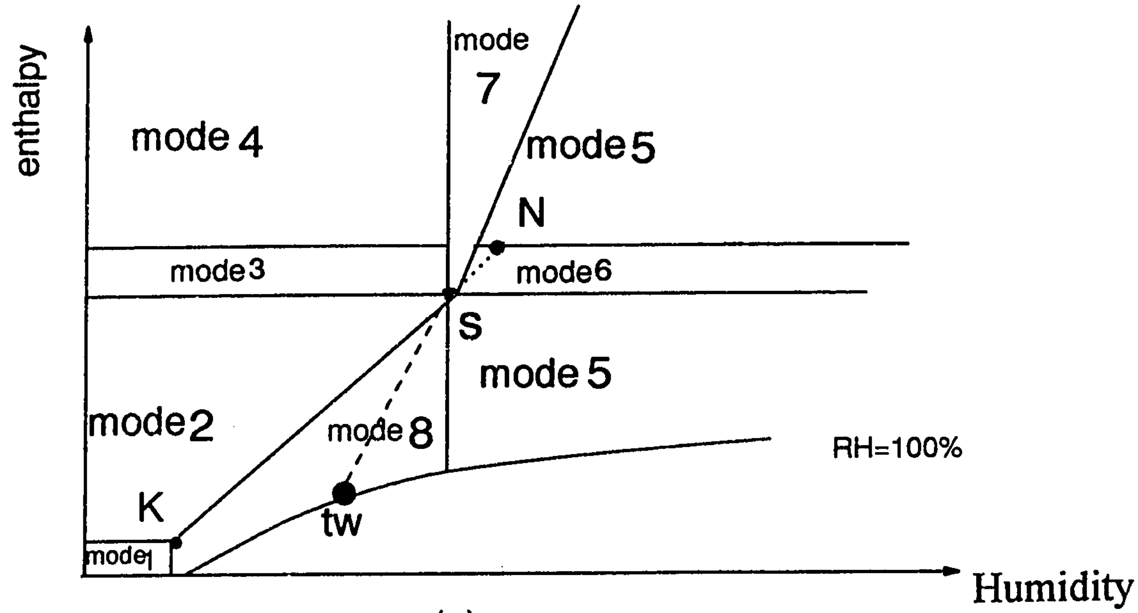
Figure A-4 Energy Saving Operation Mode Identification for THSCC System



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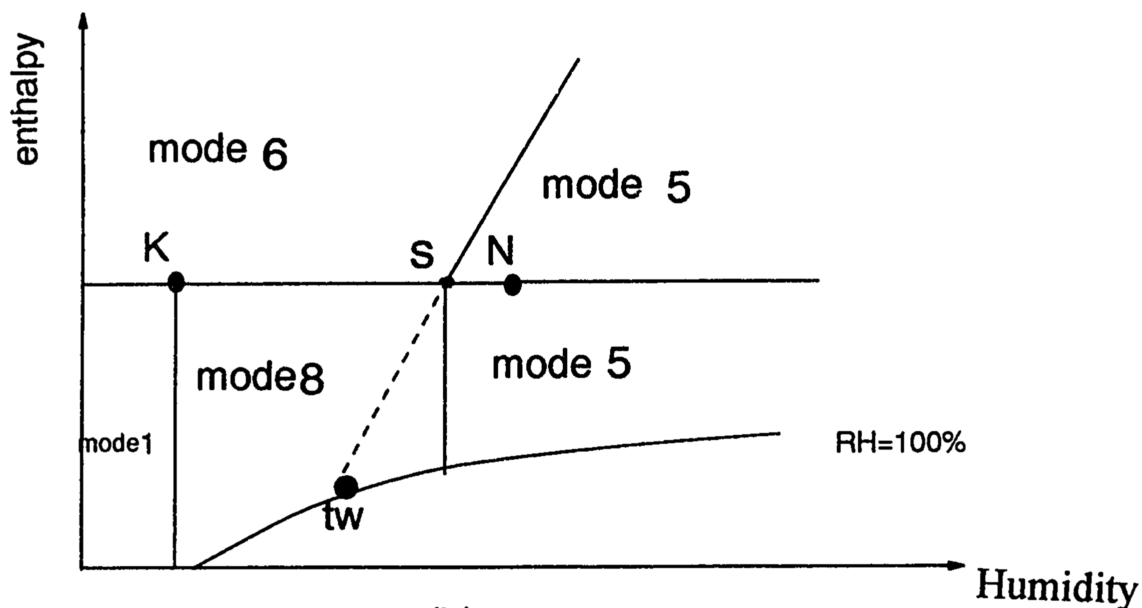

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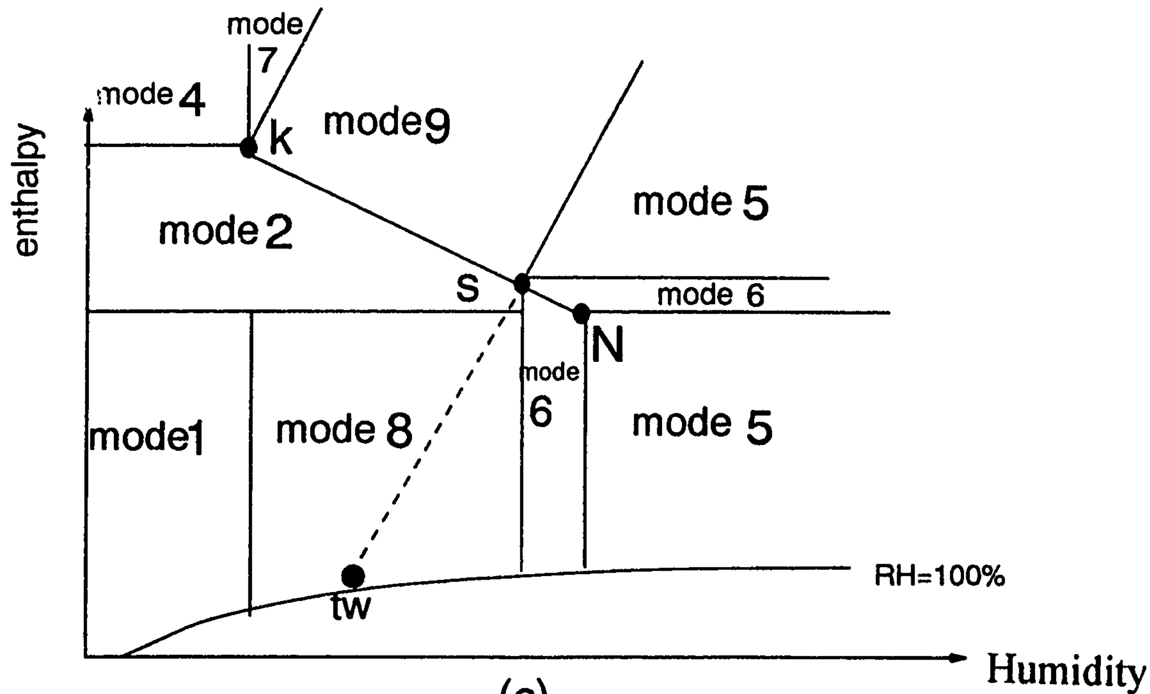

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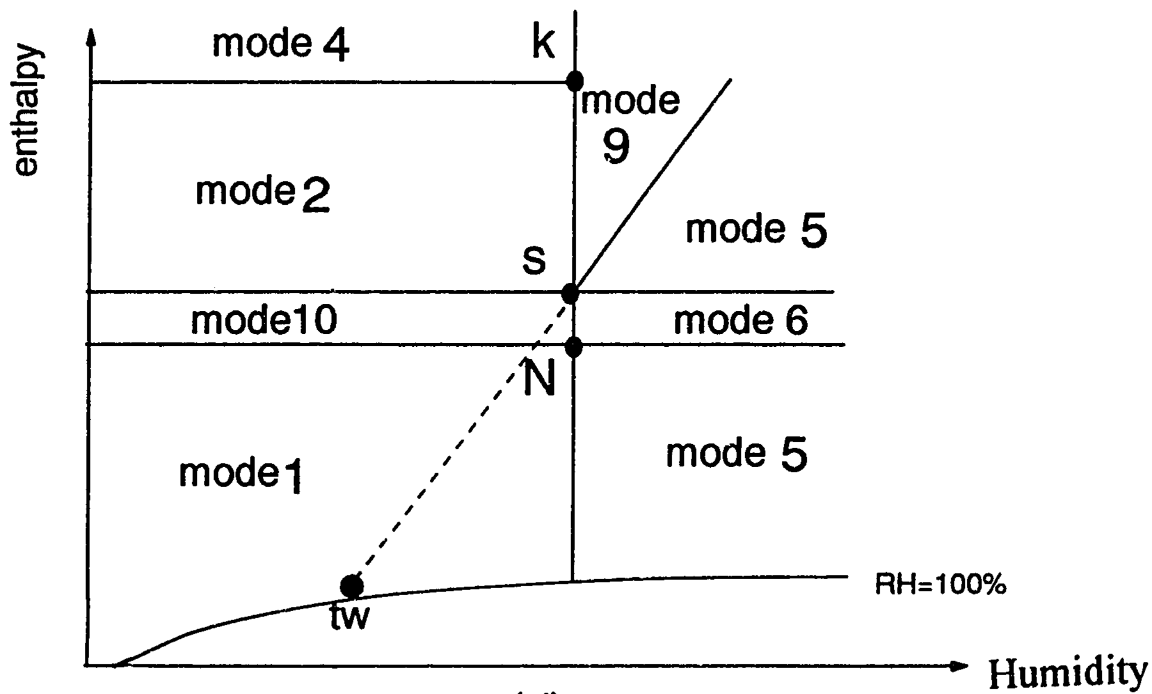

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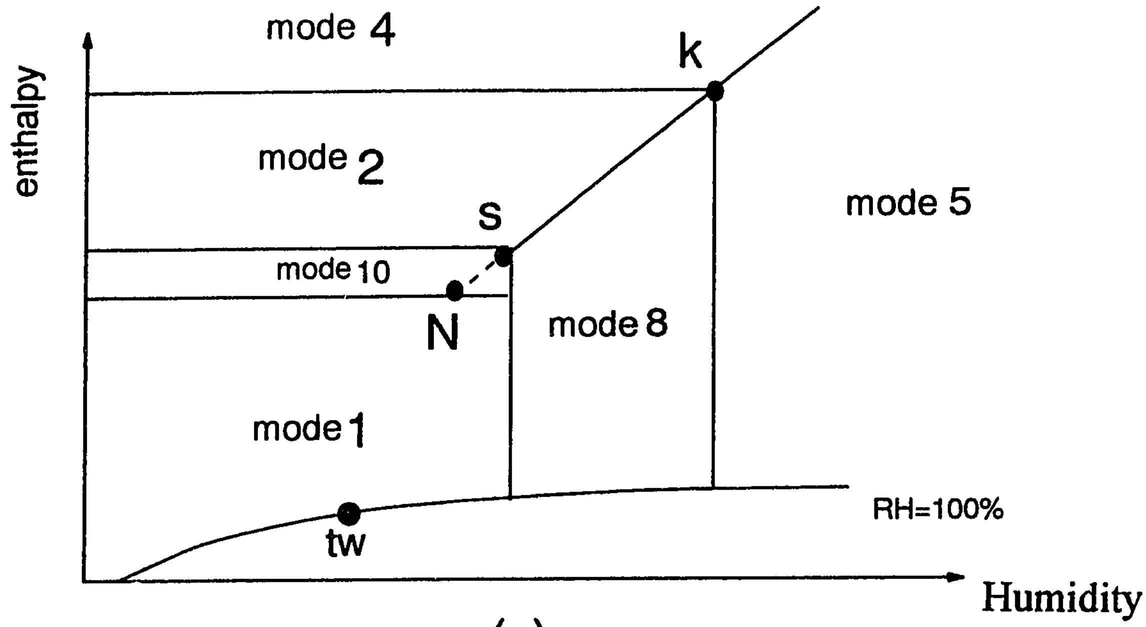

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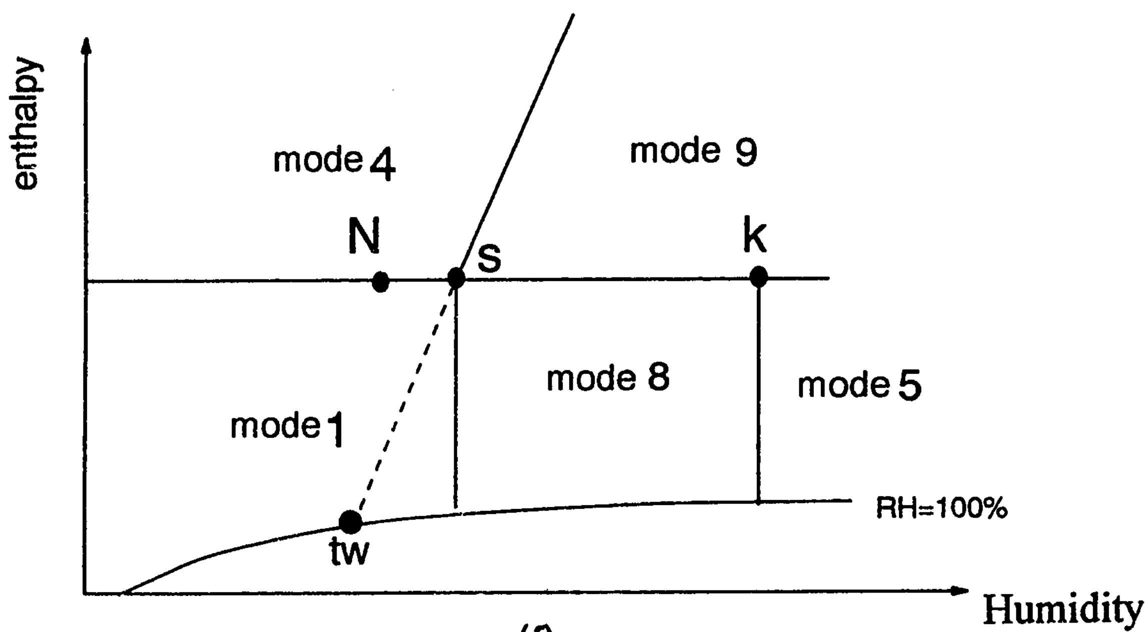

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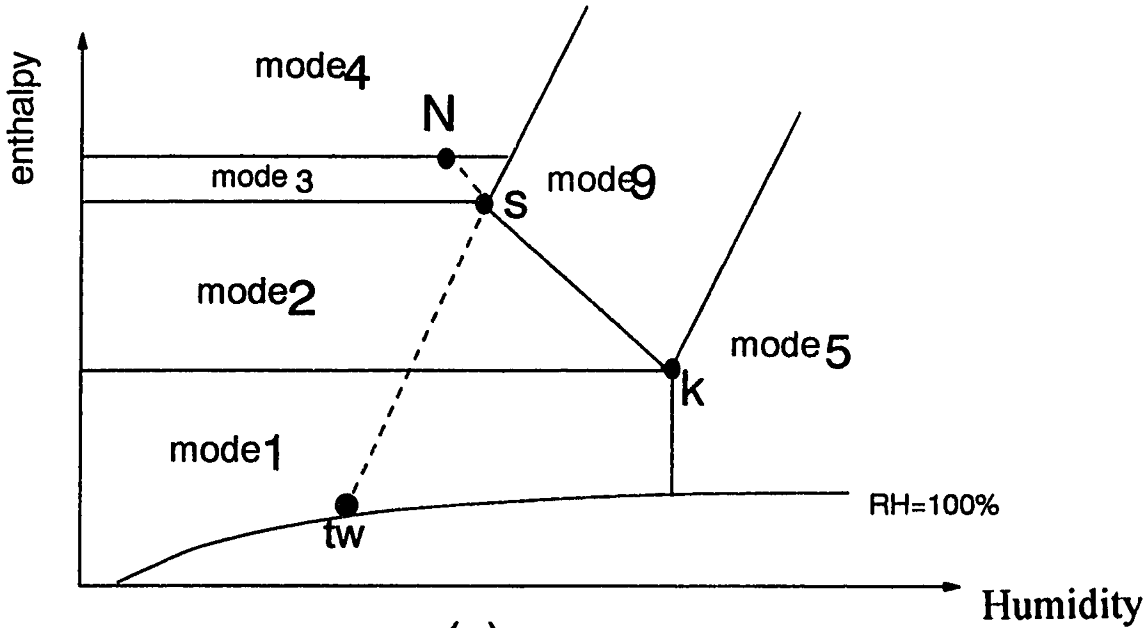

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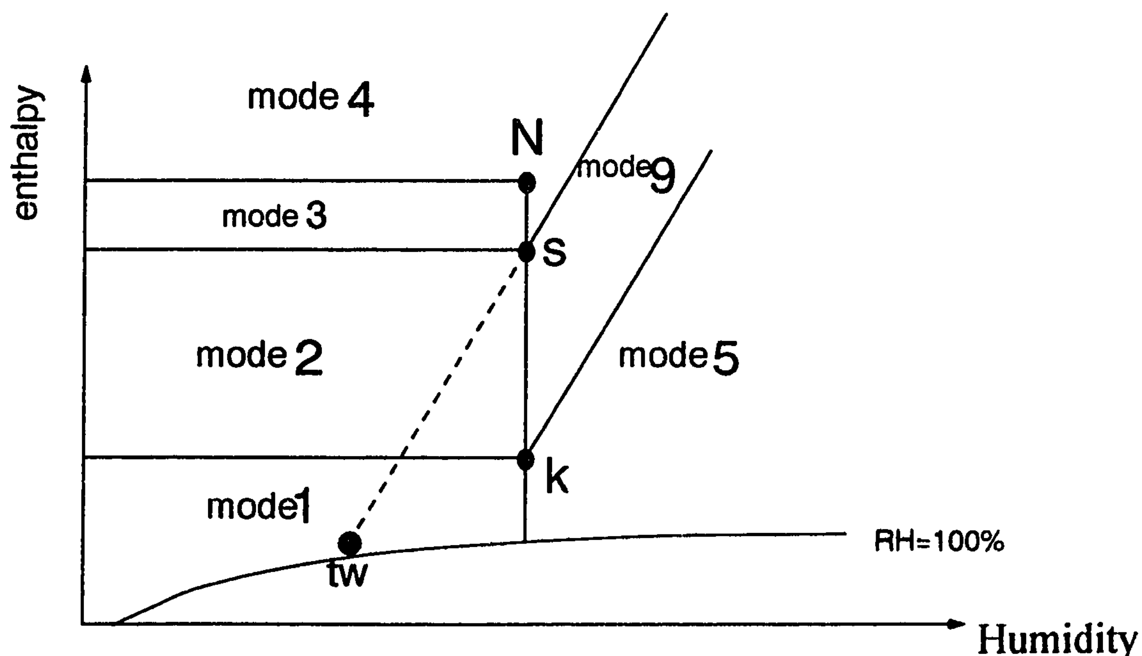

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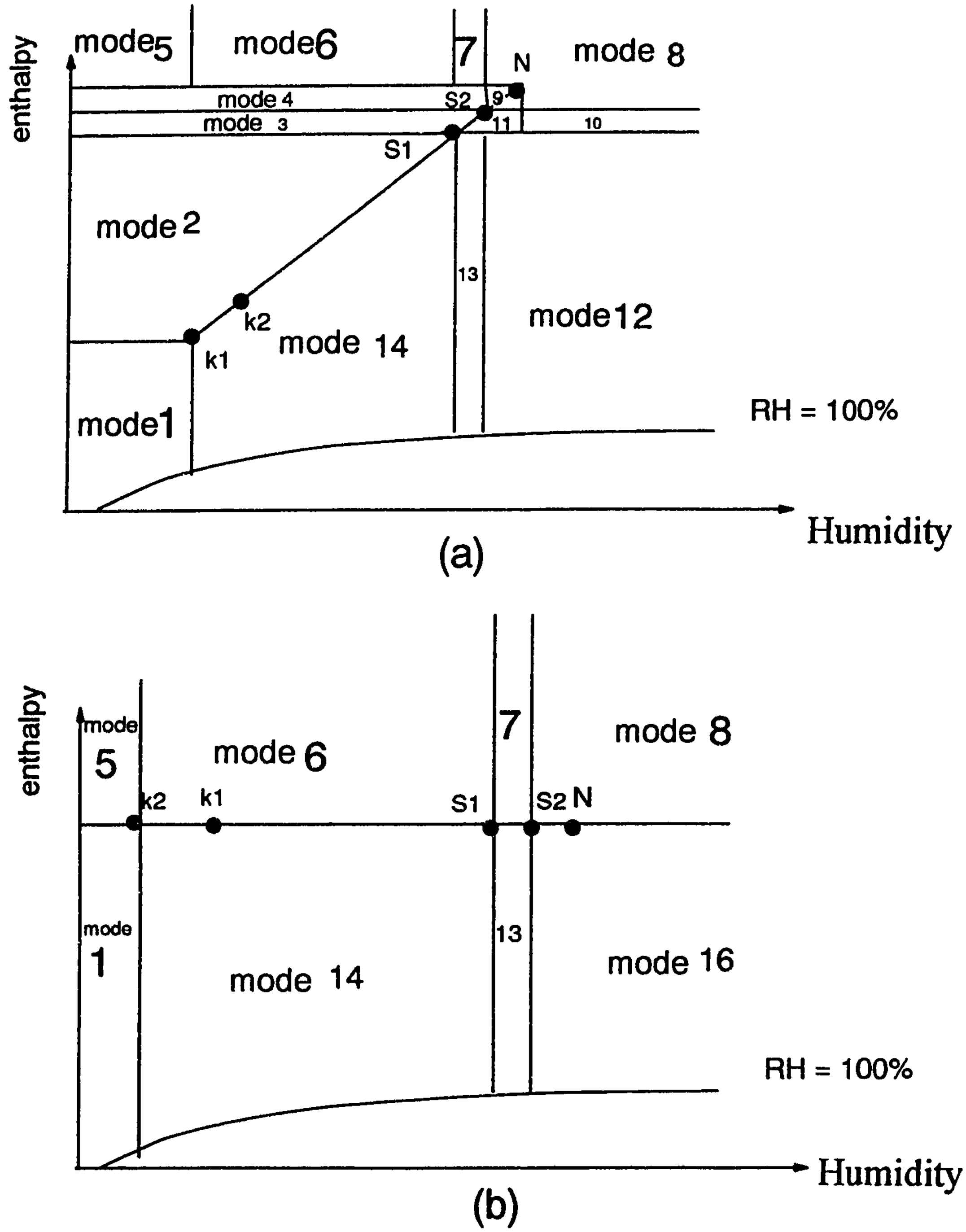

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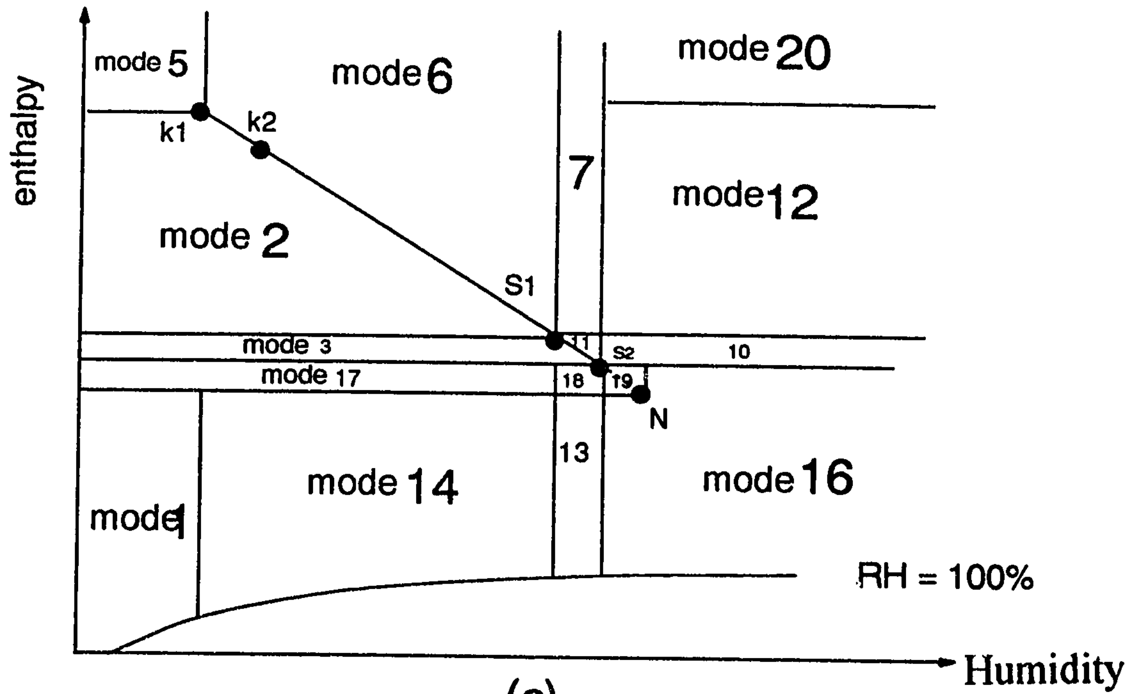

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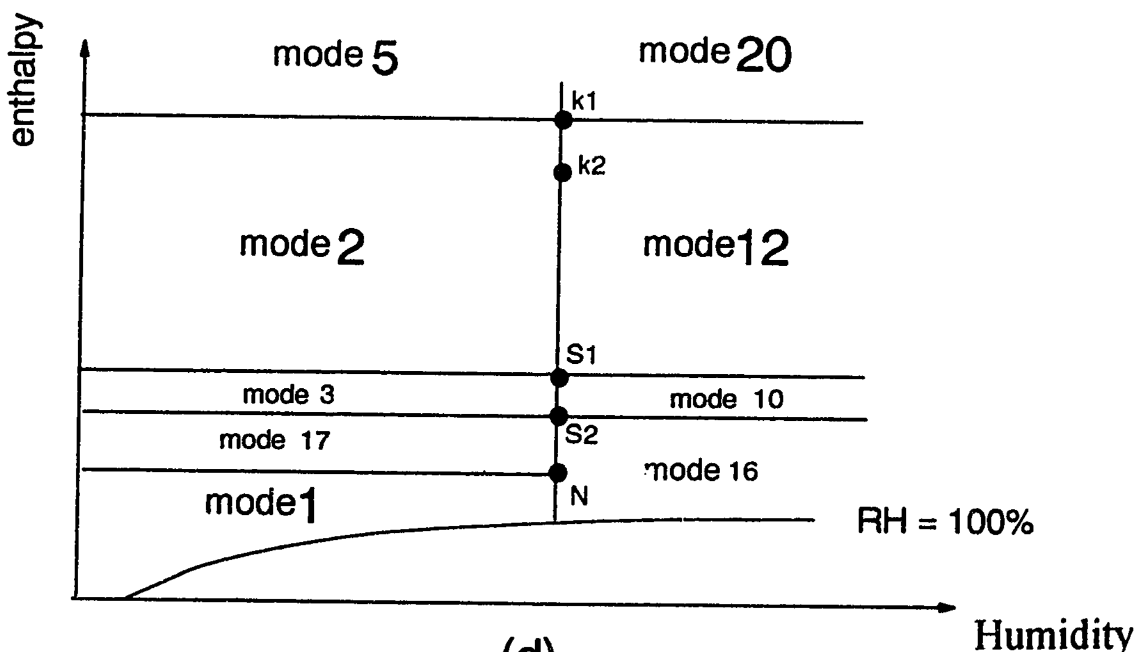

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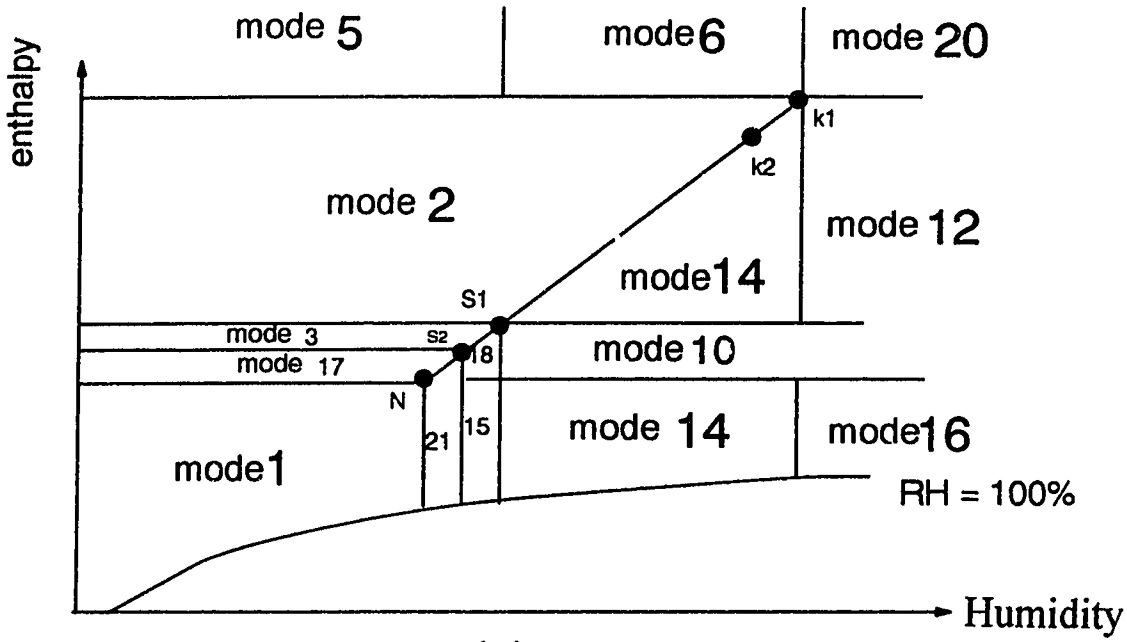

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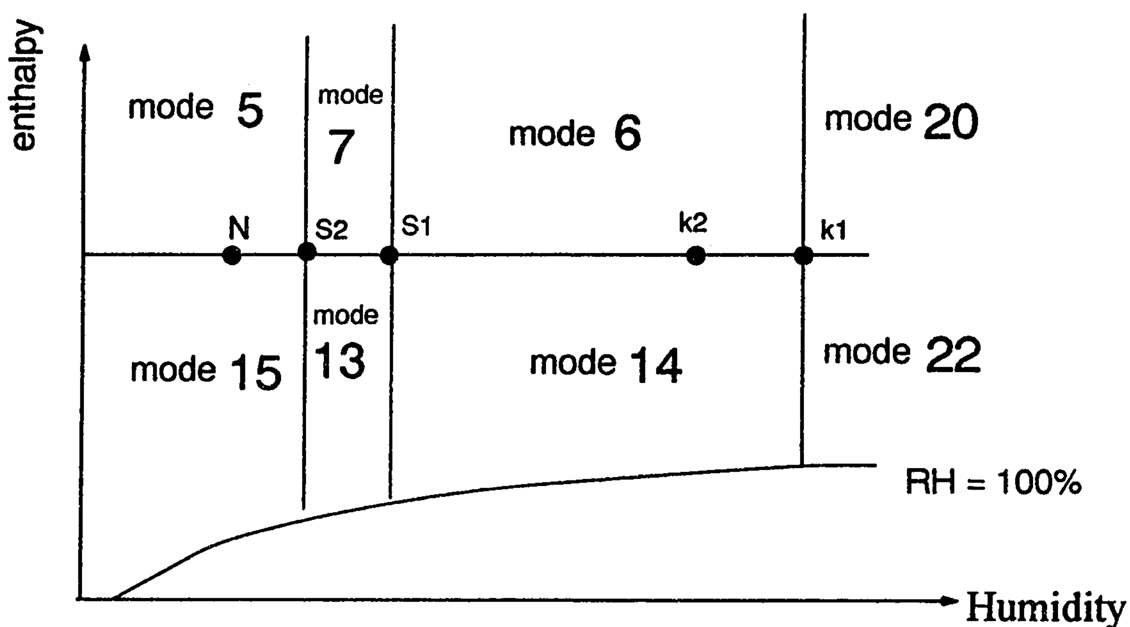

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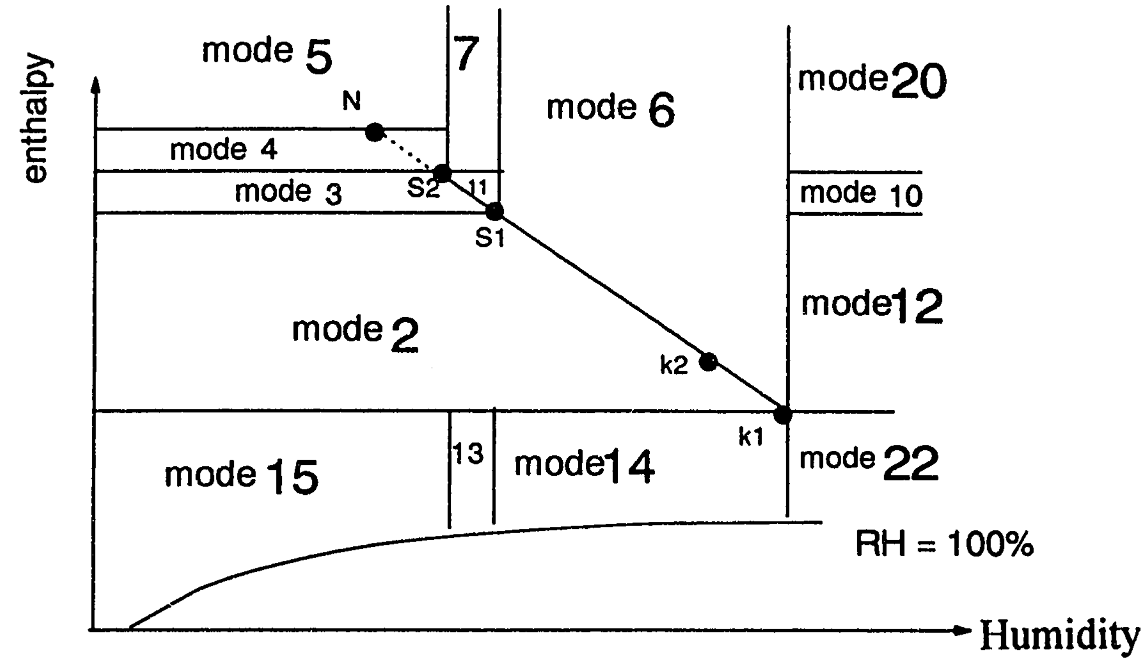

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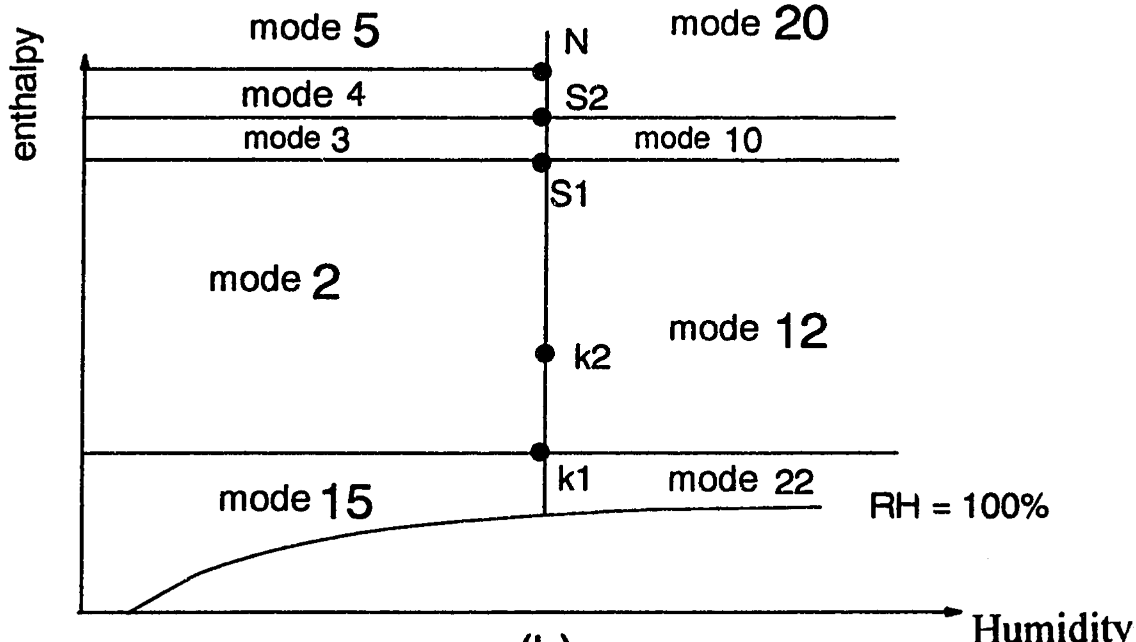

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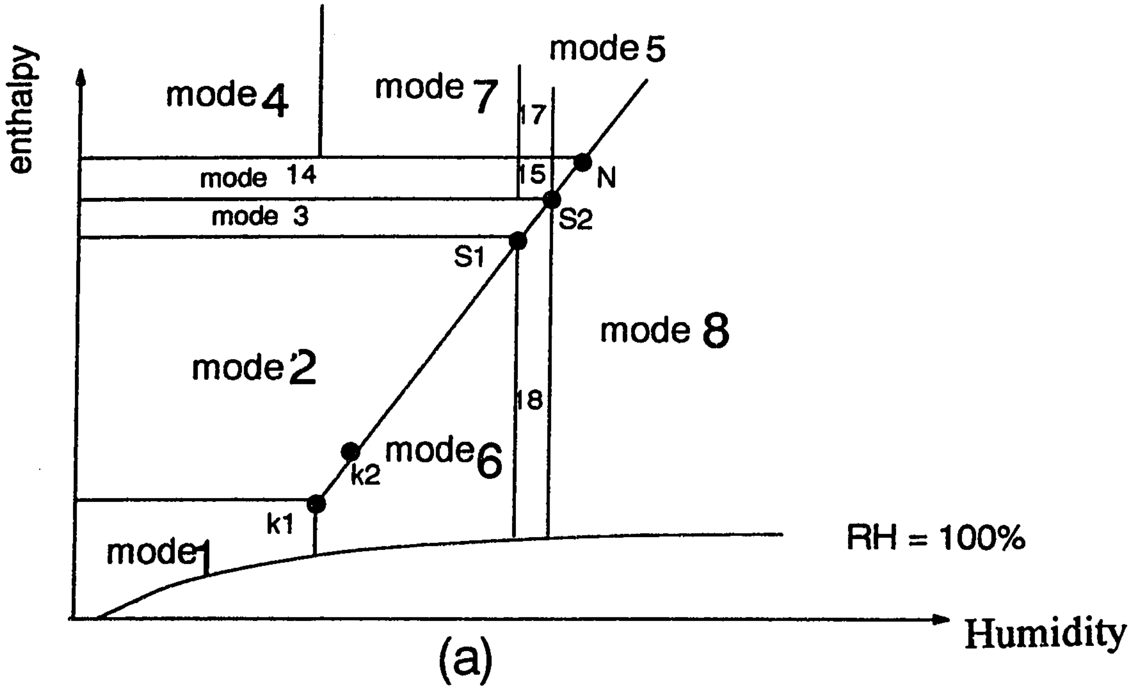


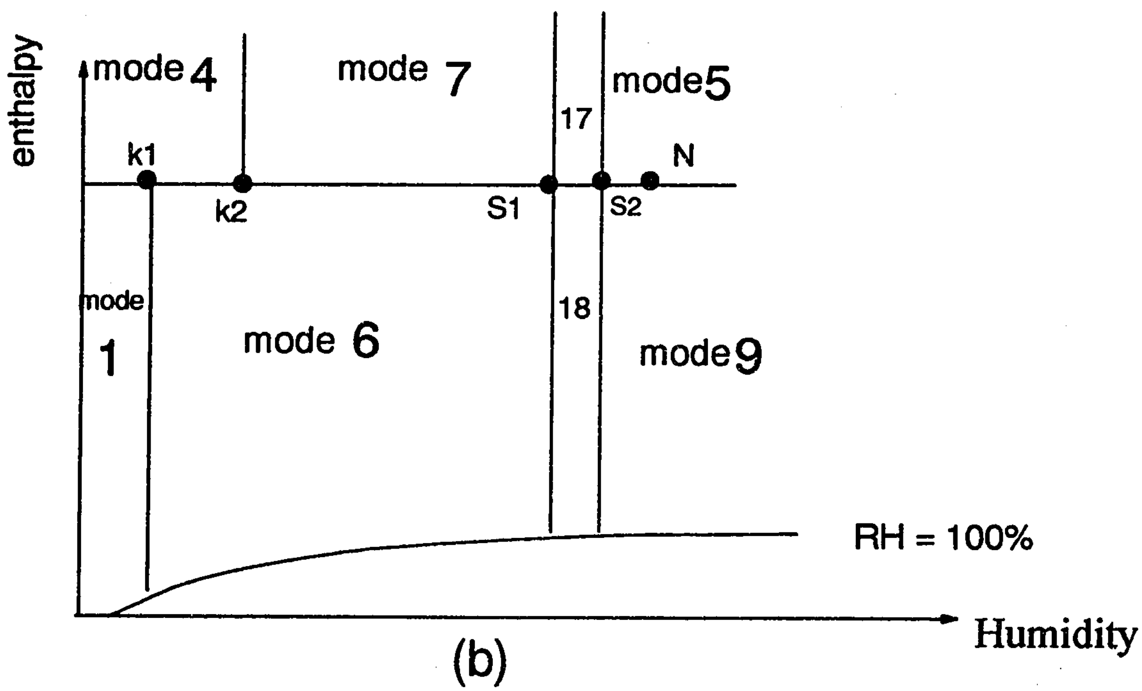


Figure A-7 Energy Saving Operation Mode Identification for THSVC System

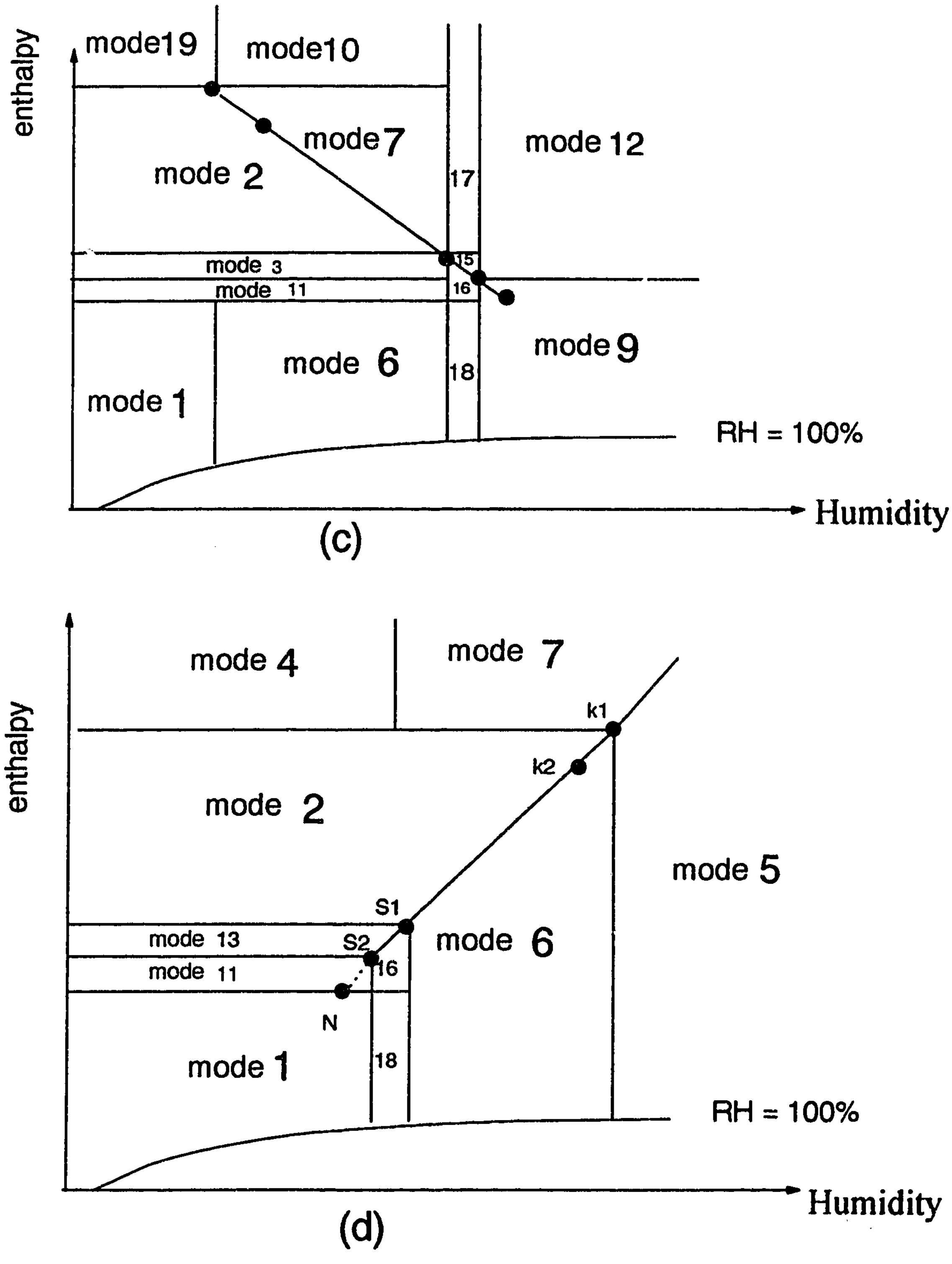


Figure A-7 Energy Saving Operation Mode Identification for THSVC System

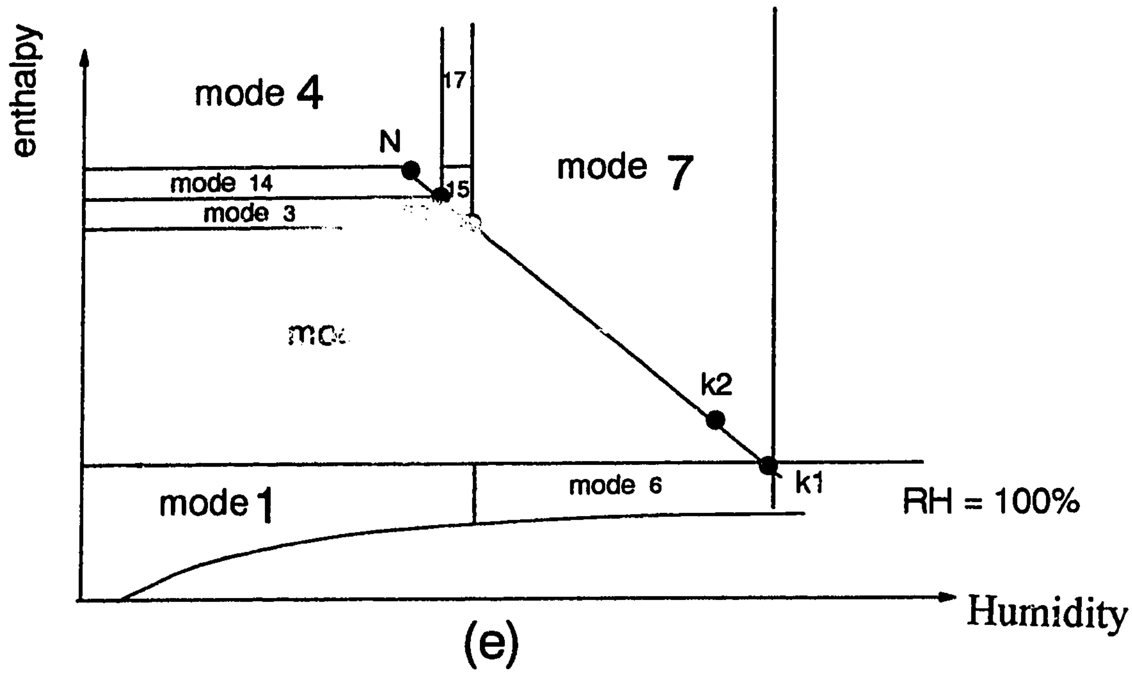


Figure A-7 Energy Saving Operation Mode Identification for THSVC System

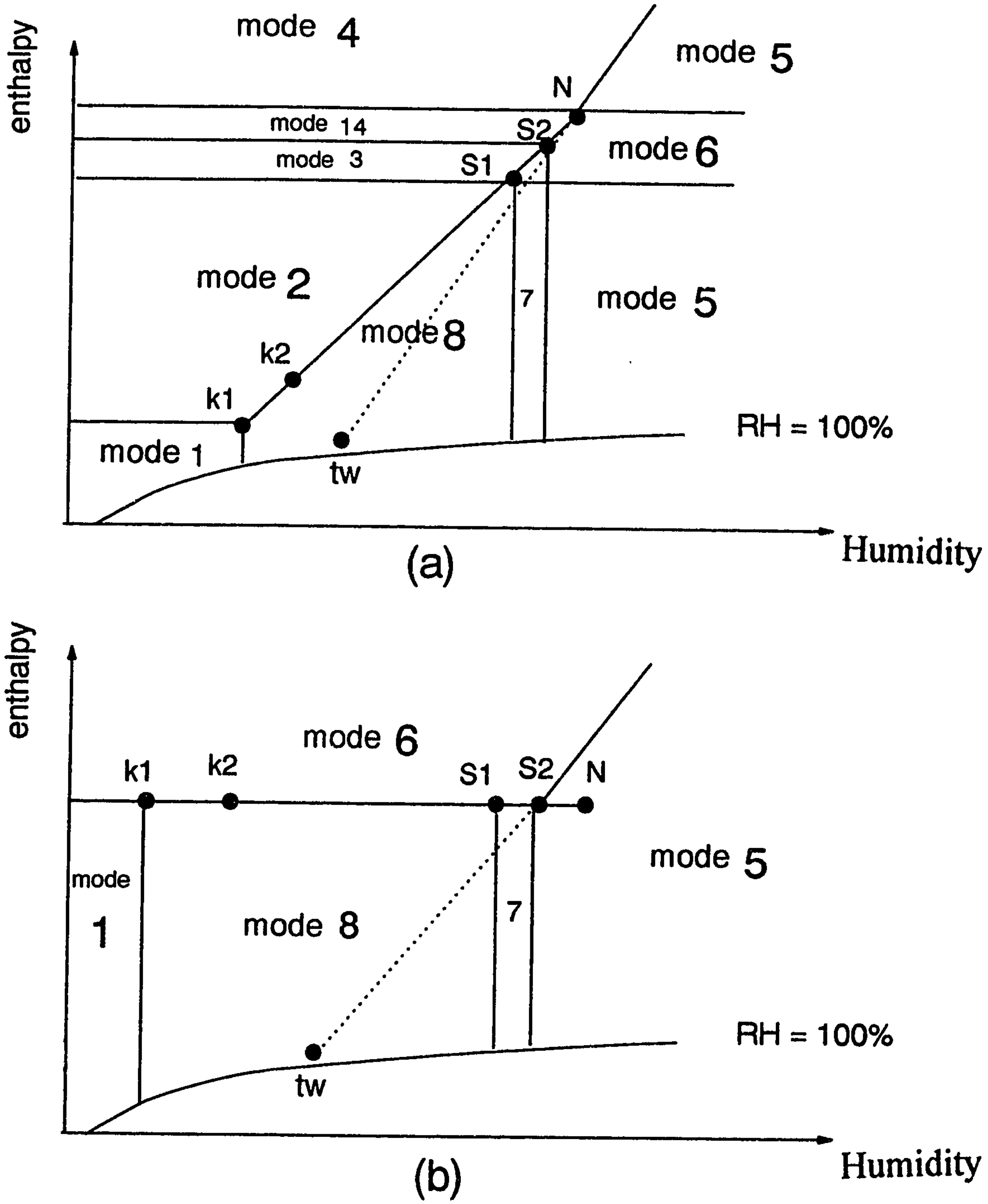
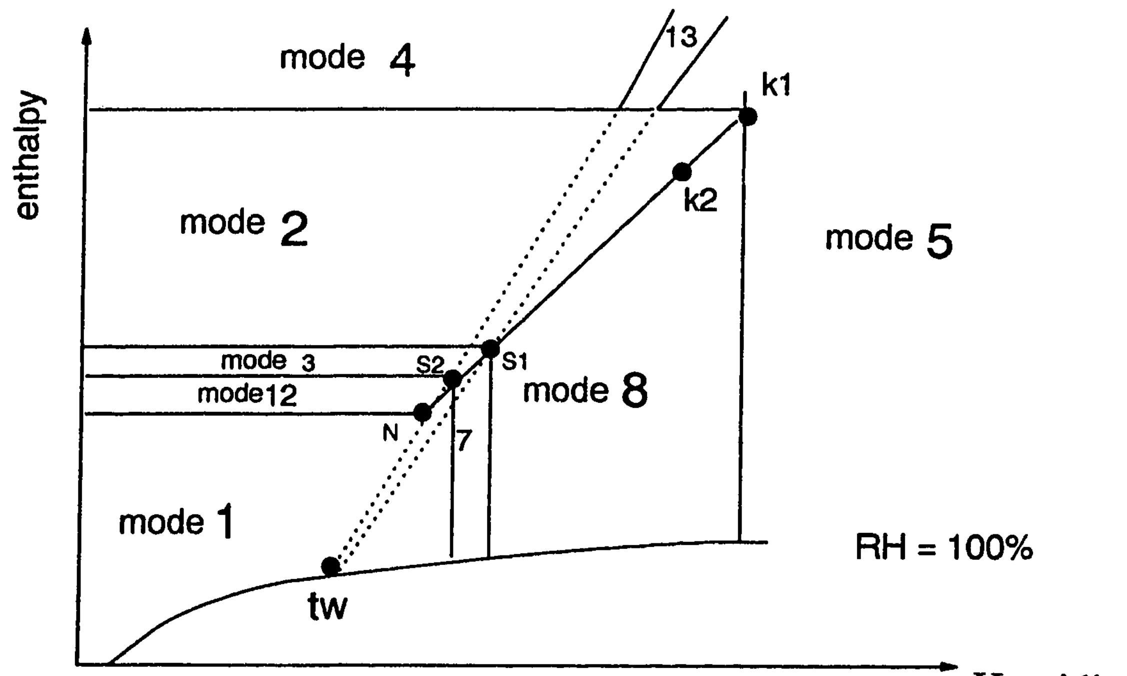
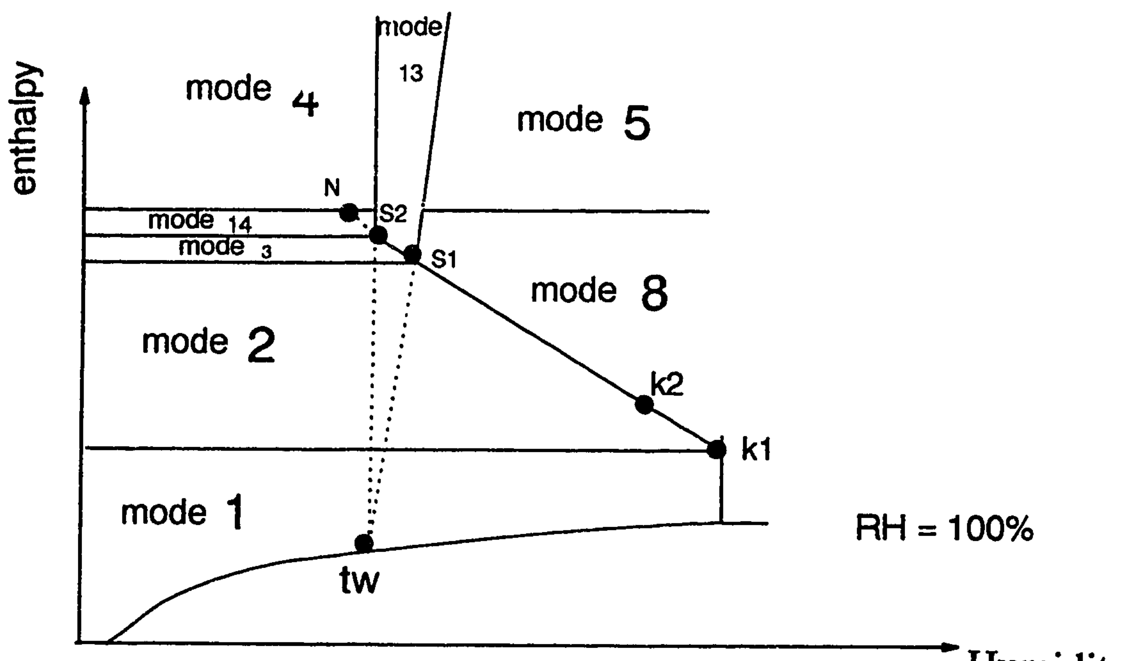


Figure A-8 Energy Saving Operation Mode Identification for THSVW System



(c)



(d)

Figure A-8 Energy Saving Operation Mode Identification for THSVW System

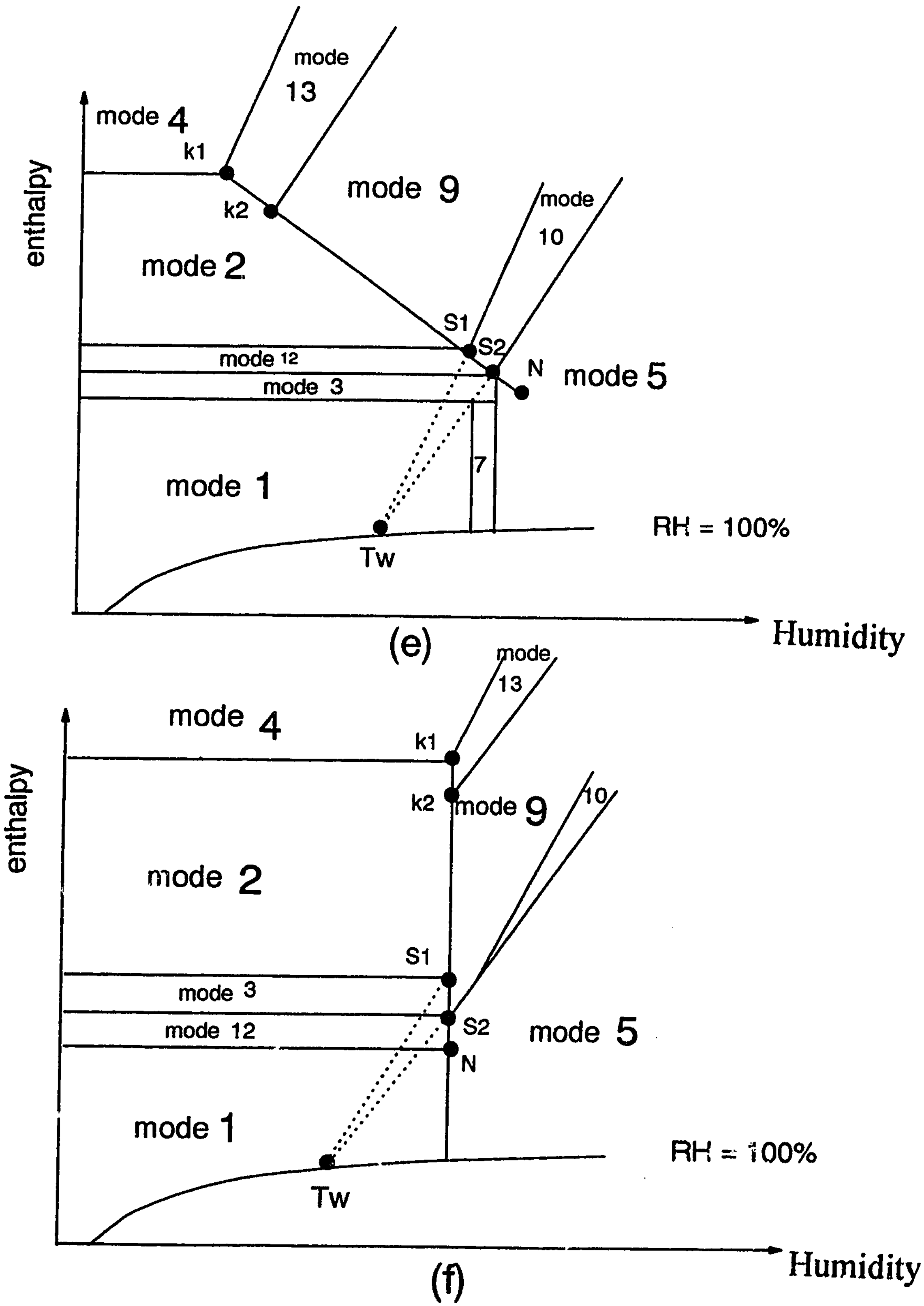


Figure A-8 Energy Saving Operation Mode Identification for THSVW System

Appendix B

Table B-1 OPERATION MODES FOR TSC SYSTEM

actuator / mode	return air damper opening U1	outside air damper opening U2	cooling coil U3	heater U4		
1	90%	10%	off	Ⓣ		
2	Ⓣ	1-U1	off	off		
3	0%	100%	Ⓣ	off		
4	90%	10%	Ⓣ	off		
5	0%	100%	off	Ⓣ		

* Ⓣ: The equipment used to control temperature

Table B-2 OPERATION MODES FOR TSV SYSTEM

mode \ actuator	return air damper opening u_1	outside air damper opening u_2	heating coil opening u_3	cooling coil opening u_4	supply volume u_5	
1	90%	10%	Ⓣ	off	min	
2	Ⓣ	1-U1	off	off	min	
3	off	100%	off	off	Ⓣ	
4	off	100%	off	Ⓣ	max	
5	90%	10%	off	Ⓣ	max	
6	90%	10%	Ⓣ	off	max	
7	off	100%	Ⓣ	off	max	
8	90%	10%	off	Ⓣ	min	

* Ⓣ: The equipment used to control temperature
* Ⓓ: The equipment used to control humidity

Table B-3 OPERATION MODES FOR THSCD SYSTEM

actuator / mode	return air damper U1	outside air damper U2	cooling coil U3	dehumidifier U4	humidifier U5	heater U6
1	90%	10%	off	off	Ⓓ	Ⓣ
2	Ⓣ	1-U1	off	off	Ⓓ	off
3	0%	100%	Ⓣ	off	Ⓓ	off
4	90%	10%	Ⓣ	off	Ⓓ	off
5	90%	10%	Ⓣ	Ⓓ	off	off
6	0%	100%	Ⓣ	Ⓓ	off	off
7	Ⓣ	1-U1	off	Ⓓ	off	off
8	90%	10%	off	Ⓓ	off	Ⓣ
9	Ⓓ	1-U1	off	off	off	Ⓣ
10	Ⓓ	1-U1	Ⓣ	off	off	off
11	0%	100%	off	Ⓓ	off	Ⓣ
12	0%	100%	off	off	Ⓓ	Ⓣ

* Ⓣ : The equipment used to control temperature
* Ⓓ : The equipment used to control humidity

Table B-4 OPERATION MODES FOR THSCC SYSTEM

actuator / mode	return air damper 1 opening U1	outside air damper opening U2	cooling coil U3	return air damper 2 opening U4	humidifier U5	heater U6
1	90%	10%	off	off	Ⓓ	Ⓣ
2	Ⓣ	1-U1	off	off	Ⓓ	off
3	0%	100%	Ⓣ	off	Ⓓ	off
4	90%	10%	Ⓣ	off	Ⓓ	off
5	90%	10%	on	Ⓓ	off	off
6	Ⓓ	1-U1	off	off	off	Ⓣ
7	Ⓓ	1-U1	Ⓣ	off	off	off
8	0%	100%	Ⓓ	Ⓣ	off	off
9	Ⓓ	1-U1	Ⓣ	off	off	off
10	0%	100%	off	off	Ⓓ	Ⓣ
11	0%	100%	off	off	Ⓓ	Ⓣ

* Ⓣ : The equipment used to control temperature
* Ⓓ : The equipment used to control humidity

Table B-5 OPERATION MODES FOR THSCW SYSTEM

actuator / mode	return air damper U1	outside air damper U2	air washer washer damper U3	air washer by pass U4	humidifier U5	heater U6
1	90%	10%	0%	100%	Ⓓ	Ⓣ
2	Ⓣ	1-U1	0%	100%	Ⓓ	off
3	0%	100%	Ⓣ	1-U3	Ⓓ	off
4	90%	10%	Ⓣ	1-U3	Ⓓ	off
5	90%	10%	Ⓓ	1-U3	off	Ⓣ
6	90%	10%	Ⓓ	1-U3	off	Ⓣ
7	90%	10%	Ⓣ	1-U3	Ⓓ	off
8	Ⓓ	1-U1	0%	100%	off	Ⓣ
9	Ⓓ	1-U1	Ⓣ	1-U3	off	off
10	0%	100%	0%	100%	Ⓓ	Ⓣ

* Ⓣ: The equipment used to control temperature
* Ⓓ: The equipment used to control humidity

Table B-6 OPERATION MODES FOR THSVD SYSTEM

actuator / mode	return air damper opening U1	outside air damper opening U2	cooling coil U3	dehumidifier U4	humidifier U5	heater U6	supply air volume U7
1	90%	10%	off	off	(D)	(T)	Min
2	(T)	1-U1	off	off	(D)	off	Min
3	off	100%	off	off	(D)	off	(T)
4	off	100%	(T)	off	(D)	off	Max
5	90%	10%	(T)	off	(D)	off	Min
6	(D)	1-U1	(T)	off	off	off	Min
7	(D)	1-U1	(T)	off	off	off	Max
8	90%	10%	(T)	(D)	off	off	Max
9	off	100%	(T)	(D)	off	off	Max
10	(T)	1-U1	off	(D)	off	off	Max
11	off	100%	(T)	off	off	off	(D)
12	(T)	1-U1	off	(D)	off	off	Min
13	(D)	1-U1	off	off	off	(T)	Max
14	(D)	1-U1	off	off	off	(T)	Min
15	90%	10%	off	off	(D)	(T)	Max
16	90%	10%	off	(D)	off	(T)	Max
17	off	100%	off	off	(D)	(T)	Max
18	off	100%	off	off	off	(T)	(D)
19	off	100%	off	(D)	off	(T)	Max
20	90%	10%	(T)	(D)	off	off	Min
21	90%	10%	off	off	(D)	(T)	Max

* (T) The equipment used to control temperature
* (D) The equipment used to control humidity

Table B-7 OPERATION MODES FOR THSVC SYSTEM

actuator / mode	return air damper 1 opening U1	outside air damper opening U2	cooling coil cool opening U3	cooling coil by pass opening U4	humidifier U5	heater U6	return air damper 2 opening U7	Supply air volume U8
1	90%	10%	off	off	Ⓓ	Ⓣ	off	Min
2	Ⓣ	1-U1	off	off	Ⓓ	off	off	Min
3	off	100%	off	off	Ⓓ	off	off	Ⓣ
4	90%	10%	Ⓣ	off	Ⓓ	off	off	Min
5	90%	10%	Ⓓ	1-U3	off	Ⓣ	off	Max
6	off	100%	Ⓓ	off	off	Ⓣ	off	Min
7	Ⓓ	1-U1	off	off	off	Ⓣ	off	Max
8	Ⓓ	1-U1	off	off	off	Ⓣ	Ⓣ	Min
9	Ⓓ	1-U1	Ⓣ	off	off	off	Ⓓ	Min
10	off	1-U1	Ⓓ	off	off	off	off	Ⓣ
11	off	100%	off	off	Ⓓ	Ⓣ	off	Max
12	off	100%	Ⓓ	Ⓣ	off	off	off	Min
13	Ⓓ	1-U1	off	off	off	Ⓣ	off	Max
14	off	100%	Ⓣ	off	Ⓓ	off	off	Min
15	off	100%	Ⓣ	off	off	off	off	Ⓓ
16	off	100%	off	off	off	Ⓣ	off	Ⓓ
17	Ⓓ	1-U1	Ⓣ	off	off	off	off	Max

* Ⓣ The equipment used to control temperature
* Ⓓ The equipment used to control humidity

Table B-8 OPERATION MODES FOR THSVW SYSTEM

actuator / mode	return air damper opening U1	outside air damper opening U2	air washer washer damper opening U3	air washer by pass opening U4	humidifier U5	heater U6	Supply air volume U7
1	90%	10%	off	off	Ⓓ	Ⓣ	Min
2	Ⓣ	1-U1	off	off	Ⓓ	off	Min
3	off	100%	off	off	Ⓓ	off	Ⓣ
4	90%	10%	Ⓣ	1-U3	Ⓓ	off	Min
5	90%	10%	Ⓓ	1-U3	off	Ⓣ	Max
6	off	100%	Ⓓ	1-U3	off	Ⓣ	Min
7	Ⓓ	1-U1	off	off	off	Ⓣ	Max
8	Ⓓ	1-U1	off	off	off	Ⓣ	Min
9	Ⓓ	1-U1	Ⓣ	1-U3	off	off	Min
10	off	100%	Ⓓ	1-U3	off	off	Ⓣ
11	off	100%	off	off	off	Ⓣ	Ⓓ
12	off	100%	off	off	Ⓓ	Ⓣ	Max
13	90%	10%	Ⓓ	off	off	off	Ⓣ
14	off	100%	Ⓣ	1-U3	Ⓓ	off	Max

* Ⓣ The equipment used to control temperature
* Ⓓ The equipment used to control humidity

Appendix C

46 POINTS TRACED. --

EGU - enginnering units
AHU - air handling unit
AC - air conditioning unit
RAD - radiation

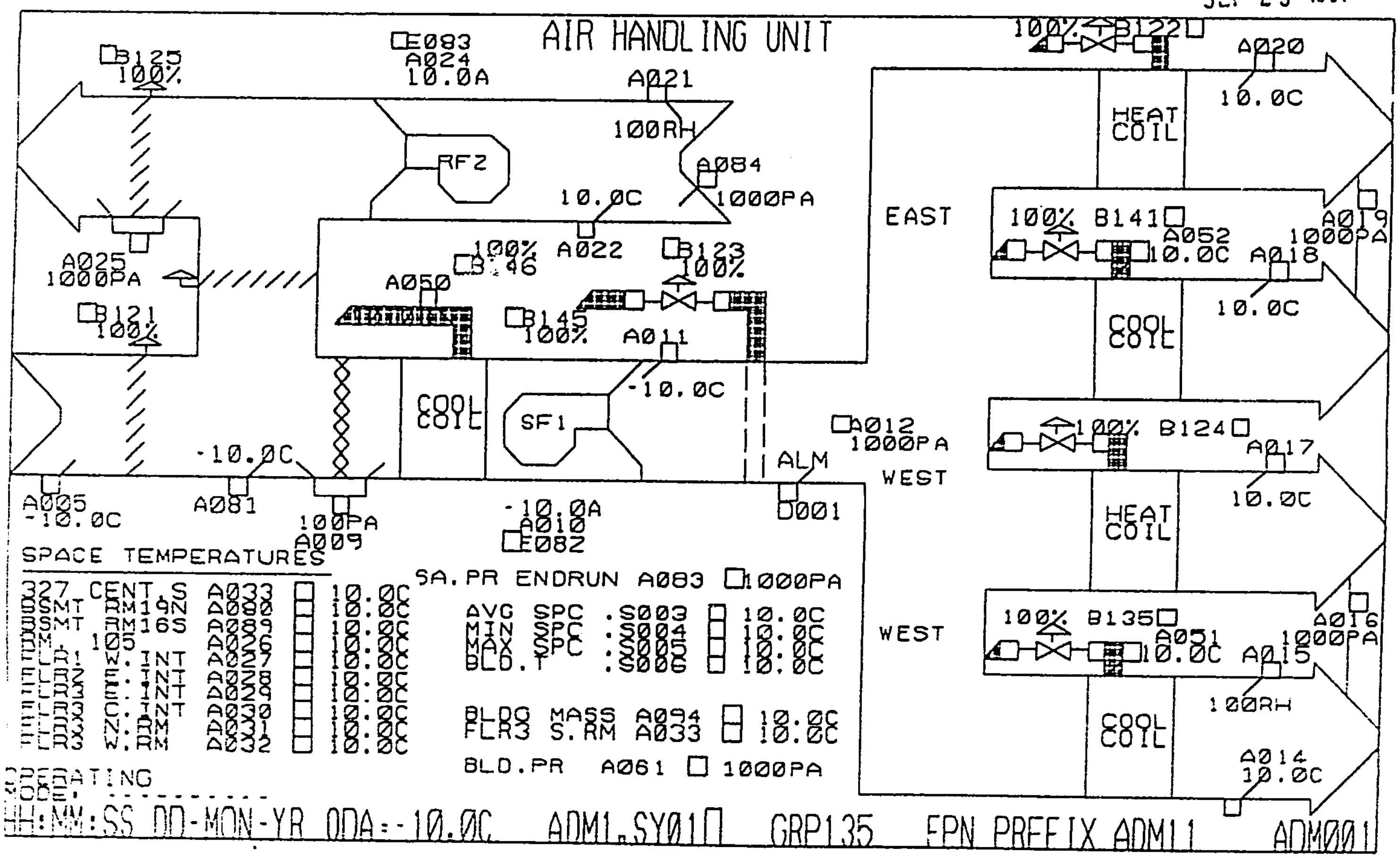
Units

C - Degrees Celsius
AMP - Amperes
PA - Pascals
RH - % relative humidity
PCT - percent 0...100%

POINT	EGU Range		Unit	Desc of function & location				
ADM11A010	10.000	120.000	AMP	SF.I	1	AHU1	ADM001	-- supply fan motor current
ADM11A011	10.000	20.000	C	SA.T	1	AHU1	ADM001	-- supply air temparature
ADM11A012	0.000	2500.000	PA	SA.PR	SPACE	AHU1	ADM001	-- supply air pressure
ADM11A014	10.000	20.000	C	CD.T	WEST	AHU1	ADM001	-- cold deck temparature
ADM11A016	-100.000	300.000	PA	SA.DP	WEST	AHU1	ADM001	-- supply air diff. pressure
ADM11A017	15.000	35.000	C	HD.T	WEST	AHU1	ADM001	-- hot deck, temparature
ADM11A018	10.000	20.000	C	CD.T	EAST	AHU1	ADM001	-- cold deck temparature
ADM11A019	-100.000	300.000	PA	SA.DP	EAST	AHU1	ADM001	-- supply air diff. pressure
ADM11A020	15.000	35.000	C	HD.T	EAST	AHU1	ADM001	-- hot deck temparature
ADM11A022	20.000	30.000	C	RA.T		AHU1	ADM001	-- return air temparature
ADM11A025	-200.000	400.000	PA	E.DP		AC1	ADM001	-- exhaust diff. pressure
ADM11A015	0.000	100.000	RH	CD.M	WEST	AHU1	ADM001	-- cold deck moisture (humidity)
ADM11A021	0.000	100.000	RH	RA.M		AC1	ADM001	-- retrun air moisture (humidity)
ADM11A051	3.000	23.000	C	CCR.T	WEST	AHU1	ADM001	-- cooling coil return temparature
ADM11A052	3.000	23.000	C	CCR.T	EAST	AHU1	ADM001	-- cooling coil return temparature
ADM11A005	-30.000	30.000	C	OA.T	NORTH	RAD	ADM002	-- outdoor air temparature
ADM11A048	-30.000	30.000	C	OA.T	EAST	RAD	ADM002	-- outdoor air temparature
ADM11A049	-30.000	30.000	C	OA.T	WEST	RAD	ADM002	-- outdoor air temparature
ADM11A054	-30.000	30.000	C	OA.T	SOUTH	RAD	ADM002	-- outdoor air temparature
ADM11A095	0.000	20.000	C	SOL.T		EAST	ADM002	-- solar temperature
ADM11A096	0.000	20.000	C	SOL.T		SW	ADM002	-- solar temperature
ADM11A097	0.000	20.000	C	SOL.T		WEST	ADM002	-- solar temperature
ADM11A026	17.000	27.000	C	SPC.T	109	SOUTH	ADM001	-- space temperature
ADM11A027	17.000	27.000	C	SPC.T	120	WEST	ADM001	-- space temperature
ADM11A028	17.000	27.000	C	SPC.T	FLR2	INTER	ADM001	-- space temperature
ADM11A029	17.000	27.000	C	SPC.T	EAST	FLR.3	ADM001	-- space temperature
ADM11A030	17.000	27.000	C	SPC.T	FLR3	INTER	ADM001	-- space temperature
ADM11A031	17.000	27.000	C	SPC.T	351	NORTH	ADM001	-- space temperature

ADM11A032	17.000	27.000	C	SPC.T	341	WEST	ADM001	-- space temperature
ADM11A033	17.000	27.000	C	SPC.T	327	SOUTH	ADM001	-- space temperature
ADM11A080	17.000	27.000	C	SPC.T	19	NORTH	ADM001	-- space temperature
ADM11A089	17.000	27.000	C	SPC.T	16	SOUTH	ADM001	-- space temperature
ADM11A061	-20.000	60.000	PA	BLD.PR		AHU1	ADM001	-- building pressure
ADM11A094	20.000	30.000	C	BLDG.T	MASS	AC1	ADM001	-- building mass
ADM11A081	-10.000	30.000	C	MA.T		AHU1	ADM001	-- mixed air temperature
ADM11A083	0.000	1000.000	PA	SA.PR	ENDRUN	AHU1	ADM001	-- supply air pressure
ADM11A084	-100.000	100.000	PA	RA.PR		AHU1	ADM001	-- return air pressure
ADM11B121	0.000	100.000	PCT	MA.DPR		AHU1	ADM001	-- mixed air damper position
ADM11B122	0.000	100.000	PCT	HD.TV	EAST		ADM001	-- hot deck temperature valve position
ADM11B123	0.000	100.000	PCT	SA.MV		AHU1	ADM001	-- supply air moisture valve position
ADM11B124	0.000	100.000	PCT	HD.TV	WEST		ADM001	-- hot deck temperature valve position
ADM11B125	0.000	100.000	PCT	E.DPR		AHU1	ADM001	-- exhaust damper position
ADM11B135	0.000	100.000	PCT	CC.TV	WEST	AHU1	ADM001	-- cooling coil temperature valve position
ADM11B141	0.000	100.000	PCT	CD.TV	EAST		ADM001	-- cold deck temperature valve position
ADM11B145	0.000	100.000	PCT	VO.CTL	SF1	AHU1	ADM001	-- supply volume control position
ADM11B146	0.000	100.000	PCT	VO.CTL	RF2	AHU1	ADM001	-- retrun volume control position

SEP 25 1991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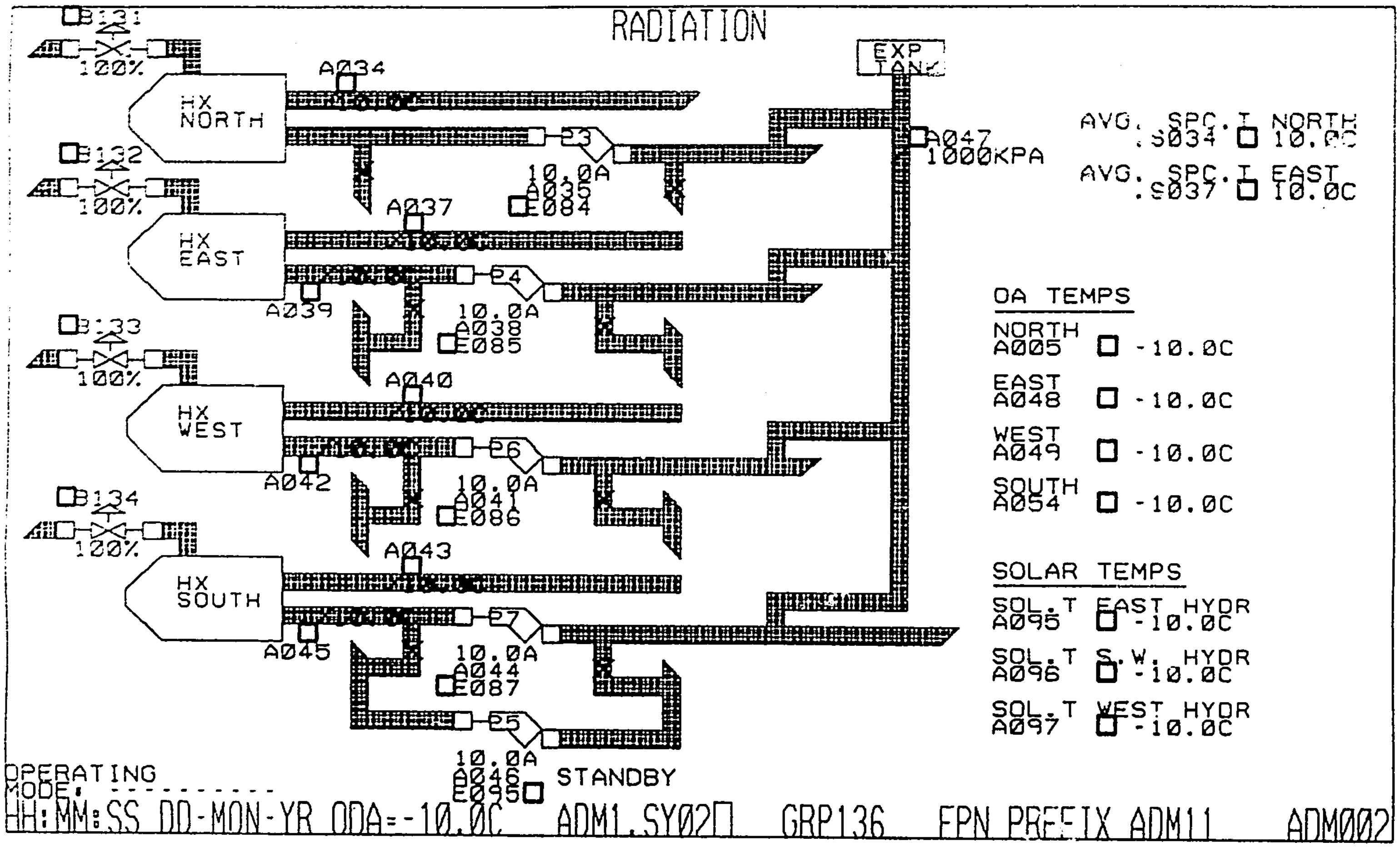
B125 100%
E083 A024 10.0A
A021 100RH
A084 1000PA
RF2
10.0C A022
100% B146
A050
B123 100%
B145 100%
A011 -10.0C
A025 1000PA
B121 100%
COOL COIL
SF1
A005 -10.0C
-10.0C A081
100PA A009
-10.0A A010 E082
ALM D001
A012 1000PA
EAST
WEST
WEST
100% B122
A020 10.0C
HEAT COIL
100% B141
A052 10.0C A018
A019 1000PA
10.0C
COOL COIL
100% B124
A017 10.0C
HEAT COIL
100% B135
A051 10.0C A015
A016 1000PA
100RH
COOL COIL
A014 10.0C
SPACE TEMPERATURES
327 CENT.S A033 10.0C
BSMT RM19N A080 10.0C
BSMT RM16S A089 10.0C
RM. 105 A026 10.0C
FLR1 W.INT A027 10.0C
FLR2 E.INT A028 10.0C
FLR3 E.INT A029 10.0C
FLR3 C.INT A030 10.0C
FLRX N.RM A031 10.0C
FLR3 W.RM A032 10.0C
SA.PR ENDRUN A083 1000PA
AVG SPC :S003 10.0C
MIN SPC :S004 10.0C
MAX SPC :S005 10.0C
BLD.T :S006 10.0C
BLDG MASS A094 10.0C
FLR3 S.RM A033 10.0C
BLD.PR A061 1000PA
OPERATING MODE: ----------
HH:MM:SS DD-MON-YR ODA:-10.0C ADM1.SY01 GRP135 FPN PREFIX ADM11 ADM001



RADIATION
B131
100%
HX NORTH
A034
P3
10.0A
A035
E084
B132
100%
HX EAST
A037
A039
P4
10.0A
A038
E085
B133
100%
HX WEST
A040
A042
P6
10.0A
A041
E086
B134
100%
HX SOUTH
A043
A045
P7
10.0A
A044
E087
P5
10.0A
A046
E095
STANDBY
EXP TANK
A047
1000KPA
AVG. SPC.T NORTH :S034 10.0C
AVG. SPC.T EAST :S037 10.0C
OA TEMPS
NORTH A005 -10.0C
EAST A048 -10.0C
WEST A049 -10.0C
SOUTH A054 -10.0C
SOLAR TEMPS
SOL.T EAST HYDR A095 -10.0C
SOL.T S.W. HYDR A096 -10.0C
SOL.T WEST HYDR A097 -10.0C
OPERATING MODE: ----------
HH:MM:SS DD-MON-YR ODA=-10.0C ADM1.SY02 GRP136 FPN PREFIX ADM11 ADM002

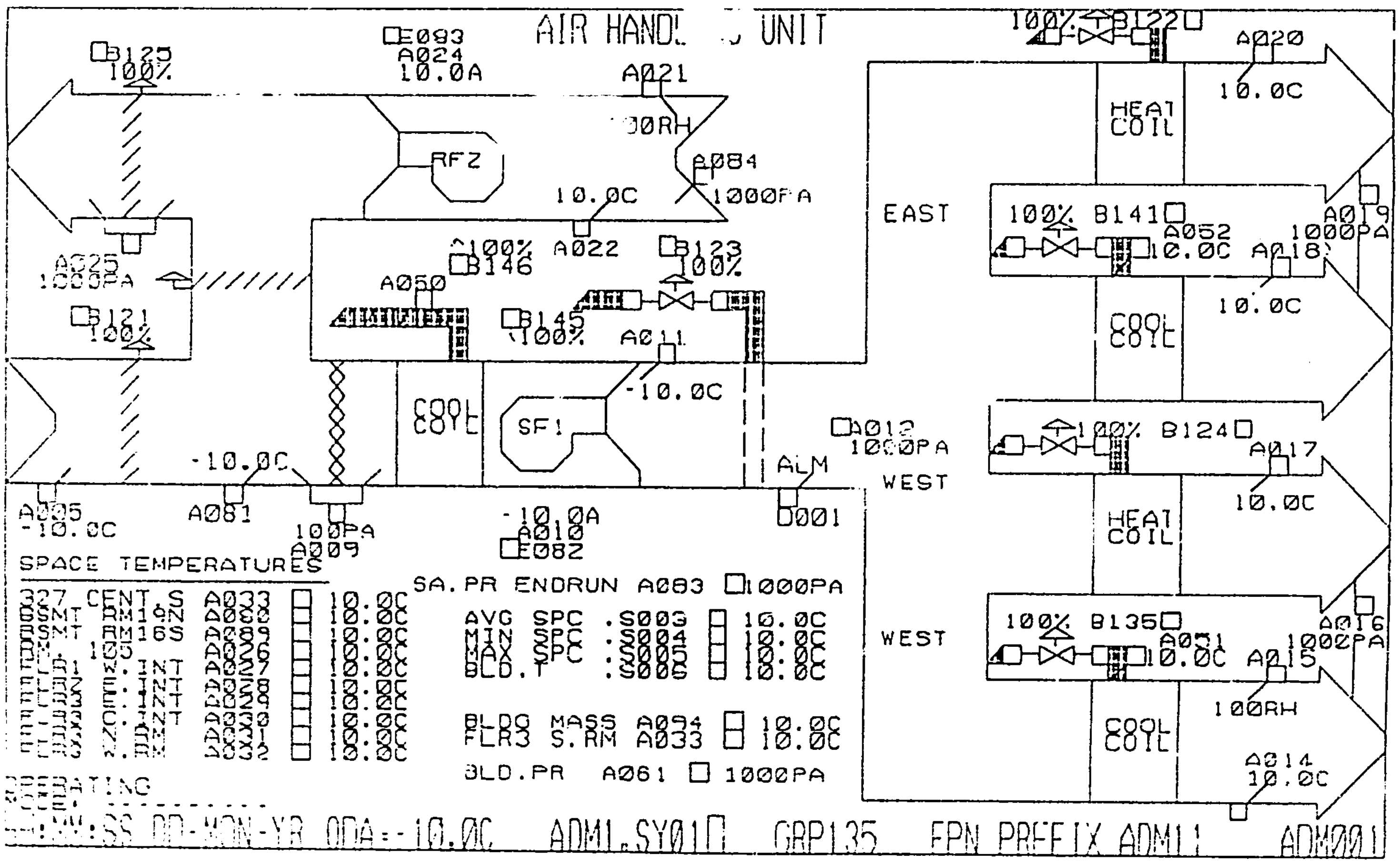


Figure 14 HVAC system of Administration Building at University of Alberta

Appendix D

Recorder Status

Type: 2101-61 Range. -48. - 4884. PPM CO2 Recorder ID: 5081

Time at Recorder: 02/03/92 08:33:43 Last Update: 04/09/91 10:47:54

Signal process: No Processing Accum: Not Sealed

Values being saved: averages

Alarm status: Low alarm @ 29. is OFF Upper alarm @ 4870. is OFF

Averaging period: 00:15:00 Amount of data recorded: 67 days 20:00:00

Storage Capacity: 6512 values records: 67 days 20:00:00

Output compressed by a factor of 1

Date	Time	Avg	
01/30/92	10:00:00	-48.	*
01/30/92	10:15:00	-48.	*
01/30/92	10:30:00	333.	*
01/30/92	10:45:00	521.	*
01/30/92	11:00:00	501.	*
01/30/92	11:15:00	492.	*
01/30/92	11:30:00	501.	*
01/30/92	11:45:00	501.	*
01/30/92	12:00:00	347.	*
01/30/92	12:15:00	492.	*
01/30/92	12:30:00	511.	*
01/30/92	12:45:00	516.	*
01/30/92	13:00:00	492.	*
01/30/92	13:15:00	453.	*
01/30/92	13:30:00	419.	*
01/30/92	13:45:00	415.	*
01/30/92	14:00:00	439.	*
01/30/92	14:15:00	458.	*
01/30/92	14:30:00	482.	*
01/30/92	14:45:00	501.	*
01/30/92	15:00:00	516.	*
01/30/92	15:15:00	506.	*
01/30/92	15:30:00	492.	*
01/30/92	15:45:00	492.	*
01/30/92	16:00:00	492.	*
01/30/92	16:15:00	492.	*
01/30/92	16:30:00	516.	*
01/30/92	16:45:00	516.	*
01/30/92	17:00:00	516.	*
[illegible]	[illegible]	[illegible]	*

01/30/92	17:45:00	458.
01/30/92	18:00:00	419.
01/30/92	18:15:00	415.
01/30/92	18:30:00	415.
01/30/92	18:45:00	415.
01/30/92	19:00:00	391.
01/30/92	19:15:00	391.
01/30/92	19:30:00	386.
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01/30/92	20:00:00	386.
01/30/92	20:15:00	405.
01/30/92	20:30:00	415.
01/30/92	20:45:00	415.
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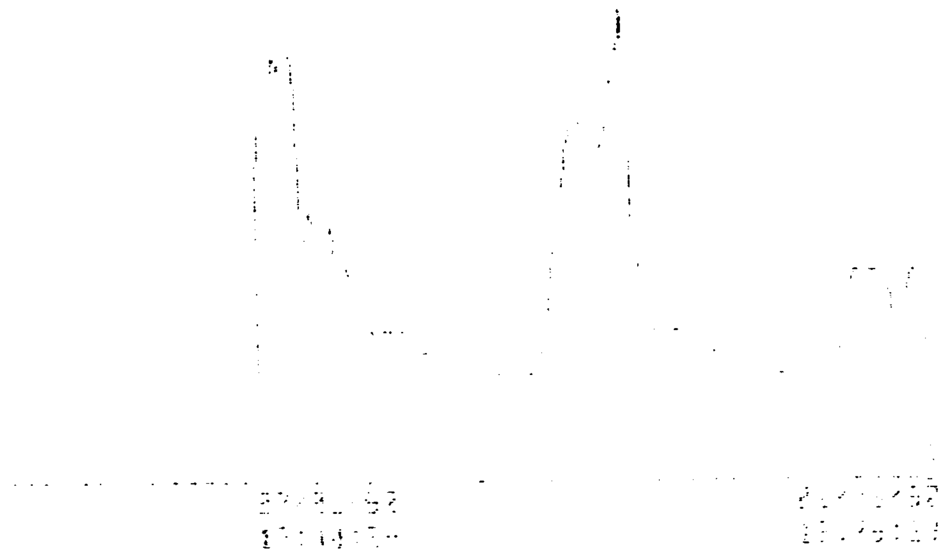
01/30/92	22:15:00	415.
01/30/92	22:30:00	391.
01/30/92	22:45:00	386.
01/30/92	23:00:00	381.
01/30/92	23:15:00	366.
01/30/92	23:30:00	362.
01/30/92	23:45:00	362.
01/31/92	00:00:00	362.
01/31/92	00:15:00	362.
01/31/92	00:30:00	362.
01/31/92	00:45:00	381.
01/31/92	01:00:00	386.
01/31/92	01:15:00	376.
01/31/92	01:30:00	362.
01/31/92	01:45:00	357.
01/31/92	02:00:00	357.
01/31/92	02:15:00	362.
01/31/92	02:30:00	362.
01/31/92	02:45:00	362.
01/31/92	03:00:00	362.
01/31/92	03:15:00	362.
01/31/92	03:30:00	362.
01/31/92	03:45:00	362.
01/31/92	04:00:00	357.
01/31/92	04:15:00	362.
01/31/92	04:30:00	362.
01/31/92	04:45:00	362.
01/31/92	05:00:00	362.
01/31/92	05:15:00	362.
01/31/92	05:30:00	362.
01/31/92	05:45:00	357.
01/31/92	06:00:00	357.
01/31/92	06:15:00	357.
01/31/92	06:30:00	357.
01/31/92	06:45:00	338.
[illegible]	[illegible]	[illegible]

01/31/92	07:30:00	352.
01/31/92	07:45:00	352.
01/31/92	08:00:00	357.
01/31/92	08:15:00	357.
01/31/92	08:30:00	36[illegible]
01/31/92	08:45:00	366.
01/31/92	09:00:00	410.
01/31/92	09:15:00	419.
01/31/92	09:30:00	468.
01/31/92	09:45:00	506.
01/31/92	10:00:00	550.
01/31/92	10:15:00	574.
01/31/92	10:30:00	598.
01/31/92	10:45:00	593.
01/31/92	11:00:00	574.
01/31/92	11:15:00	574.
01/31/92	11:30:00	636.
01/31/92	11:45:00	680.
01/31/92	12:00:00	733
01/31/92	12:15:00	709.
01/31/92	12:30:00	622.
01/31/92	12:45:00	559.
01/31/92	13:00:00	501.
01/31/92	13:15:00	458.
01/31/92	13:30:00	439.
01/31/92	13:45:00	463.
01/31/92	14:00:00	516.
01/31/92	14:15:00	516.
01/31/92	14:30:00	516.
01/31/92	14:45:00	501.
01/31/92	15:00:00	554.
01/31/92	15:15:00	641.
01/31/92	15:30:00	680.
01/31/92	15:45:00	733.
01/31/92	16:00:00	776.
01/31/92	16:15:00	198.
01/31/92	16:30:00	251.
01/31/92	16:45:00	-48. *

PPM_CO2

Recorder ID: [illegible]

[illegible] Bldg Mechanical Room
[illegible] - [illegible]/2/92 [illegible]



D-5

Recorder Status

Type: 2101-61 Range: -48. - 4884. PPM CO_2 Recorder ID: 5081

Time at Recorder: 02/05/92 16:34:25 Last Update: 04/09/91 10:47:54

Signal process: No Processing Accum: Not Scaled

Values being saved: averages

Alarm status: Low alarm @ -29. is OFF Upper alarm @ 4870. is OFF

Averaging period: 00:15:00 Amount of data recorded: 67 days 20:00:00

Storage Capacity: 6512 values records: 67 days 20:00:00

Output compressed by a factor of 1

Date	Time	Avg	
02/03/92	09:29:59	-48.	*
02/03/92	09:44:59	-33.	*
02/03/92	09:59:59	622.	*
02/03/92	10:14:59	675.	*
02/03/92	10:29:59	680.	*
02/03/92	10:44:59	685.	*
02/03/92	10:59:59	733.	*
02/03/92	11:14:59	747.	*
02/03/92	11:29:59	[illegible]	*
02/03/92	11:44:59	[illegible]	*
02/03/92	11:59:[illegible]	[illegible]	*
02/03/92	12:14:[illegible]	[illegible]	*
02/03/92	12:29:59	[illegible]	*
02/03/92	12:44:59	786.	*
02/03/92	12:59:59	767.	*
02/03/92	13:14:59	670.	*
02/03/92	13:29:59	579.	*
02/03/92	13:44:59	526.	*
02/03/92	13:59:59	550.	*
02/03/92	14:14:59	574.	*
02/03/92	14:29:59	559.	*
02/03/92	14:44:59	559.	*
02/03/92	14:59:59	574.	*
02/03/92	15:14:59	574.	*
02/03/92	15:29:59	564.	*
02/03/92	15:44:59	559.	*
02/03/92	15:59:59	550.	*
02/03/92	16:14:59	516.	*
02/03/92	16:29:59	516.	*
02/03/92	16:44:59	516.	*
02/03/92	16:59:59	511.	*
02/03/92	17:14:59	492.	*
02/03/92	17:29:59	492.	*
02/03/92	17:44:59	453.	*

02/03/92	17:59:59	431.	
02/03/92	18:14:59	415.	
02/03/92	18:29:59	415.	
02/03/92	18:44:59	415.	
02/03/92	18:59:59	415.	
02/03/92	19:14:59	415.	
02/03/92	19:29:59	415.	
02/03/92	19:44:59	415.	
02/03/92	19:59:59	415.	
02/03/92	20:14:59	415.	
02/03/92	20:29:59	415.	
02/03/92	20:44:59	415.	
02/03/92	20:59:59	415.	
02/03/92	21:14:59	415.	
02/03/92	21:29:59	415.	
02/03/92	21:44:59	415.	
02/03/92	21:59:59	415.	
02/03/92	22:14:59	415.	
02/03/92	22:29:59	415.	
02/03/92	22:44:59	415.	
02/03/92	22:59:59	405.	
02/03/92	23:14:59	386.	
02/03/92	23:29:59	386.	
02/03/92	23:44:59	386.	
02/03/92	23:59:59	386.	
02/04/92	00:14:59	386.	
02/04/92	00:29:59	386.	
02/04/92	00:44:59	386.	
02/04/92	00:59:59	386.	
02/04/92	01:14:59	386.	
02/04/92	01:29:59	386.	
02/04/92	01:44:59	376.	*
02/04/92	01:59:59	357.	*
02/04/92	02:14:59	357.	*
02/04/92	02:29:59	357.	*
02/04/92	02:44:59	357.	*
02/04/92	02:59:59	357.	*
02/04/92	03:14:59	357.	*
02/04/92	03:29:59	357.	*
02/04/92	03:44:59	357.	*
02/04/92	03:59:59	357.	*
02/04/92	04:14:59	362.	*
02/04/92	04:29:59	357.	*
02/04/92	04:44:59	357.	*
02/04/92	04:59:59	357.	*
02/04/92	05:14:59	357.	*
02/04/92	05:29:59	357.	*
02/04/92	05:44:59	357.	*
02/04/92	05:59:59	357.	*
02/04/92	06:14:59	357.	*
02/04/92	06:29:59	357.	*
02/04/92	06:44:59	357.	*
02/04/92	06:59:59	357.	*
02/04/92	07:14:59	357	*

02/04/92	07:59:59	357.
02/04/92	08:14:59	357.
02/04/92	08:29:59	357.
02/04/92	08:44:59	362.
02/04/92	08:59:59	400.
02/04/92	09:14:59	419.
02/04/92	09:29:59	473.
02/04/92	09:44:59	506.
02/04/92	09:59:59	559.
02/04/92	10:14:59	579.
02/04/92	10:29:59	588.
02/04/92	10:44:59	612.
02/04/92	10:59:59	651.
02/04/92	11:14:59	675.
02/04/92	11:29:59	680.
02/04/92	11:44:59	675.
02/04/92	11:59:59	689.
02/04/92	12:14:59	675.
02/04/92	12:29:59	675.
02/04/92	12:44:59	675.
02/04/92	12:59:59	675.
02/04/92	13:14:59	665.
02/04/92	13:29:59	656.
02/04/92	13:44:59	651.
02/04/92	13:59:59	670.
02/04/92	14:14:59	675
02/04/92	14:29:59	716.
02/04/92	14:44:59	743.
02/04/92	14:59:59	781.
02/04/92	15:14:59	781.
02/04/92	15:29:59	834.
02/04/92	15:44:59	820.
02/04/92	15:59:59	670.
02/04/92	16:14:59	550.
02/04/92	16:29:59	516.
02/04/92	16:44:59	497.
02/04/92	16:59:59	492.
02/04/92	17:14:59	463.
02/04/92	17:29:59	444.
02/04/92	17:44:59	415.
02/04/92	17:59:59	415.
02/04/92	18:14:59	415.
02/04/92	18:29:59	415.
02/04/92	18:44:59	410.
02/04/92	18:59:59	415.
02/04/92	19:14:59	415.
02/04/92	19:29:59	415.
02/04/92	19:44:59	415.
02/04/92	19:59:59	415.
02/04/92	20:14:59	415.
02/04/92	20:29:59	415.
02/04/92	20:44:59	415.
02/04/92	20:59:59	415.
02/04/92	21:14:59	410.

02/04/92	21:14:59	415.
02/04/92	21:59:59	415.
02/04/92	22:14:59	405.
02/04/92	22:29:59	386.
02/04/92	22:44:59	386.
02/04/92	22:59:59	386.
02/04/92	23:14:59	366.
02/04/92	23:29:59	357.
02/04/92	23:44:59	357.
02/04/92	23:59:59	357.
02/05/92	00:14:59	357.
02/05/92	00:29:59	357.
02/05/92	00:44:59	357.
02/05/92	00:59:59	357.
02/05/92	01:14:59	357.
02/05/92	01:29:59	357.
02/05/92	01:44:59	357.
02/05/92	01:59:59	357.
02/05/92	02:14:59	357.
02/05/92	02:29:59	357.
02/05/92	02:44:59	357.
02/05/92	02:59:59	357.
02/05/92	03:14:59	357.
02/05/92	03:29:59	362.
02/05/92	03:44:59	357.
02/05/92	03:59:59	357.
02/05/92	04:14:59	357.
02/05/92	04:29:59	357.
02/05/92	04:44:59	357.
02/05/92	04:59:59	357.
02/05/92	05:14:59	357.
02/05/92	05:29:59	357.
02/05/92	05:44:59	357.
02/05/92	05:59:59	357.
02/05/92	06:14:59	352.
02/05/92	06:29:59	342.
02/05/92	06:44:59	338.
02/05/92	06:59:59	333.
02/05/92	07:14:59	333.
02/05/92	07:29:59	338.
02/05/92	07:44:59	352.
02/05/92	07:59:59	357.
02/05/92	08:14:59	357.
02/05/92	08:29:59	357.
02/05/92	08:44:59	357.
02/05/92	08:59:59	386.
02/05/92	09:14:59	415.
02/05/92	09:29:59	434.
02/05/92	09:44:59	458.
02/05/92	09:59:59	473.
02/05/92	10:14:59	492.
02/05/92	10:29:59	492.
02/05/92	10:44:59	492.
02/05/92	10:59:59	492.

02/05/92	11:29:59	492.	
02/05/92	11:44:59	492.	
02/05/92	11:59:59	492.	
02/05/92	12:14:59	492.	
02/05/92	12:29:59	492.	
02/05/92	12:44:59	492.	
02/05/92	12:59:59	468.	
02/05/92	13:14:59	439.	
02/05/92	13:29:59	424.	
02/05/92	13:44:59	419.	
02/05/92	13:59:59	453.	
02/05/92	14:14:59	463.	
02/05/92	14:29:59	473.	
02/05/92	14:44:59	487.	
02/05/92	14:59:59	492.	
02/05/92	15:14:59	492.	
02/05/92	15:29:59	492.	
02/05/92	15:44:59	468.	
02/05/92	15:59:59	318.	
02/05/92	16:14:59	-48.	*