UDC 628.511:697.94:621.314.5

CLEAN ROOM ENERGY SAVING OPERATION

Soichi Yashima
Yuzo Kobayashi
Takayuki Yamaguchi

1 INTRODUCTION

The matters related to energy saving which were hot subjects in news papers and magazine are not as popular as before these days due to the down trend of oil price. In the cleam rooms (hereinafter abbreviated to as CR), however, energy saving is still the important theme to be actively examined.

A CR which is built to maintain temperature and humidity in a constant level and to clean the air within the CR requires about ten times (Class 10,000) to 30 times (Class 100) as great as the power required in office buildings using an ordinary air conditioning system. (About 50W per square meter in an office building using an ordinary air conditioning system) This large running cost urges the energy savings.

To plan a CR of large running cost ratio as mentioned above, a comprehensive economical judgement standard is required while an ordinary office building can be evaluated with a value of the initial investment (construction cost). However, the analyzation is very complicated and it is very difficult to evaluate the efficiency. Espeically, when the reflection to the manufacturing cost is taken into considerations, the idea that the unit price should be reduced by raising the cleanliness (so that the manufacturing yielding point can be improved) contradicts the idea of energy saving that the manufacturing unit price should be reduced by saving energies.

Consequently, conclusions are not always identical, and based on the actual operating status of a CR, examinations must be made on case by case basis.

2 POSSIBILITY OF ENERGY SAVING OPERATION

Based on air flows, there are turbulent flow conventional type and larminar flow type CR systems. For these types, the cleanliness calculating equations are expressed as shown in *Table 1* with the assumption [Value of particles flowing into the CR is balanced with value of particles flowing out of the CR under the constant state]. In this case, however, provisions (1) The particle diameter destribution and density are same at both inside and outside of the CR, (2) The particle source or particles flowed into the CR are dispersed evenly and momentarily, must be placed.

Now, to make the meanings of the equations clear, when the special conditions are set up as;

Only HEPA filter is used $\rightarrow \eta_2 = \eta_3 = 0$

The room air tightness is perfec $\rightarrow Q_{ns} = Q_{nr} = 0$, $Q_r = Q_s$, $Q_f = (1-r)Q_s$

Then, the following equations can be established.

$$C = C_1 + C_2 = (1-\eta_1)(1-r)C_0 + M/Q_s \quad \cdots\cdots (1)$$

$$C_s = C_1 + C_{2s} = (1-\eta_1)(1-r)C_0 + (1-\eta_1)r\frac{M}{Q_s} \quad \cdots\cdots\cdot (2)$$

where, $(1\text{-}\eta_1)r \ll 1$

From the above equations, the lst term C_1 related to the concentration of particles floating in the air C_0 and 2nd term related to the particle generating value M (or supplied/exhausted air volume Q_s) can be extracted. Thus, it can be understood that the equations are physically and directly understandable. (*Fig. 1*) The points to be here are that the relationship between Q_s and M required in maintaining cleanliness is primary inverse proportions, and it means that, for example, when particle generating value reduces to a half, volume of supplied and exhausted air can be reduced to a half.

Fig. 1 Relationships among concentration of particle, volume of generated particles and ventilation value

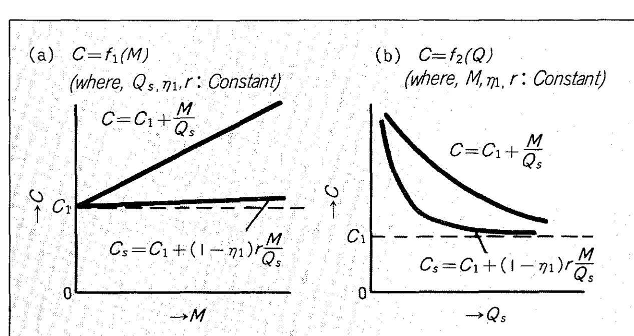
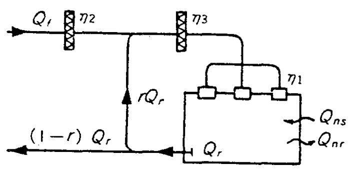
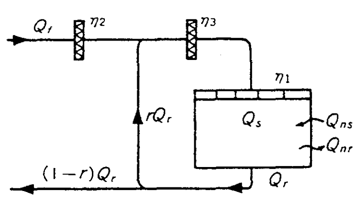


Table 1 CR system cleanliness calculating equations

	System	Cleanliness calculating equation
Turbulent type (conventional CR)		(1) Value of particles flowed into CR $(1-\eta_1)(1-\eta_3)\ \{(1-\eta_2)\ C_0Q_f+rCQ_r\}+C_0Q_{ns}+M$ (2) Value of particles flowed out of CR CQ_r+CQ_{nr} Under the normal condition, (1) is equal to (2), and therefore, $C=\frac{\{(1-\eta_1)(1-\eta_2)(1-\eta_3)\ Q_f+Q_{ns}\}\ C_0+M}{\{1-r\ (1-\eta_1)(1-\eta_3)\}\ Q_r+Q_{nr}}$ Under a special condition, $C=(1-\eta_1)(1-r)\ C_0+M/Q_s$
Laminar flow type CR		The point which differs from the conventional type CR is that the concentration of blown out air C_s flows as is upto the contamination generated point. When balance of particle is taken into consideration, $C_sQ_s+C_OQ_{ns}+M=CQ_r+CQ_{nr}$. Also, $C_sQ_s=(1-\eta_3)(1-\eta_1)\ \{(1-\eta_2)\ C_0Q_f+rCQ_r\}$ Hence, $C_s=\frac{(1-\eta_1)(1-\eta_3)\left\{(1-\eta_2)\ C_0Q_f+rQ_r\left(\frac{C_0Q_{ns}+M}{Q_r+Q_{nr}}\right)\right\}}{\left\{1-\frac{(1-\eta_3)(1-\eta_1)\ rQ_r}{Q_r+Q_{nr}}\right\}Q_s}$ Under a special condition, $C_s=(1-\eta_1)(1-r)\ C_0+(1-\eta_1)\ r\frac{M}{Q_s}$

(Note)

Q_f : Volume of flesh outside air
Q_r : Volume of air exhausted by machine (m^3/h)
Q_s : Volume of air supplied to machine (m^3/h)
Q_{ns} : Volume of air supplied naturally (m^3/h)
Q_{nr} : Volume of air exhausted naturally (m^3/h)

r : Tail gas recirculating ratio
C : Concentration of particle floating in the room (Particles/m^3)
C_O : Concentration of particle floating in the outside air (Particles/m^3)
C_s : Concentration of particle floating in the supplied air (Particles/m^3)
M : Particles generated in CR (Particles/h)

η_1 : Efficiency of main filter
η_2 : Efficiency of prefilter
η_3 : Efficiency of intermediate filter
Special condition: $\eta_2=\eta_3=Q_{ns}=Q_{nr}=0$
$\rightarrow Q_r=Q_s,\ Q_f=(1-r)\ Q_s$
$r(1-\eta_1)\ll 1$

Table 2 Particles generated from human body by worn cloth and motion

(Unit : Particles/person. minute)

Motion \ Particle diameter \ Cloth		Ordinary working wear	White robe type dust-free cloth	Overall type dust-free cloth	Austin
		0.3μm or greater (X10^6)	0.3μm or greater (X10^6)	0.3μm or greater (X10^6)	0.3μm or greater (X10^6)
Static state	Standing	0.543	0.151	0.019	–
	Sitting	0.448	0.142	0.015	–
	Standing or sitting	–	–	–	0.100
Moving state	Vertical motions of arm	4.450	0.462	0.049	–
	Front bending of upper body	3.920	0.775	0.039	–
	Free motions of arm	3.470	0.570	0.052	–
	Taking cap off	2.620	–	–	–
	Vertical and horizontal neck motions	1.230	0.187	0.022	–
	Twisting upper body	2.240	0.390	0.032	–
	Extension and contraction	4.160	1.110	0.064	–
	Stepping	4.240	1.200	0.115	–
	Walking	5.360	1.285	0.157	–
	Motions to sit down on a chair or stand up from the chair	–	–	–	2.500
	Walking (5.6km/h)	–	–	–	7.500

Particle source are briefly classified into (1) Human body, (2) Interior finishing materials, and (3) Manufacturing machines. To grasp these quantitatively, a number of experiments have been accumulated and various devises have been made on the system design. For example, wall and ceiling materials the surfaces of which are hardly to be

Table 3 Class of cleanliness and number of ventilations (Volume of ventilated air)

Class	Fed. st. 209B (USA)	Tech. Ordh TO-0025-203 (US Air Force)	NASA NHB5340.2	Company A	Company B	Company C
100,000	} 20 times/h	} 20 times/h or more	} 20 times/h	10 to 20 times/h	–	15 to 30 times/h
10,000				20 to 30 times/h	30 times/h	40 to 50 times/h
1,000	–	–	–	35 to 45 times/h	60 to 120 times/h	45 to 55 times/h
100	0.45m±20%	Horizontal Vertical	0.45m/s±0.1m/s	Surface velocity 0.5m/s (laminar)	0.5m/s	200 to 700 times/h

peeled off are used, and the floor is finished with epoxy coating to minimize dust caused by frictions during people walkings. Further, in a semiconductor process, etc., influence to the CR is minimized by using a draft chamber. Conclusively, the largest factor of particle source is human body, and as an equation to calculate particle value in the electronic industries, the following equation is available.

$M = 10^6$ particles/min· person x (Number of workers) + 45 x 10^4 particles/min·m^2 x (area) . . . . (3)

1st term: (Value of particles generated from humanbeing)

2nd term: (Value of particles generated from other than humanbeing)

However, as it may be understood from other papers in this special issue and example of measurement indicated in *Table 2*, the values greatly change depending on type of worn cloth and operating conditions. Yet, it should be noted that even if the workers wear the same clothes, the minimum value differs from the maximum value in one digit.

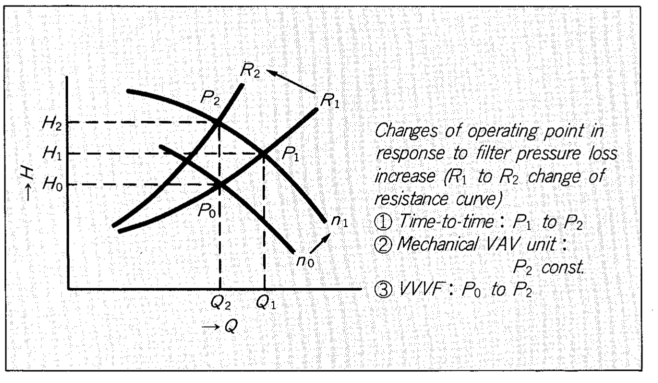
Table 3 shows the classes of cleanliness and number of ventilations (volume of ventilated air) as a design standard and from this table, it can be understood that the values vary. However, a considerably high energy saving can be expected by adjusting volume of air in the CR designed and executed with the above mentioned idea after grasping the actual particle value and an adequate operating system. In this case, however, the purpose of the ventilation is not only for maintenance of cleanliness but also for maintenance of temperature and humidity. Further, the room environment cannot be maintained evenly unless the lower limit value of blown out air velocity overcomes the up stream and has an inducing effect. Furthermore, when draft value is large, forsecuring the positive pressure as a CR, the ventilation value cannot be reduced unreasonably.

3 PRACTICAL EXAMINATIONS OF ENERGY SAVING

3.1 VVVF contol and other controls

As the HEPA filter and other filters used in the air conditioning system of a CR are operated, value of sticked particle increases, causing pressure loss to increase. For this reason, as for the characteristics of the air conditioning fan,

Fig. 2 Characteristic curves of fan and operating points



the machines and equipment must be selected with the air volume reduction due to a pressure loss increase taken into considerations so that the rated efficiency and air volume can be maintained until the filter replacing period. This also means contrarily that when the filter is new, more volume of air than the rating is supplied.

Normally, it is said;

HEPA filter: 25 to 50 mmAq, 3 to 5 year service life

Intermediate filter: 15 to 30 mmAq, 1 to 2 year service life.

with these changes taken considerations, the initial air volume must be assumed to be 1.2 to 1.4 times great as the rating.

Air volume increase and blown out air velocity increse at the initial time period are considered to be inconvenient for use, and it may sometimes be suppressed with a damper of the air conditioning system or automatically controlled by a mechanical VAV unit.

While, reflecting the recent advancement of semiconductor application technologies, it has been recognized that a constant air volume supplying system is effective in saving energy. This new system employs VVVF system and is operated by a motor under variable speeds. *Fig. 2* indicates operation acting points by using characteristic curves of the fan. In the above indicated three case, a considerable difference is presumed in the required power ($P \propto QH$) and used electric power ($WH = \int P_{dt}$). For example, when electrical power value WH_1 required by the time-to-time operations up to the service life period of the filter T is obtained, it is calculated as shown below.

Fig. 3 VVVF control of constant cleanliness

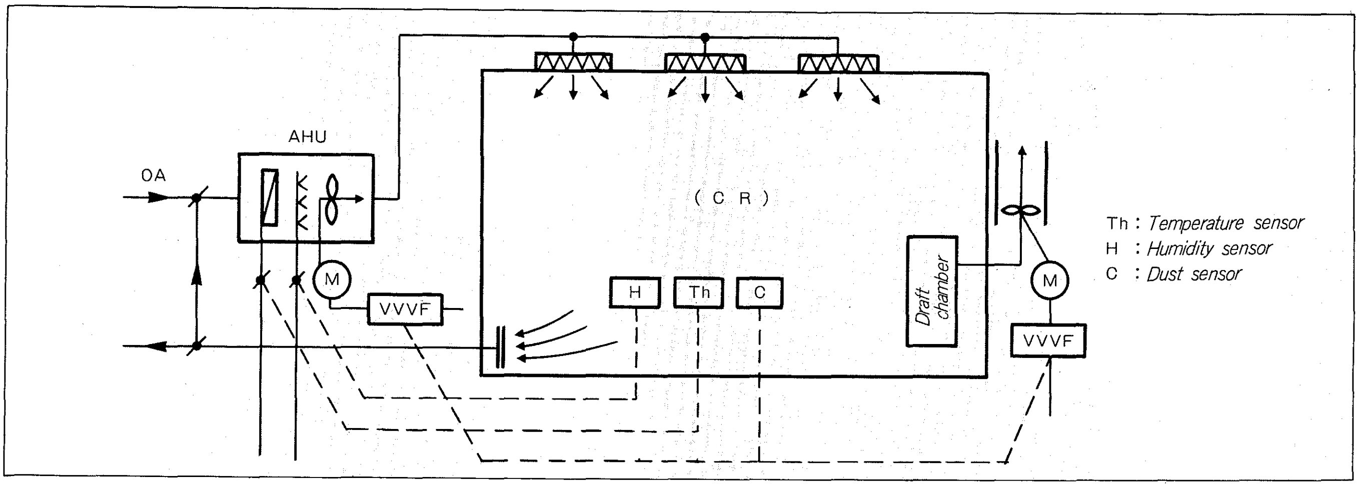
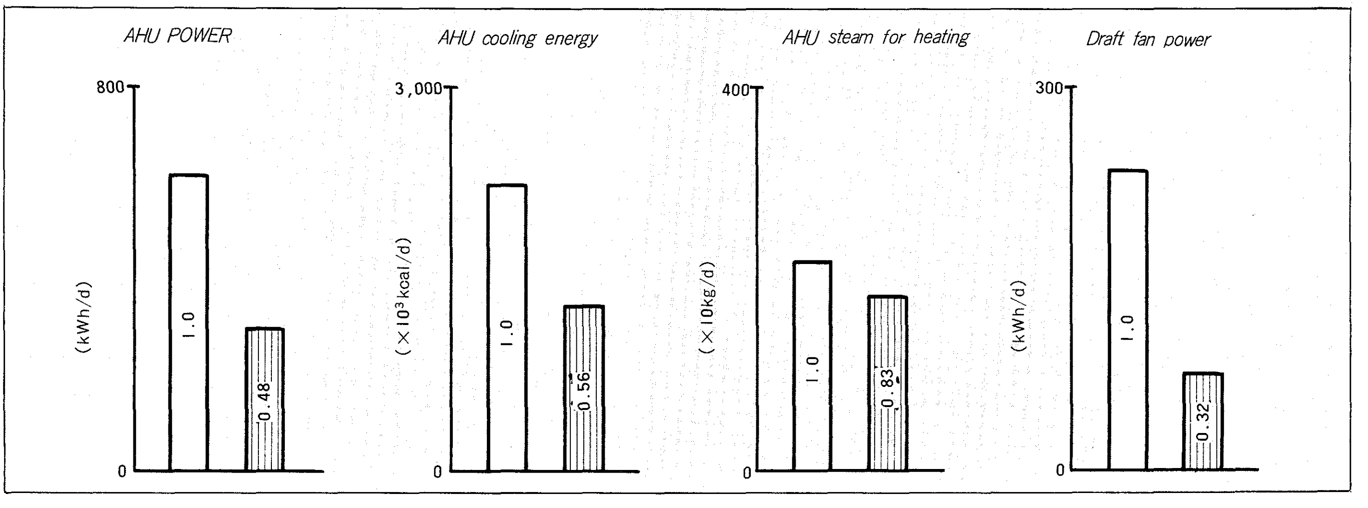


Fig. 4 Energy saving by VVVF



and vapor required for temperature and humidity controls can be reduced by reducing draft value at break time and by suppressing volume of air used to maintain a constant room pressure, and range of the energy saving can be expanded.

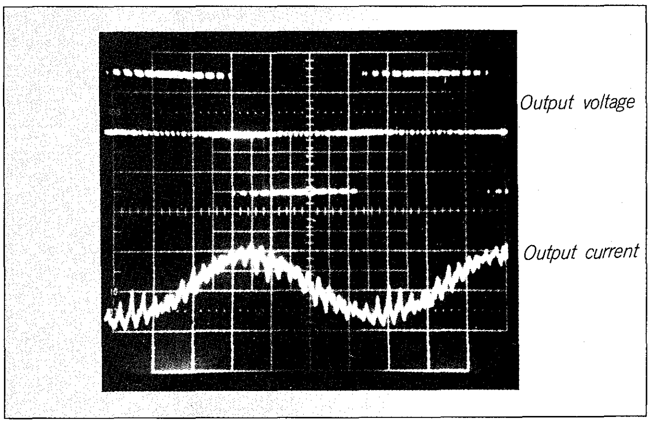
In an automatic interlocked control system, power consumption and other energies saved by the VVVF system were actually measured. *Fig. 4* shows the results.

[4] VVVF SYSTEM

Various types are available for saving energies through variable speed AC motor operations. Fuji Electric uses, as the standard system, VVVF (Variable Voltage Variable Frequency) of FRENIC$^{(R)}$ 5000 series and FVR series which use transistor inverter for square reduction torque load such as a fan and pump.

This system uses Fuji Electric's own sinewave PWM control to change frequency, improving system efficiency and reducing torque pulsation. Further, the soft start/stop time can be adjusted toward a wide range so that the system can be applied even to a load having a large inertia.

Fig. 5 Output waveform of sine wave PWM transistor inverter



$$WH_1 = \int_0^T P(t)\,dt = \int_0^T Q(t)\cdot H(t)\,dt \quad \ldots\ldots\ldots (4)$$

where, $Q(t)$ is recognized to be $\frac{Q_2 - Q_1}{T}t + Q_1$, and $H(t)$ is recognized to be $\frac{H_2 - H_1}{T}t + H_1$.

Table 4 Various operating systems and power consumptions

Operating system / Compared item	(1) Time-to-time	(2) Mechanical VAV	3 VVVF	Remarks
Content	Operated in an approximately constant speed, and wind value reduces from Q_1 to Q_2 in response to increase of pressure loss.	Air valve control is made automatically so that a constant wind value (Q_2) operation can be performed.	Motor speed is controlled automatically so that a constant wind value (Q_2) operation can be performed.	
Change of required power P	$Q_1H_1 \rightarrow Q_2H_2$ $P_1=\frac{\Delta Q \cdot \Delta H}{T^2}t^2 + \frac{\Delta Q \cdot H_1 + Q_1 \cdot \Delta H}{T}t + Q_1H_1$	Q_2H_2 = const. $P_2=Q_2H_2$	$Q_2H_0 \rightarrow Q_2H_2$ $P_3=\frac{Q_2(H_2-H_0)}{T}t + Q_2H_0$	$\Delta Q=Q_2-Q_1$ $\Delta H=H_2-H_1$
Used power ($WH=\int_0^T P dt$)	WH_1 = *Equation (5)* indicated above	$WH_2=Q_2H_2T$	$WH_3=\frac{1}{2}Q_2(H_0+H_2)T$	
Power comparison	1.0	0.93～1.01	0.65～0.79	

Thus, equation (4) is rearranged to be;

$$WH_1 = \frac{1}{3}(Q_1H_1 + Q_2H_2 + \frac{1}{2}\overline{Q_1H_2 + Q_2H_1})T \quad .. (5)$$

Table 4 shows WH_2 and WH_3 obtained in the same manner for the mechanical type VAV unit and VVVF system.

When these systems are compared and examined, $WH_1 \geqq WH_2 > WH_3$ at the portion where *Q-H* curve is slowly coming down (Q_1/Q_2 is large), and $WH_2 \geqq WH_1 > WH_3$ at the portion where curve is coming down comparatively rapidly (Q_1/Q_2 is close to 1). In any cases, in comparison with other control systems, VVVF system is always capable of saving energy by 20 to 35%.

To be more practically, when the capacity of the motor of AHU for the CR the area and class of which are respectively 100m^2 and 10,000 (other conditions are omitted) is 40kW, and the system is operated up to the HEPA filter life period (for example, assuming it to be three years), the electric power charge reaches about 15 million yens. While, when the VVVF system is applied, 3 to 5.5 million yens can be saved (using the coefficient of comparison in *Table 3*), and it can be understood that the cost of the VVVF system can be reimbursed within 1.5 to 3 years.

3.2 VVVF control for particle value change

Generally, the funds for building a CR and relative equipment are high, and therefore, normally, the operating ratio is high (for the purpose of reimbursement). However, as described in [2] above, generated particle value can be greatly reduced by selecting a proper cloth, and thus, level of the management has been improved. Then, changes of generated particle value analyzed by time, day, month and year greatly vary depending on the operating condition, non-operating condition, condition of the security and production density. (*Table 5*) Further, when process automation is advanced as the recent trend, one worker handles multiple number of equipment, and works are limited to material attaching, material detaching, inspection and monitoring, movements of the workers within the room and types of motion affect generated particle value change greatly.

Table 5 Dust level in CR

Dust source / CR state	Working	Not working	Maintenance
People	○	(○)	(○)
Equipment	○	○	(○)
Others (leakage, interior furnishing, etc.)	○	○	○
Dust amount	Large	Medium	Small
Dust change	Large	Medium	Small

(Note): (○) is suppressed to the necessary minimum.

In addition, in many cases, CR is used for the purpose of a research and development. Especially, in case of a CR used for nospecified purposes and for noconstant work, the VVVF control of a constant cleanliness is extremely effective as shown in *Fig. 3*.

Furthermore, when the CR is provided with a draft fan to eliminate special gas and local heat, recirculation ratio (*r*) of the air conditioning system to AHU is reduced, and air is supplied mainly to 0A. In a system like this, cooling energy (*Fig. 5* shows output waveforms of the inverter.)

Moreover, this system can be applied to 200V and 400V as for voltage and 0.4 to 110kW as for motor capacity, which covers a sufficient range for an air conditioning system. However, when the capacity is further greater, thyristor inverter type is selected. *Table 6* shows the general specifications of the standard self-standing type panel (*Fig. 6*). For the practical applications, the following matters must be taken into considerations:

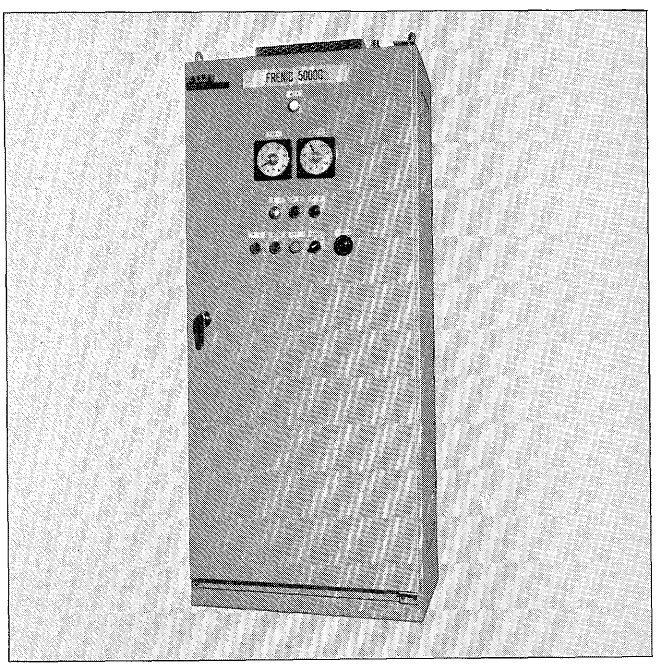
(1) Capacity: Motor rating, actual load rating, reduction capacity

Table 6 Standard external dimensions of VVVF system

System	Capacity (kVA)	Maximum capacity of applicable motor	200V				400V			
			With (mm)	Depth (mm)	Height (mm)	Weight (kg)	Width (mm)	Depth (mm)	Height (mm)	Weight (kg)
FVR (Transistor system)	1.5	0.4, 0.75	280	120	320	7	–	–	–	–
	3	1.5, 2.2	290	220	320	12	–	–	–	–
	5	3.7	280	230	320	14	–	–	–	–
	7.5	5.5	280	260	350	15	–	–	–	–
	10	7.5	280	260	350	16	–	–	–	–
	8	5.5	500	440	900	70	–	–	–	–
	10	7.5	500	440	900	70	600	600	1,650	80
FRENIC 5000 (Transistor system)	15	11	600	540	1,150	135	600	600	1,650	150
	20	15	600	540	1,150	135	600	600	1,650	150
	24	18.5	700	540	1,150	180	600	600	1,650	150
	30	22	700	540	1,150	180	600	600	1,650	250
	37	30	700	540	1,150	230	600	600	1,650	250
	47	37	900	600	1,650	280	600	600	1,650	250
	57	45	900	600	1,650	350	600	600	1,950	300
	70	55	900	600	1,650	350	600	600	1,950	350
	95	75	–	–	–	–	1,000	800	1,950	400
	140	90/110	–	–	–	–	1,200	800	2,150	550

NOTE) (1) The standard FVR is of a unit type. The indicated dimensions are the unit.
(2) When bypass switch is attached, 300mm must be added to the maximum width.

Fig. 6 VVVF standard self-standing panel



(2) Main circuit: Existence and nonexistence of bypass circuit
(3) Speed control: Manual, automatic, programmer, timer schedule (including control system in case of automatic)
(4) Control condition: Cleanliness, temperature, humidity, pressure, flow, time, season, and remote-direct-automatic switching control
(5) Control range: Control from the applied system, limit by the system
(6) Panel configuration: Self-standing, Wall support, etc.
(7) Delivery condition: Elevator, machine hatch, entrance door, etc.
(8) Installed place: Installed space, limitions on installation work, etc.
(9) Others: Noise, vibtation and other environmental conditions, etc.

Especially, when considering an application of this system to an already existing CR, (6) through (9) should be examined particularly carefully.

5 POSTSCRIPT

When examining energy saving methods in a wide mean, it is necessary to examine not only the matters of operations but also design problems such as building structures and equipment. However, as the problems are complicated, this paper has discussed only the air conditioning system which occupies the majority of the subject of energy. As other methods, there are collection of discharged heat, outside air cooling, reheating of coolant water and introduction of solar system. However, as the VVVF system can be used commonly; the paper discussed energy savings around the VVVF system. Number of examples of introductions of the VVVF system into already existing CRs is increasing, making a great energy saving effect. It is considered that the idea of "Work hard first, enjoy later" in an economical mean, to be more specific, a trial to reduce running cost by adding various equipment will be more active in the CR systems. In this meaning, it will be the author's great pleasure if this paper is used as a reference.