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A DYNAMIC THERMAL COMFORT ENHANCED WORK PRODUCTIVITY IMPROVEMENT SCHEME

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ABSTRACT

This paper reports the experimental study on thermal comfort in air-conditioned office room with constraints on productivity and energy saving. The study aims to define a dynamic thermal comfort scheme to predict the optimal temperature setting. The thermal comfort study examined is based on questionnaire surveys examined among workers in three factories. A laboratory based experiment including a collection of sampled key data and analysis at some intervals each day is conducted. An air conditioning controller system with thermal comfort, productivity, work efficiency and energy saving constraints is developed and tested.

The experiments show that temperature setting to 25 °C in the morning and at 24 °C in the afternoon yield the most optimal productivity and energy saving.

Keywords: Dynamic thermal comfort (DTC), optimal temperature, work productivity, Microcontroller decision unit.

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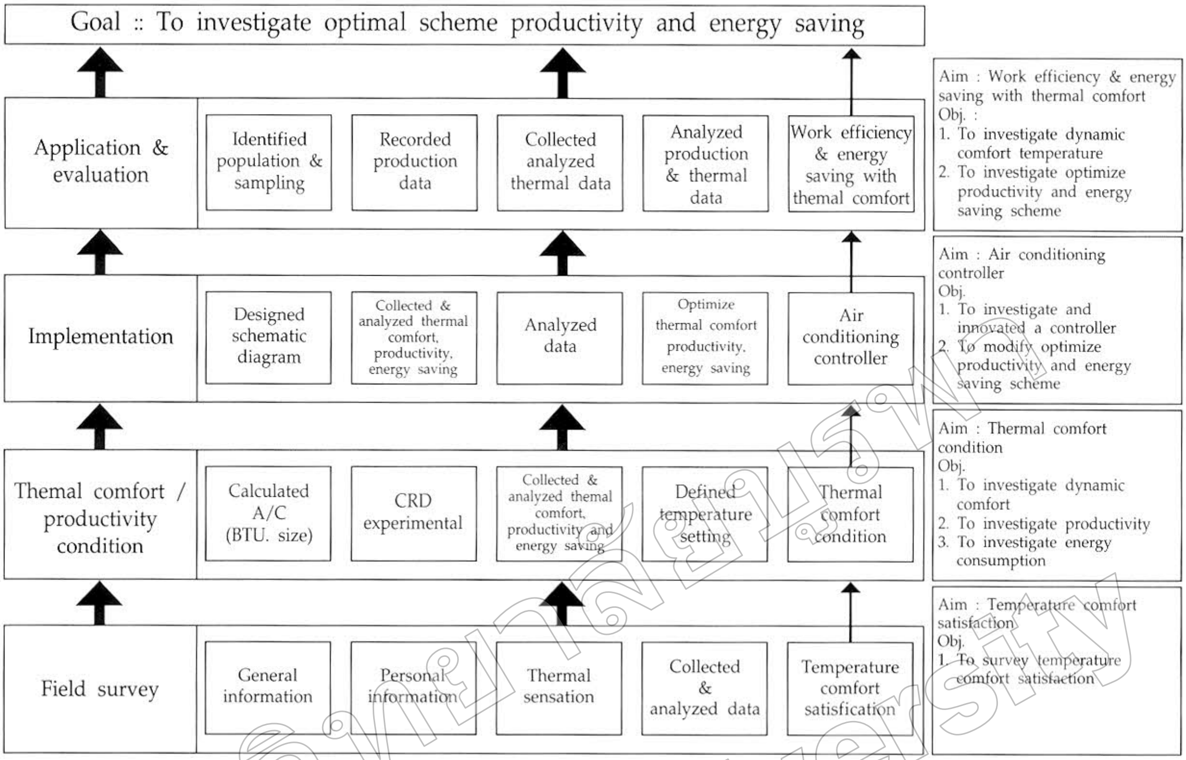

Figure 2. The schematic thesis of a dynamic thermal comfort enhanced work productivity improvement scheme.

Consequently, more intensive experiments were conducted in our laboratory to simulate the working environment at the factory with volunteer workers. This method provides more elaborative study of workers' behaviors and reactions under controlled environment (Khedari et al., 2004). The test site layout is shown in Figure 3. The area is approximately 24 sq. m., equipped with two split-type air conditioners. A 10-channel data logger with temperature sensors and CO_2 sensors were installed to gather necessary information. The volunteer workers aged between 20-35 years old were instructed to complete a set of skilled works in varied temperature from 21-29 °C with the range of relative humidity between 30-70%. During the experiment, CO_2 level was also monitored.

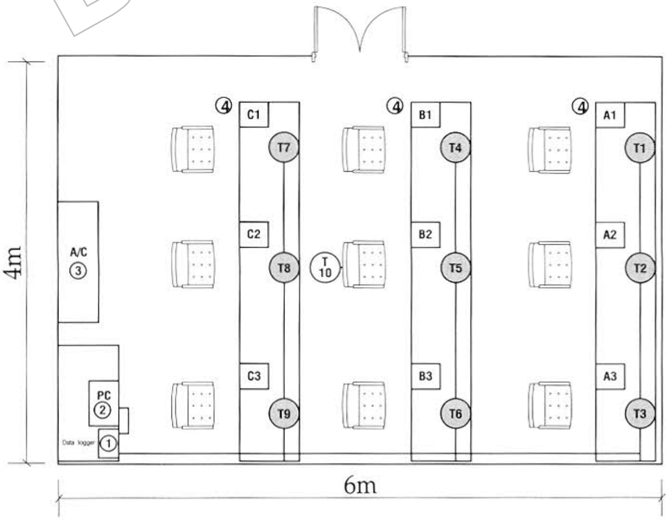

Figure 3. Showing laboratory of thermal.

Material and devices in figure:

1. Temperature data logger 10 channels : 1 unit
2. Desk top computer: 1 unit
3. Air conditioner; 26,000 btu : 1 unit
4. Tables & chairs for volunteers: 9 persons (A1-A3, B1-B3, C1-C3)

We analyze the findings in the previous experiments and design a new programmable electronic controller for split-type air-conditioning systems. The controller ensures that the temperature setting provides both optimal thermal comfort and energy saving resulting in optimal productivity. Figure 4 illustrates the concept design of the controller. The temperature sensors, both inside and outside of the room, as well as CO_2 sensors are used to provide sufficient input information to the controller. The temperature in the room can then be controlled by turning the compressor on/off. The CO_2 level in the room can also be controlled by the ventilation fan pumping fresh air from outside into the room.

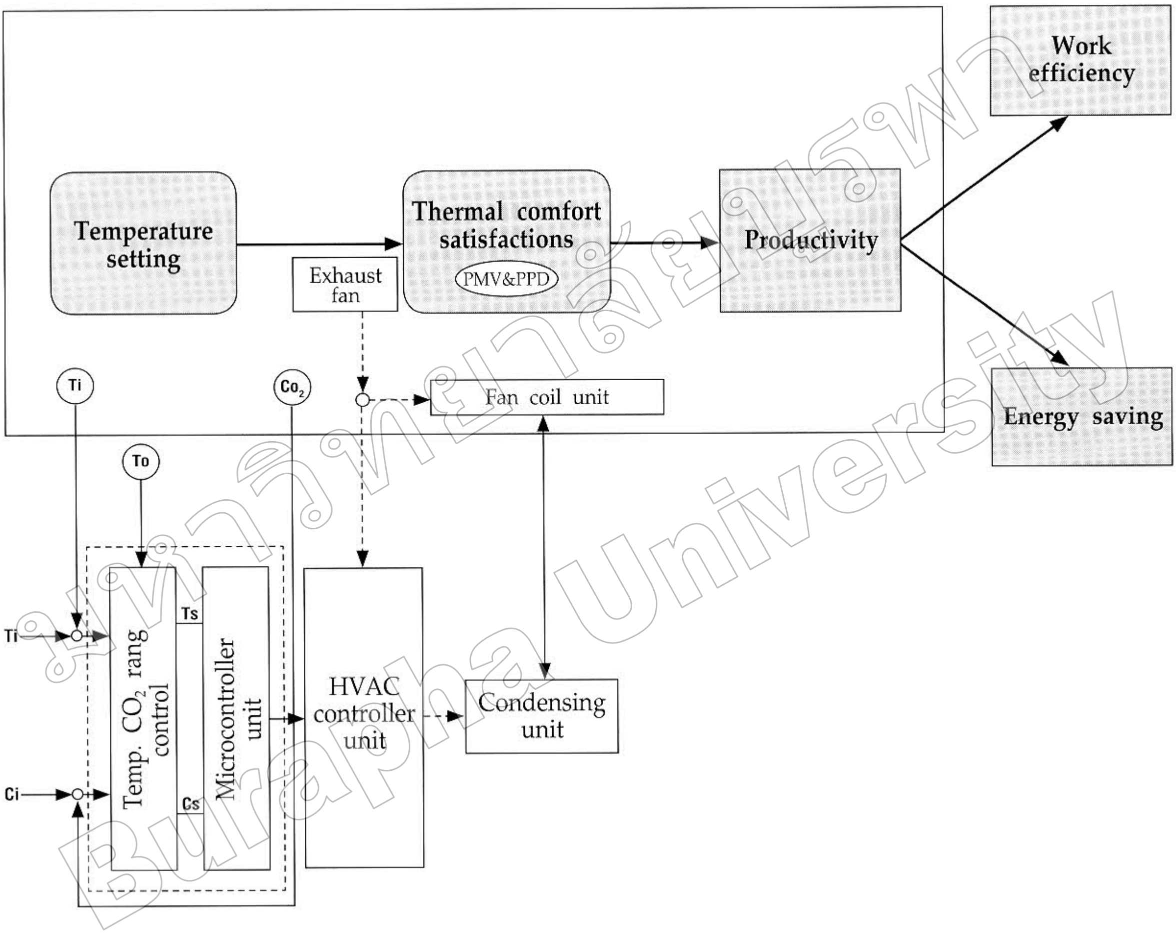

Figure 4. Showing block diagram of thermal comfort controller.

Last, the on-site experiment was then conducted again at the electronic factories with recommended temperature setting. Satisfaction of thermal comfort and working efficiency were examined (Liang and Du, 2007).

Optimization model

The study of thermal comfort controlling to maximize satisfaction for workers and make the most of energy saving. The maximum efficiency and high productivity have occurred (Chu et al., 2004).

We define this input is to impose maximum benefit according the block diagram is ready and its equation:

$$\text{maxz} = f(x) \tag{3}$$

$$f(x) = (a1.\ x1) + (a2.\ x2)... + (an.\ xn) = \Sigma_1^n = 1\ ajxj \tag{4}$$

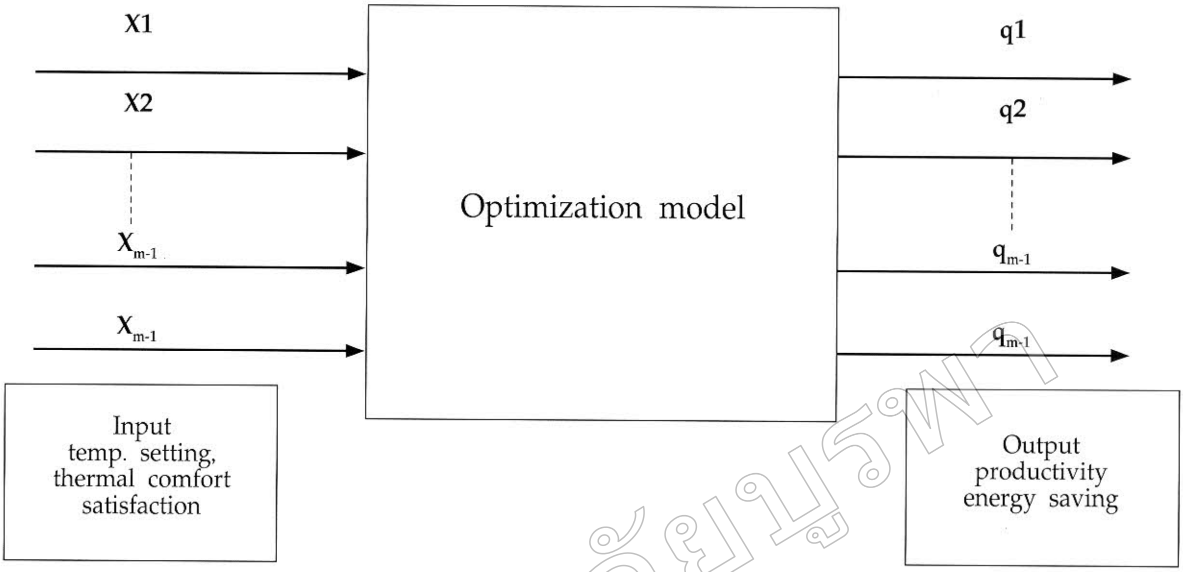

Figure 5. Showing block diagram of optimization model.

RESULTS AND DISCUSSIONS

The results were divided into four parts. First, the investigation of thermal comfort satisfaction had been obtained. Three factories (called by pseudo-name Factory A, B, and C herewith) had been chosen. We found that the temperature in each factory was controlled at 24 ˚C, 25 ˚C, and 23 ˚C using 120, 100, and 250 ton-BTU air-conditioning systems, respectively. The working areas were 1,000, 2,000, and 5,000 sq.m. The total workers were 1,500, 800, and 4,000. The air-conditioning system in each factory was switched on 24, 10, and 24 hours/day with the power consumption of 13.2 kW, 11 kW, and 27.5 kW, respectively.

Table 1. Thermal comfort survey on especial line production in factories.

Detail	Factory			Average
	A	B	C	
1) Gender				
Male (N)	17	11	74	34
Female (N)	67	42	172	94
2) Age (years)	24	25.4	25.8	25
3) Weight (kilograms)	49	49.6	51.2	50
4) High (centimeters)	160	160.7	153.4	158
5) Clothing	uniform	uniform	uniform	uniform
6) Thermal sensation (PMV) mean	-0.46	-0.61	-0.35	-0.47
Standard deviation (SD)	0.91	0.93	1.13	0.99

Table 1 shows the satisfaction rate of thermal comfort in each factory. On average, the average age of workers was approximately 25 years, weight of 25 kg, and height of 158 cm. Note that the female workers outnumber the male by three times due to the fact that the electronic manufacturers prefer female delicate assembly skills. The average weight and height of workers in this study go along well with the average values of Thai population. All workers wear uniform. The average satisfaction rate was found to be -0.47, with standard deviation (SD) of 0.99. The satisfaction rate was found to be negative, but was still in the 'comfort' level.

Second, we elaborate more on our study by simulating the working environment in a properly controlled laboratory. The experiment was conducted in a room with 4x6x3 m (WxLxH) in dimension and 72 m^3 in volume. One side of the wall was made of plastered bricks of 6x3 m in dimension. Another side was 4x3 m painted gypsum. The other two sides were glass with aluminum frames with the size of 6x3 and 4x3 m, respectively. The room was equipped with a 26,000 BTU, 220V, 50 Hz air-conditioning system. The experimental results are shown in Tables 2-3 and Figures 6-10.

Table 2. The mean of experimental data in the morning (8.00–12.00 am.) at 21-29 ˚C.

Temp. (˚C)	PMV	Thermal comfort satisfaction (%)	Productivity working (%)	Energy consumption (Unit= kW-h)
21	-1.24	18.86	57.11	4.59
22	-1.17	22.70	57.10	4.48
23	-1.04	30.97	58.26	4.22
24	-0.61	65.18	60.10	3.73
25	-0.58	67.61	61.64	3.02
26	0.93	39.01	60.84	2.42
27	1.72	3.68	59.17	2.25
28	1.84	2.19	56.14	2.20
29	1.96	1.24	55.96	2.20

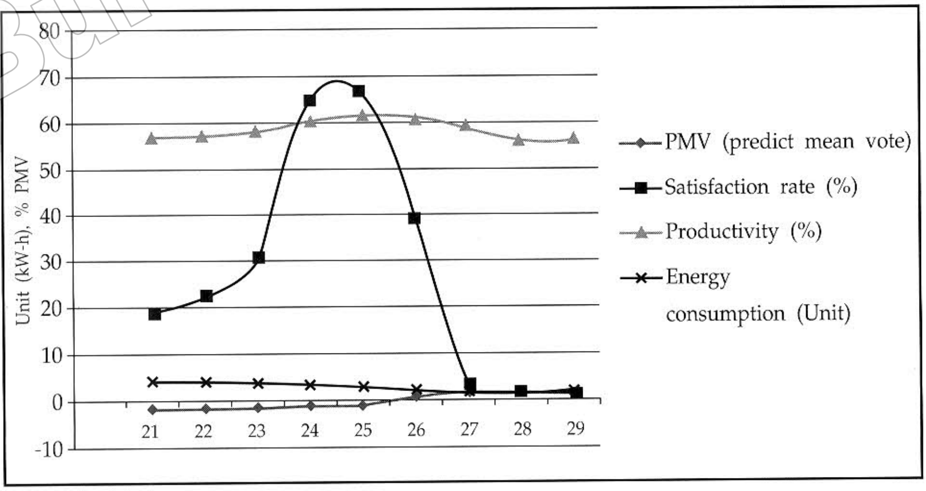

Figure 6. The relation of PMV, thermal comfort satisfaction, energy consumption, and productivity working with temperature setting at 21-29 ˚C in the morning

According to Table 2 and Figure 6, we found that the temperature setting of 25 ˚C was most appropriate. With the setting, the thermal comfort satisfaction rate was 67.61% and PMV was -0.58. The yield available efficiency was 61.64% and energy usage was 3.02.

Table 3. The mean of experimental data in the afternoon (13.00 – 16.00 pm.) at 21-29 ˚C.

Temp. (˚C)	PMV	Thermal comfort satisfaction (%)	Productivity working (%)	Energy consumption (Unit: kW-h)
21	-1.98	1.13	56.84	4.68
22	-1.78	2.85	58.22	4.48
23	-1.67	4.50	60.35	4.42
24	-0.49	74.58	64.02	4.02
25	-0.5	73.83	61.46	3.63
26	1.33	14.59	58.45	2.50
27	2.06	0.75	55.72	2.27
28	2.14	0.48	55.09	2.12
29	2.26	0.24	40.01	2.03

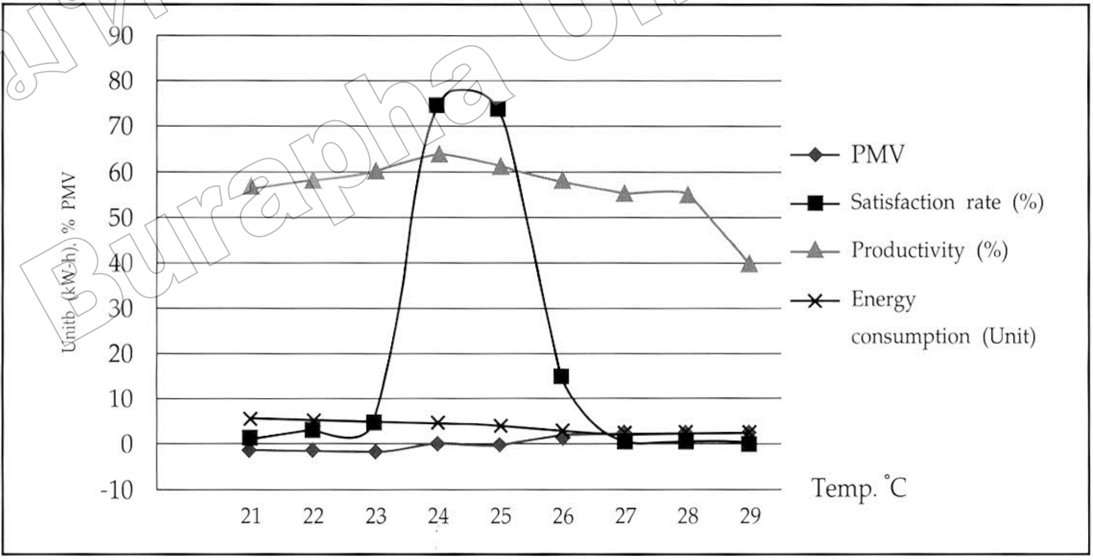

Figure 7. The relation of PMV, thermal comfort satisfaction, energy consumption, and productivity working with temperature setting 21-29 ˚C in the afternoon.

According to Table 3 and Figure 7, we found that the temperature setting of 24 ˚C was most appropriate. With the setting, the thermal comfort satisfaction rate was 74.58% and PMV was -0.49. The yield available efficiency was 64.02% and energy usage was 4.02.

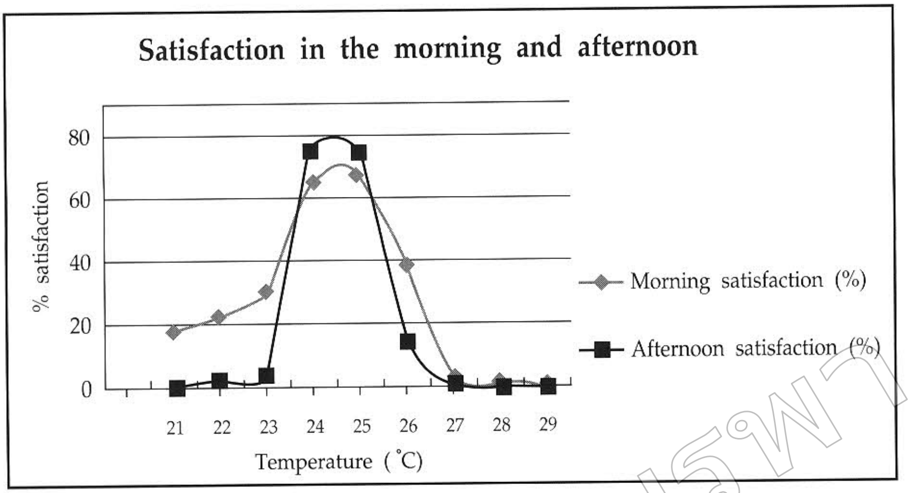

Figure 8. The thermal comfort satisfaction rate (%) in the morning and afternoon with temperature setting 21-29 ˚C.

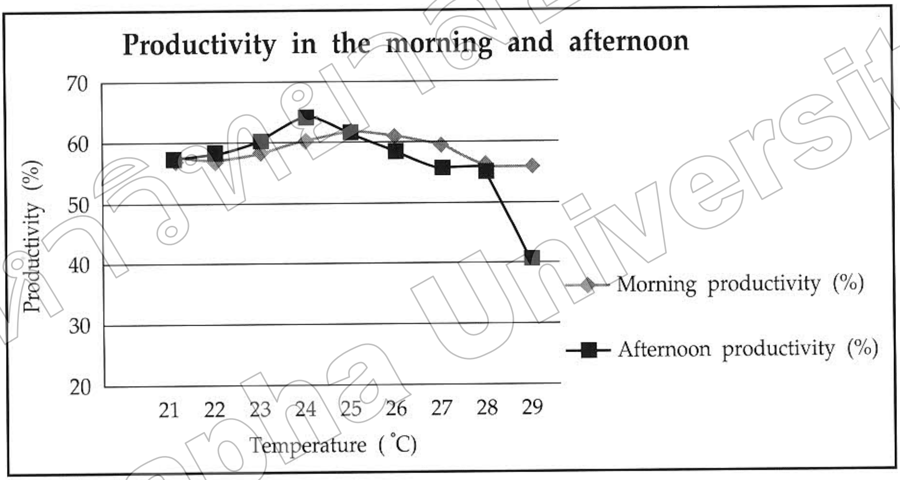

Figure 9. The productivity working (%) in the morning and afternoon with temperature setting 21-29 ˚C.

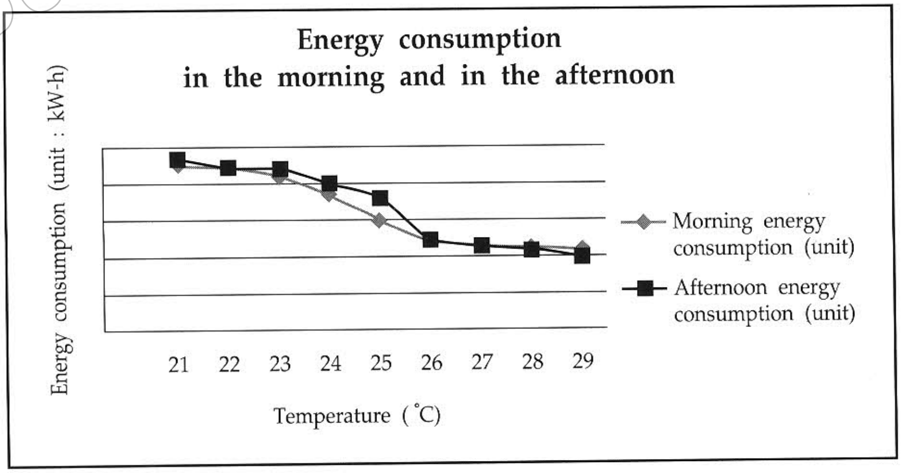

Figure 10. The energy consumption in the morning and afternoon with temperature setting 21-29 ˚C.

Figures 8-10 compare the experimental results in the morning and the afternoon. We found that the optimal temperature in the morning was higher than in the afternoon. This indicated that the heat load in the morning was less than that in the afternoon. However, the satisfaction rate in morning was less than that in the afternoon, as shown in Figures 8-9. However, the optimal temperature setting for the electronic manufacturing factory was 24°C. This setting certainly causes higher energy consumption due to a lower temperature setting, as shown in Figure 10.

We analyzed findings in the previous investigation and designed a programmable electronic controller for split-type air-conditioner systems. The block diagram of the controller is shown in figure 11. There were four main parts in the controller, i.e. temperature sensors, CO$_2$ sensors, Microcontroller Decision Unit (MDU), drivers, and display. The temperature sensors sense both inside and outside of the room and send the information to MDU for processing. CO$_2$ sensors measured the CO$_2$ level in the room. MDU received all the measured data, process and send the controlling signal to the driver part. The driver thus switches the compressor on/off according to the received signal. The controller display had designed to show all detailed information about current temperature, voltage and current, energy consumption, and CO$_2$ level.

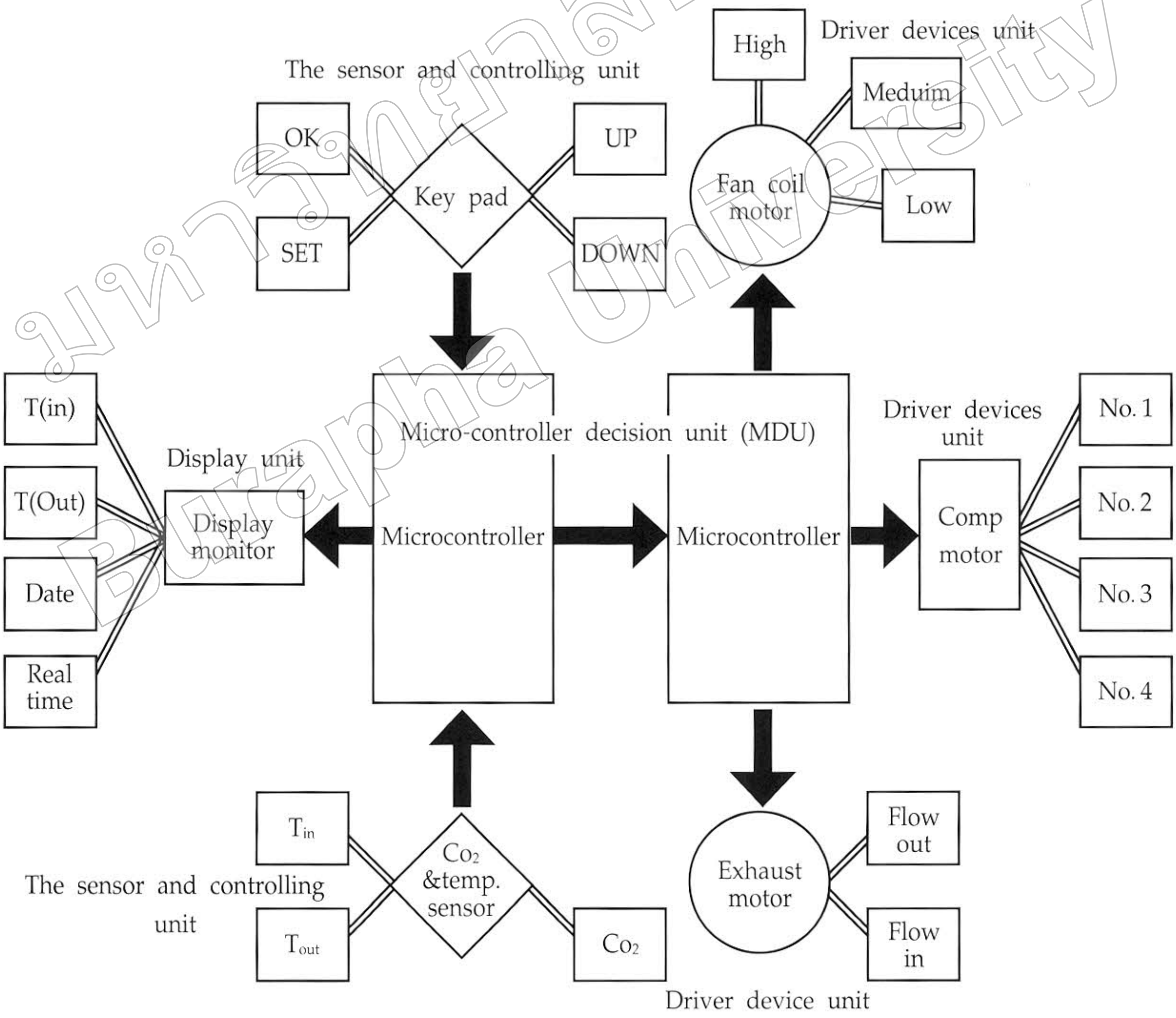

Figure 11. The diagram of air-conditioning controller system for comfortable temperature and energy saving.

The controller worked in two modes, automatic and semi-automatic (Chu et al., 2004). In automatic mode, the device controlled the temperature in the room to 26 ˚C between 08.00 -12.00 h and to 24 ˚C during 13.00-16.00 h. In semi-automatic mode, the users were allowed to program the temperature setting during the time in a day (Liang and Du, 2007).

Consequently, we applied our approach to the same factories by setting the temperature to 25 ˚C in the morning (08.00-12.00 h) and 24 ˚C in the afternoon (13.00-16.00 h). The satisfaction rate of workers and productivity is shown in Tables 4-5.

1. Thermal comfort survey

Table 4. Thermal comfort surveying in high tech factory.

Thermal sensation (PMV)	Morning	Afternoon
Mean	-0.46	-0.51
Standard deviation(SD)	0.91	0.95

According to Table 4, we found that the satisfaction rate for the morning and afternoon were in the 'comfort level'. Workers almost had the same feeling with the set temperature with a slightly higher satisfaction in the morning.

2. Enhance productivity

Table 5. Enhance productivity.

Month (2009)	Productivity			kW-h (Unit)
	Input	Output	η (out/ in*100)	
January	1778.4	1758.26	98.87	7110
February	765.95	743.21	97.03	6553
March	872.69	829.95	95.10	6687
April	519.85	487.06	93.69	6339
May	1015.2	970.05	95.57	6685
June	892.29	829.95	93.01	6644
July	729.65	717.46	98.33	6548
August	892.69	925.93	92.52	6595
September	619.85	687.06	97.94	6427
October	812.49	839. 56	97.19	6699
November	519.85	487.06	93.69	6243
December	1235.5	1223.6	99.04	6847
Mean	**887.85**	**861.78**	**95.99**	**6614**

According to Table 5, we found that the mean per month of efficiency working was 95.99% and the mean of energy usage was 6614 kW-h. Effect of thermostat setting on daily thermal comfort and total transmission loads during "moderate" months in this table were what we had proposed as ideal monthly thermostat settings for the based on climatic conditions averaged over a number of years.

In conclusion, in this paper we presented a scheme to enhance work productivity and energy saving. The thermal comfort for workers in air-conditioning room has been investigated and the study shows that the most optimal setting temperature for morning shift is 25 ˚C and in the afternoon shift is 24 ˚C. In addition, we developed a novel air-conditioning controller that takes in to account the comfortable temperature and energy saving for split-type air-conditioning system. The scheme has been practically applied in the real factories yielding a satisfactory results in both satisfaction and energy saving.

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