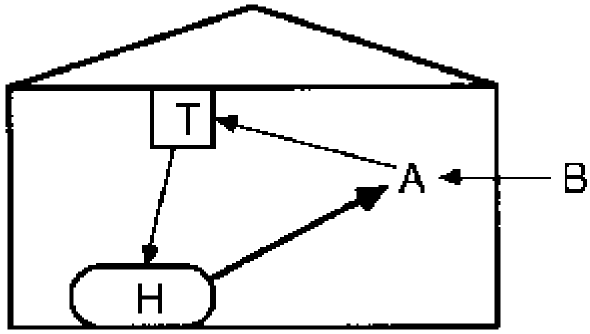
Chapter 10. Ventilation Control and Quantification of Performance

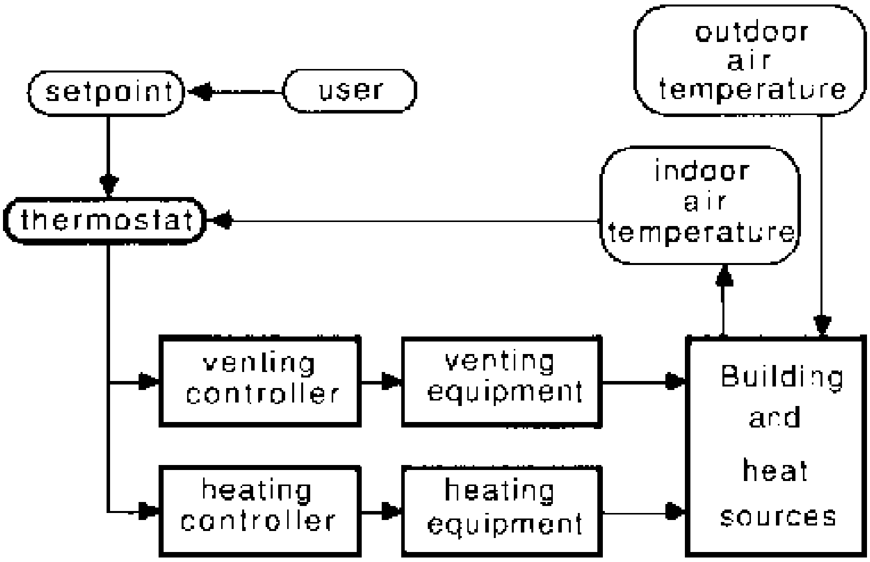
通風控制與降溫效果量化指標的建立

10-1. Introduction

右圖所示為控制系統示意圖，A 為室內溫度，B 為室外溫度，T 為溫度調節器(Thermostat，又稱恆溫器，包括感測、設定與輸出等三個動作)，H 為加熱器。



一般包括加熱與通風的溫度控制系統如圖 10-1 所示，外溫與室內之其它熱源影響建築物之散熱情況，直接影響內溫。內溫與恆溫器之設定值控制通風口、風扇與加熱器之開閉。通風口、風扇與加熱器對室內溫度的影響屬於負回授(饋)控制(negative feedback control)，負回授(饋)代表此次的動作幅度愈大，下次所需的動作幅度則愈小。



常見的回授(饋)控制包括：

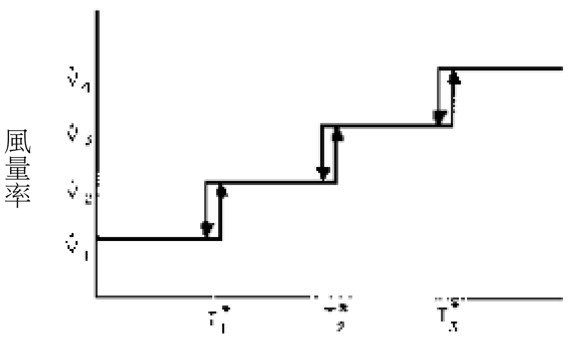
On/Off Control	Simple, Less accurate, Overshoot
比例控制 Proportional control	The rate at which the controlled parameter is delivered is proportional to the difference between the reference input and the controlled output. This applies correction in proportion to the size of the error.
積分控制 Integral control	Limits small long-term offsets from set-points. Acts to integrate error over time and bring the average error to zero. This applies correction in proportion to the integral of the error.
微分控制 Derivative control	DC is used when a rapid response is desired. The time derivate of error determines the magnitude of the response. DC is useful to prevent sudden large departures of the controlled variable from the setpoint. This applies correction in proportion to the rate of change of the error.

$$P = K_P E_P + K_I \int_0^t E_P dt + K_D \frac{dE_P}{dt} + P_t(0)$$

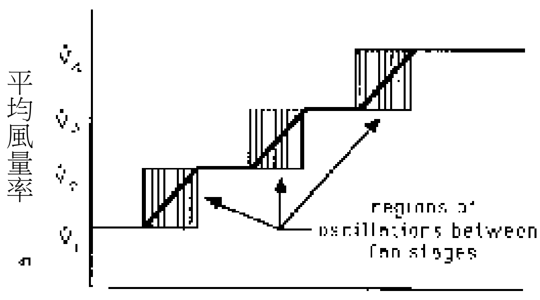
10.2. Duty Factors, staged fan systems using single speed fans

風機系統的 Duty Factor 定義為全年的平均風量率(m^3/s)除以該系統的最大風量率。如果風機系統的 Duty Factor 與風機之效率為已知，則風機之全年使用成本即可計算求得。

圖 10-2. (下方左圖)所示的控制系統有 4 個風量，需要使用三個 Thermostat 設定三個室內溫度設定值(T_1^*,T_2^*,T_3^*)。圖 10-3. (下方右圖) 所示為另一類控制系統，其平均風量率與外溫呈平滑函數關係。



室內溫度



室外溫度

第三種為如表 10-1 所示的方法。

Table 10-1. Outdoor air temperatures corresponding to n thermostat setpoints and n + 1 ventilation stages

Thermostat Setpoint	Ventilation Rate $\dot{V}_1$	$\dot{V}_2$	$\dot{V}_3$	. . .	$\dot{V}_n$	$\dot{V}_{n+1}$
SP_1	$(t_o)_{1,1}$	$(t_o)_{1,2}$				
SP_2		$(t_o)_{2,2}$	$(t_o)_{2,3}$			
SP_3			$(t_o)_{3,3}$			
⋮						
SP_n					$(t_o)_{n,n}$	$(t_o)_{n,n+1}$

上表中 t_o 可用式 10-1 計算，其中動物所提供之顯熱改用式 10-2 的一元二次式表示 (可使用 POLYNOM 程式求出 a, b, c 係數之值)，經重組得式 10-3 可用來計算 t_i，得式 10-4 可用來計算 t_o。

$$t_0 = \left[-q_{prod} + \left(\sum UA + FP + mc_p\right)t_i\right] / \left(\sum UA + FP + mc_p\right) \quad \text{(10-1)}$$

$$q_{prod} = a + bt_i + ct_i^{\,2} \quad \text{(10-2)}$$

$$t_i = \frac{-(b - HLF - mc_p) - \sqrt{(b - HLF - mc_p)^2 - 4c(a + HLFt_0 + mc_p t_0)}}{2c} \quad \text{(10-3)}$$

$$t_o = \frac{-ct_i^{\,2} - (b - HLF - mc_p)t_i - a}{HLF + mc_p} \quad \text{(10-4)}$$

$$\begin{aligned}\dot{V}_{ave} = {} & \dot{V}_1 P[-\infty < t_o < (t_o)_{1,1}] \\ & + 1/2(\dot{V}_1 + \dot{V}_2)P[(t_o)_{1,1} < t_o < (t_o)_{1,2}] \\ & + \dot{V}_2 P[(t_o)_{1,2} < t_o < (t_o)_{2,2}] \\ & + 1/2(\dot{V}_2 + \dot{V}_3)P[(t_o)_{2,2} < t_o < (t_o)_{2,3}] \\ & + \dot{V}_3 P[(t_o)_{2,3} < t_o < (t_o)_{3,3}] + \end{aligned} \quad \text{(10-6)}$$

$$\text{duty factor} = \dot{V}_{ave} / \dot{V}_{n+1}. \quad \text{.........} (10\text{-}7)$$

10-3. Ventilating Efficiency Ratios and the Cost of Ventilation

$$VER = (m^3/s \text{ of air delivery}) / (kW \text{ of electricity}) \quad \text{.........} (10\text{-}8)$$

$$\cos t = \frac{(8760 hrs/yr)(\max\ capacity)(duty\ factor)(unit\ elect.\ \cos t)}{Ventilating\ Efficiency\ Ratio} \quad \text{.........} (10\text{-}9)$$

Example 10-1.請計算一台風量為 5.5 m3/s 的風扇運作一年的操作成本，假設風扇的 VER 為 8 m3/s-kW，電費為 0.11 US$/kWh 且工作比 (duty factor) 為 0.6。

Sol: cost = 8760 * 5.5 * 0.6 * 0.11 / 8 = 397.49 US$ / yr

10-4. The Cost of Ventilating Animal Housing, an Example

Example 10-2. 位於美國科羅拉多州丹佛市的某繫留式牛舍採取機械通風，該牛舍飼養了 150 頭平均重量為 550 kg 的乳牛。假設設計的牛舍的包含牆壁、天花板、週邊等的結構熱損失因子總計為 900 W/K，室內照明為 10 W/m^2，牛舍地板面積為 1500 m^2。最小與最大通風風量率為 2.9 與 21 m^3/s，風扇的 VER 為 9 m3/s-kW，每度電費為 0.1 US$。請選擇風扇的控制段數與各階段的設定溫度值，並估算全年的通風成本。

Stage	Percentage of Maximum	m^3/s
1	13.8	2.9
2	19	4.0
3	25	5.3
4	45	9.5
5	100	21.0

Air Temp,C	Sensible Heat Prod., W/kg
-1	1.9
10	1.5
15	1.2
21	1.1
27	0.6

$$q_{prod} = (150\ \text{cows})\ (500\ \text{kg})\ (550 / 500)^{0.734}(q'_{prod})$$
$$= 149{,}600 - 2473t - 42.4t^2,$$

+ 15000

here t is indoor air temperature, C.

nsible heat production within the airspace includes anima
hts. Heat from lights is not a function of indoor air ter
at production within the barn is

$$q_{barn} = 164{,}600 - 2473\ t - 42.4t^2.$$

a = 164600
b = -2473
c = -42.4

Indoor Air Temperature, C	Air Density, kg/m^3
9	1.05
13	1.03
17	1.02
21	1.00

Ventilating rate : $m = (5.3\ m^3/s)*(1.02\ kg/m^3) = 5.41\ kg/s$

$$t_o = \frac{-(-42.4)(13)^2 - [-2473 - 900 - (5.41)(1006)](13) - 164{,}600}{900 + (5.41)(1006)} = -6.75$$

Thermostat Setpoint, C	Ventilation Rate, kg/s 2.90	4.08	5.41	9.69	21.42
9	- 27.4	- 18.8 C			
13		- 12.0	- 6.75 C		
17			- 0.39	6.63 C	
21				12.2	16.8 C

$$
\begin{aligned}
P[-\infty < t_o < -27.4\,C] &= P[-\infty < t_o < -34.4] + P[-34.4 < t_o < -28.9] \\
&\quad + P[-28.9 < t_o < -27.4] \\
&= [0\text{ hrs} + 1\text{ hr} + (8\text{ hrs})(-28.9 + 27.4) \\
&\quad /(28.9 + 23.3)] / 8760 \\
&= [0\text{ hrs} + 1\text{ hr} + 2\text{ hrs}] / 8760\text{ hrs} \\
&= 0.0003
\end{aligned}
$$

Temperature Range	Hours Per Year in the Range (a)	Probability of the Range
to -27.4	3	0.0003
-27.4 to -18.8	35	0.0040
-18.8 to -12.0	157	0.0179
-12.0 to -6.75	366	0.0418
-6.75 to -0.39	1132	0.1292
-0.39 to 6.63	1833	0.2092
6.63 to 12.2	1485	0.1696
12.2 to 16.8	1227	0.1401
16.8 up	2522	0.2879

(a) rounded to the nearest hour

$$
\begin{aligned}
\dot{V}_{ave} &= (2.9\text{ m}^3/\text{s})(0.0003) + 1/2(2.9\text{ m}^3/\text{s} + 4.0\text{m}^3/\text{s})(0.0040) \\
&\quad + (4.0\text{ m}^3/\text{s})(0.0179) + 1/2(4.0\text{ m}^3/\text{s} + 5.3\text{ m}^3/\text{s})(0.0418) \\
&\quad + (5.3\text{ m}^3/\text{s})(0.1292) + 1/2(5.3\text{ m}^3/\text{s} + 9.5\text{ m}^3/\text{s})(0.2092) \\
&\quad + (9.5\text{ m}^3/\text{s})(0.1696) + 1/2(9.5\text{ m}^3/\text{s} + 21\text{ m}^3/\text{s})(0.1401) \\
&\quad + (21\text{ m}^3/\text{s})(0.2879), \\
&= 0.00087 + 0.01380 + 0.07160 + 0.19437 + 0.68476 + 1.548 \\
&\quad + 1.61120 + 2.13653 + 6.04590 \\
&= 12.30711, \text{ or } 12.3\text{ m}^3/\text{s}.
\end{aligned}
$$

Cost = 8760 * 21 * 0.59 * 0.1 / 9 = $1206, or approximately $8 per cow per year.

10-5. Program DUTYFACT

air pressure = 101.325 exp(-0.00011943 z) – 6.799 x 10^{-6} z – 6.976 x 10^{-8} z^2 (10-10)

Example 10-3. 續上題，請使用 Dutyfact 軟體重做上題，另外亦假設風扇分階段採等間隔，請計算通風的成本。

Fan Stage	Ventilation Rate, m^3/s
1	2.9
2	4.0
3	5.3
4	9.5
5	21.0

Fan Stage	Fans to Operate	m^3/s at 12.5 Pa
1	5 - model b	2.85
2	7 - model b	3.99
3	7 - model b	
	2 - model c	5.35
4	7 - model b	
	2 - model c	
	2 - model e	9.35
5	7 - model b	
	2 - model c	
	2 - model e	
	2 - model d	
	2 - model j	21.21

Thermostat Setpoint, C	Ventilation Rate, m^3/s				
	2.85	3.99	5.35	9.35	21.21
9	- 27.46	- 18.93 C			
13		- 12.19	- 6.69 C		
17			- 0.34	6.44 C	
21				12.00	16.83

Temperature Range	Probability of the Range	Fan Operation
to - 27.46	0.000349	stage 1 only
- 27.46 to - 18.93	0.003854	stages 1 and 2
- 18.93 to - 12.19	0.016545	stage 2 only
- 12.19 to - 6.69	0.043454	stages 2 and 3
- 6.69 to - 0.34	0.130651	stage 3 only
- 0.34 to 6.44	0.201918	stages 3 and 4
6.44 to 12.00	0.169281	stage 4 only
12.00 to 16.83	0.147024	stages 4 and 5
16.83 up	0.286924	stage 5 only

Fan Stage	VER, m^3/s-kW
1	3.660
2	3.660
3	3.631
4	4.075
5	5.642

Fan Stage	Ventilation Rate, m^3/s
1	2.90
2	7.43
3	11.95
4	16.48
5	21.00

Fan Stage	Fans to Operate	m^3/s at 12.5 Pa
1	5 - model b	2.85
2	5 - model b	
	4 - model d	7.57
3	5 - model b	
	8 - model d	12.29
4	5 - model b	
	8 - model d	
	2 - model e	16.29
5	5 - model b	
	8 - model d	
	2 - model e	
	2 - model f	21.25

Example 10-4. 續範例 10-2，請嘗試調整各階段的溫度設定值，並討論對通風成本的影響。

Setpoints	Yearly Ventilation Cost (Electricity
9, 13, 17, 21	$2244.84
9, 13, 19, 21	$2180.09
9, 15, 19, 21	$2169.21
9, 13, 21, 25	$1916.93
9, 15, 21, 25	$1905.41 ←
9, 15, 21, 22	$2052.22
5, 13, 17, 21	$2245.37
9, 15, 17, 21	$2234.09

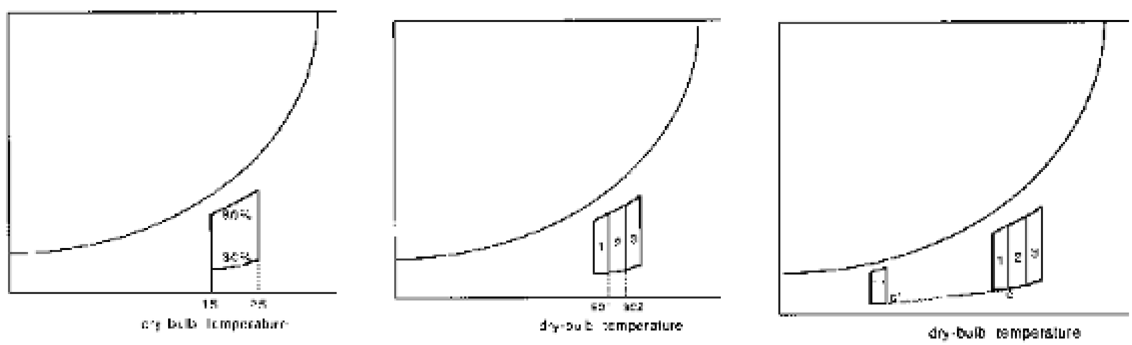
最貴的不代表最差，最便宜的也不代表最好，還須看該設定條件對動物的影響。如果最貴的設定條件能讓動物的產能表現每年增加超過 400 美元，而電費最大相差 300 多美元，那表示該設定條件還是值得投資的。

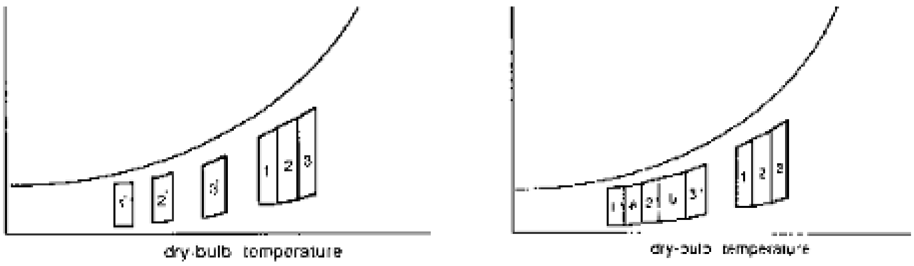
10-6. Quantifying Environment Control Effectiveness

Acceptable Weather Space (AWS)
Climate Space (CS)
Production Space (PS)
Environment-Control Effectiveness Index (EEI)

$$q_s = (\sum UA + FP + mc_p)(t_i - t_0) \quad \text{(10-11)}$$

$$\dot{m}_p = m(W_i - W_0) \quad \text{(10-12)}$$





PS：　1，2，3　三區
AWS： 1', a, 2', b, 3' 五區
EEI: 落於　AWS 區間內的累計機率值
WEI: 落於　PS 區間內的累計機率值

補充：DOS 版程式　weaplot 使用台灣氣象資料

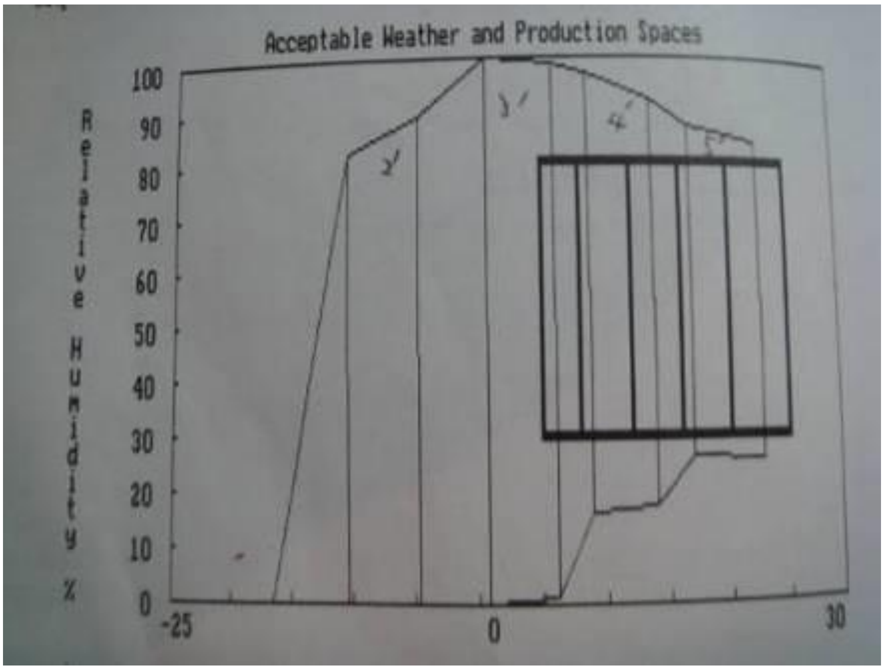
10-6.1. Program WEATHER

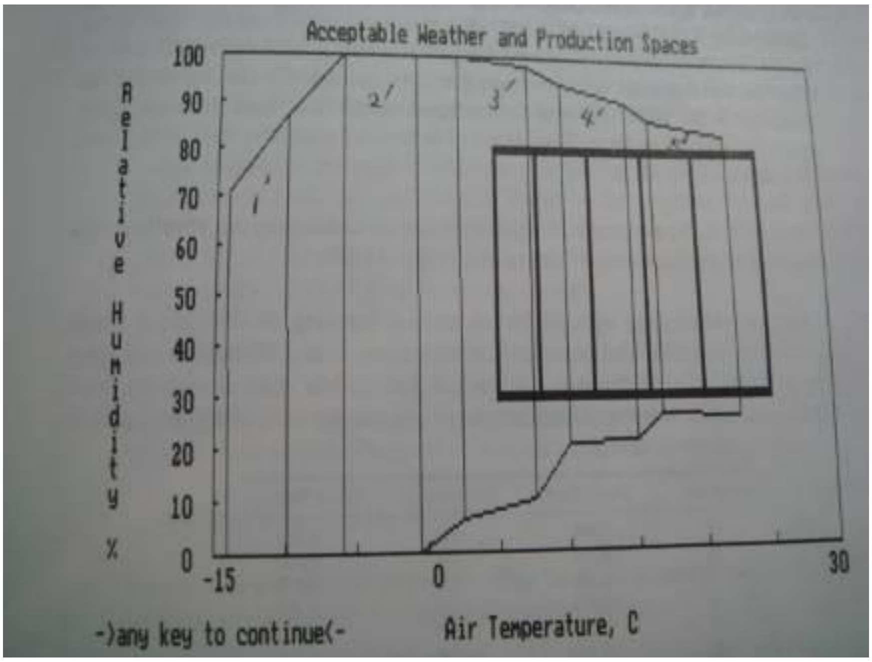
Weather.dat 內含 溫度 (-30~35 deg.C)，濕度 (0~100%) 共 66 x 101 筆機率數據

-30	0	0.0000000000
-30	1	0.0000000000
-30	2	0.0000000000
—	—	—
-30	100	0.0000000000
-29	0	0.0000000000
-29	1	0.0000000000
—	—	—
-20	58	0.0000293204
—	—	—
0	50	0.0000586407
0	51	0.0001466018
—	—	—
9	97	0.0011141735
—	—	—
35	100	0.0000000000

10-6.2. Example use of WEATHER

Example 10-5. 假設如範例 9-4 所述的乳牛舍位於海拔 300m 的紐約州綺色佳，牛舍飼養了 62 頭平均重量為 550 kg 的乳牛，其 UA 與 FP 值分別為 640 與 105 W/K。生產空間為 5 ~ 25 度 C，30~80 % RH，各階段風量分別為 1.16, 1.74, 2.88, 4.24 與 8.96 m3/s，各階段溫度設定點分別為 8, 12, 16 與 20 度 C，請問此設計是否適當？





10-7. Ventilation Control in Greenhouses

- 在相同地區溫室所用的風扇的 duty factor 應比禽畜舍中所用風扇的 duty factor 較小，因為不需全年操作。.
- 對溫室而言，因為作物的適溫範圍頗為狹窄，所以在控制器的溫度設定值上做變化以節約耗電量的可行性就小多了。只有在一開始選擇風扇時挑選效率高的風扇並注意時時維護保持風扇於最佳的操作性能才是最重要的。維護項目包括皮帶鬆緊度、

軸承、百葉窗等。

- 溫室通風的設計通常設定為 3 個階段(3-stage system)，最低階段為冬季通風之用，為最大風量的 15%，第 2 階段則多半為最大風量的 50% 。
- 通風的最低設定溫度應高於開始加熱的設定溫度至少 3 度 C。

補充：Matlab 版的 ventcost.m 程式，使用台灣各地的氣象資料