Ch.5 Steady-State Energy and Mass Balance
能量與質量守衡之穩態分析

Steady-state thermal analysis is evaluating the thermal equilibrium of a system in which the temperature remains constant over time. Energy and mass balance deals with the conservation of energy and conservation of mass laws to open systems or control volumes of interest.

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5-1. Introduction

建築物環控分析主要涉及三項重要觀念：

1. 控制容積 Control Volumes
2. 能量守恆 Conservation of Energy
3. 質量守恆 Conservation of Mass

Processes in thermodynamics, fluid mechanics, and heat transfer can be viewed in two ways:

1. To examine a process with a focus on its internal features.
2. To enclose the process with an imaginary boundary and examine only what passes across the boundary. (Control Volume approach, black box approach)

The general balance equation can be written as

Accumulation = Input + Generation - Output - Consumption

顯熱守恆 (Sensible energy balance) 分析主要構成項：(圖5-1)

q_s	空間中由動物體獲得的顯熱
q_m	空間中由機械元件獲得的顯熱
q_{so}	空間中由太陽獲得的顯熱
q_{vi}	透過通風進入空間的空氣(室外空氣)本身所含有的顯熱
q_h	空間中由加熱系統獲得的顯熱

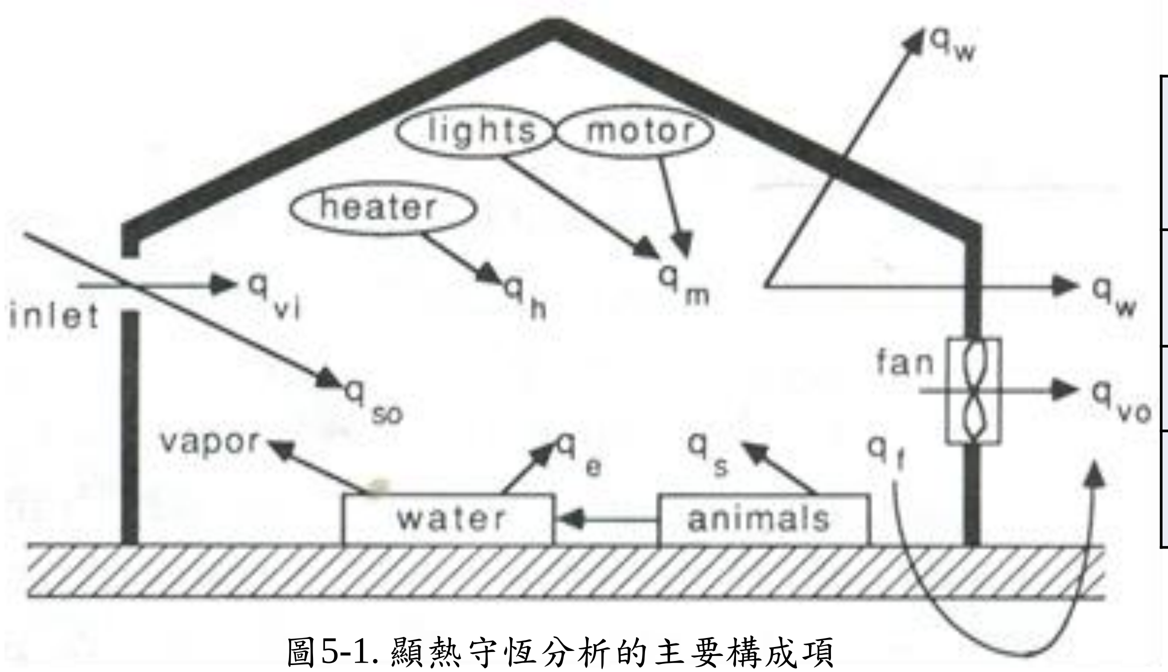


圖5-1. 顯熱守恆分析的主要構成項

q_w	穿透結構體(牆、屋頂、窗、門地板、天花板等)所傳入或傳出的顯熱
q_f	穿透地板(主要發生在周邊)所傳入或傳出的顯熱
q_e	空間中顯熱轉換為潛熱的速率
q_{vo}	透過通風離開空間的空氣 (室內空氣)本身所含有的顯熱

Gains - Losses = Change of Storage

Steady state means no change of storage, thus, **Gains = Losses**

$q_s + q_m + q_{so} + q_h + q_{vi} = q_w + q_f + q_e + q_{vo}$ …eq.5-1

質量守恆(Mass balance) 分析主要構成項：(圖5-2)

m_{vi}

透過通風進入空間的某成分(水汽、二氧化碳等)的質量

m_p

空間中由動物體獲得的顯熱

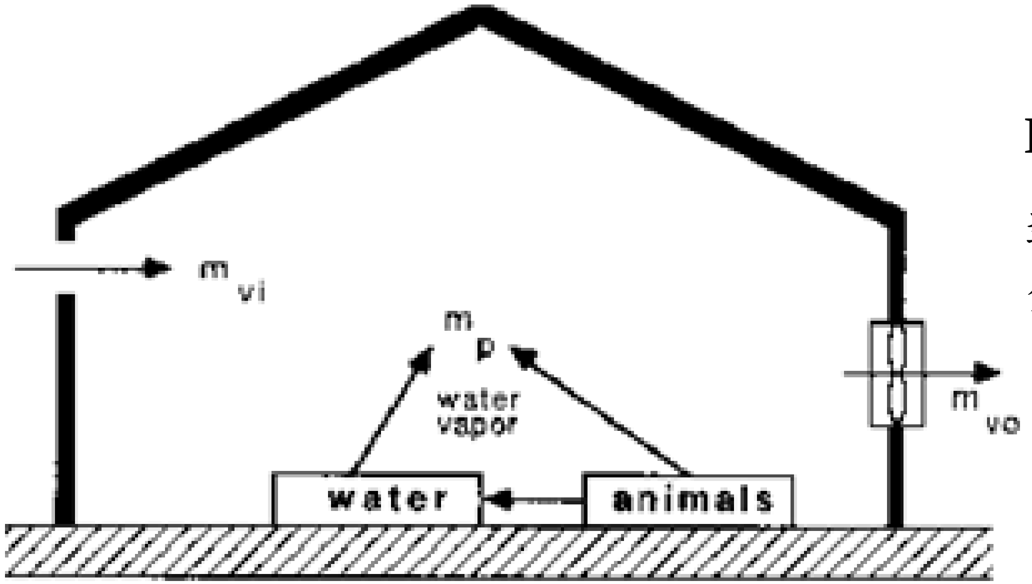


圖5-2. 質量守恆分析的主要構成項

m_{vo}

透過通風離開空間的的某成分(水汽、二氧化碳等)的質量

$$m_p + m_{vi} = m_{vo} \quad \text{… eq.5-2}$$

5-2. Components of the Sensible Energy Balance

5-2.1 Sensible heat produced by Animals, q_s

Appendix 5-1. P403

MP : moisture production
LHP: latent heat production
SHP: sensible heat production
THP: total heat production

Animal	Air Temperature	MP mg/kg s	LHP W/kg	SHP W/kg	THP W/kg
Dairy cow, 500 kg	-1 C	0.21	0.5	1.9	2.4
	10	0.28	0.7	1.5	2.2
	15	0.36	0.9	1.2	2.1
	21	0.36	0.9	1.1	2.0
	27	0.50	1.3	0.6	1.9

哺乳類動物的顯熱產生量與體表面積呈線性相關
哺乳類動物的顯熱產生量與體重的0.734次方成正比

Ex. 5-1 試求 100頭 590 kg乳牛，處於 12 ºC室溫下的顯熱產生量

Determine the sensible heat production from 100 (590kg) dairy cows housed in a barn at 12 C.

$$q_s)500kg = 1.2 + (2/5)(1.5-1.2) = 1.32\ W/kg$$

$$Q_s)500kg = 1.32 * 500 = 660\ W/cow@500\ kg$$

$$q_s)590kg = 660 * (590/500)^{0.734} = 745\ W/cow@590\ kg$$

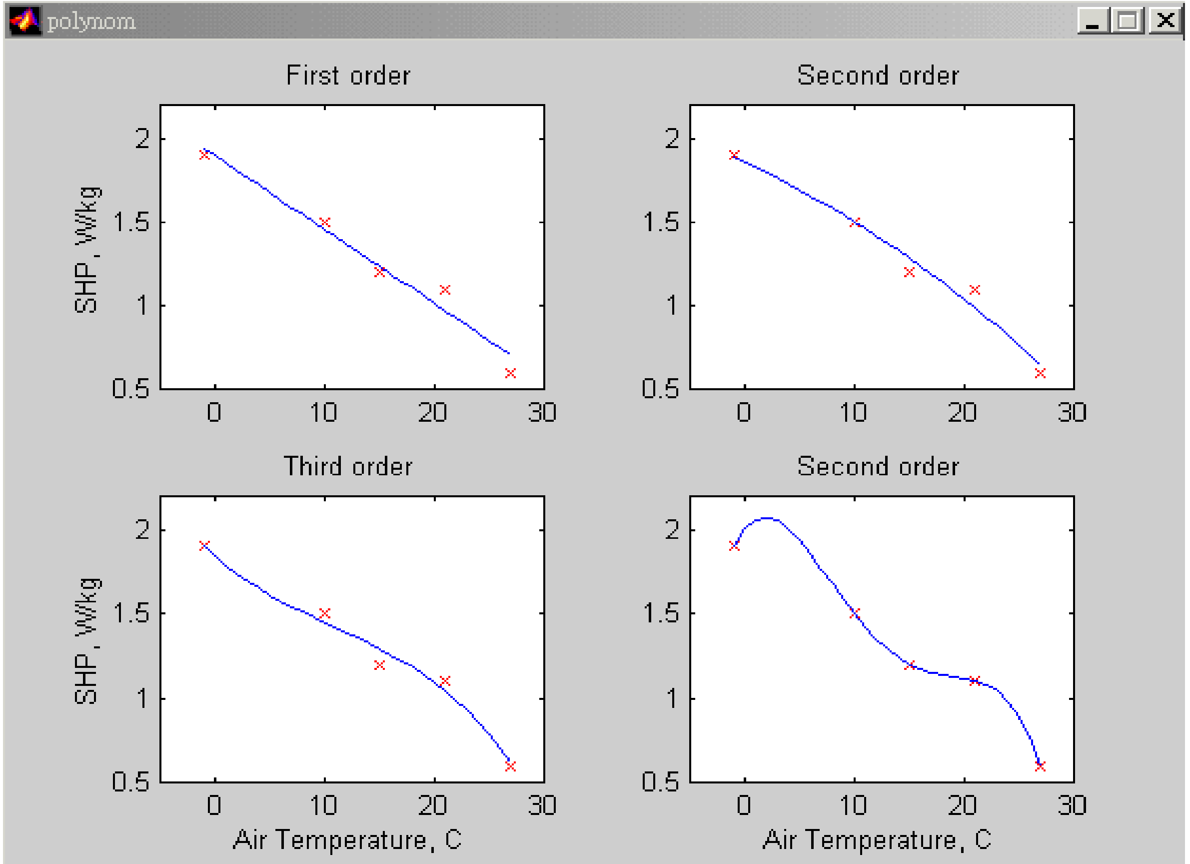
$$Q_s)590kg = 100\ cows * 745 = 74500\ W = 74.5\ kW$$

Animal	Air Temperature	MP mg/kg s	LHP W/kg	SHP W/kg	THP W/kg
Dairy cow, 500 kg	-1 C	0.21	0.5	1.9	2.4
	10	0.28	0.7	1.5	2.2
	15	0.36	0.9	1.2	2.1
	21	0.36	0.9	1.1	2.0
	27	0.50	1.3	0.6	1.9

Ex.5-2 請建立二元多項式來求出不同溫度下 500 kg乳牛的顯熱產生量。可使用Excel 中工具功能表中的資料分析工具箱中的迴歸功能。以下提供使用 Matlab 撰寫的程式。輸入 polynom，產生一個視窗，學習 Polyfit

$$q_s)500\ kg = 1.86 - 3.074 \times 10^{-2}\ t_{air} - 5.268 \times 10^{-4}\ (t_{air})^2$$

Observed	Predicted
1.9 W/kg	1.9 W/kg
1.5	1.5
1.2	1.3
1.1	1.0
0.6	0.6




Chap 5相關電腦軟體
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Chap 5 相關電腦軟體
下載執行程式：
1. 課本範例 Polynom, ex5-5, 5-6, Psy.m：下載 1 zip file (Matlab 程式)
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輸入 snell_law(1)，產生兩個視窗：學習 Polyfit 與 fplot 指令

Polynomial Regression Equations for Dairy Cow (500 kg) only

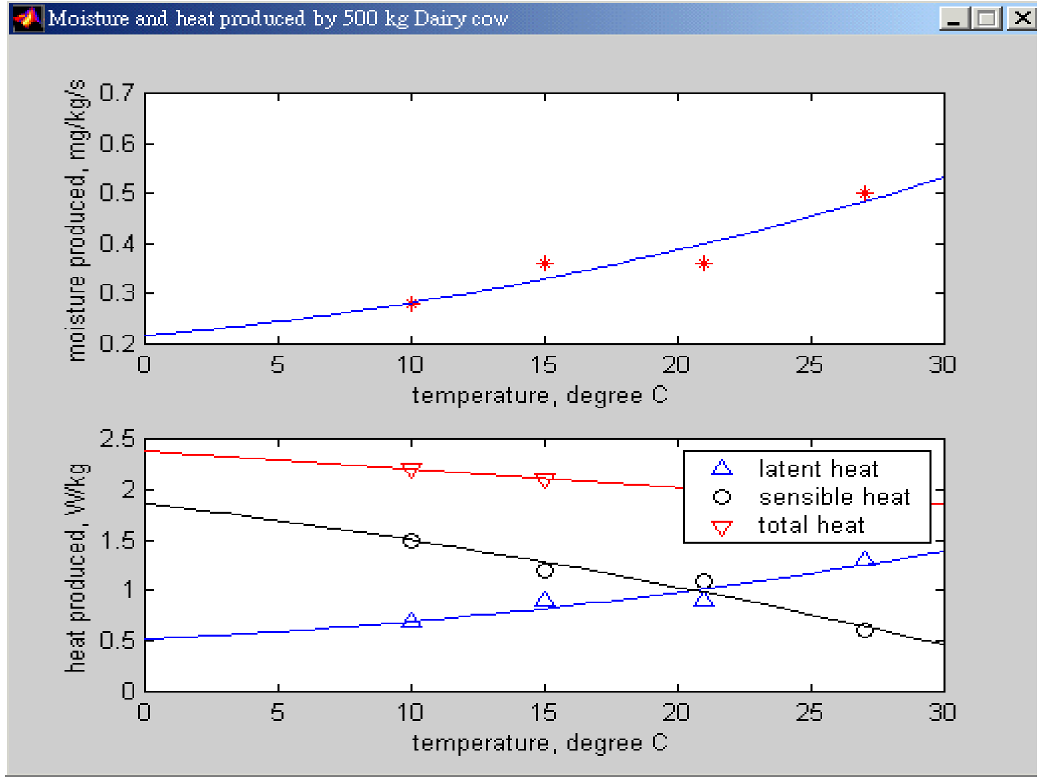
Moisture production (in mg/kg/s) = 0.21711+ (0.0045486)*T+ (0.00019848)*T^2

Latent heat production (in W/kg) = 0.52148+ (0.011559)*T+ (0.00057509)*T^2

Sensible heat production (in W/kg) = 1.8603+ (-0.030741)*T+ (-0.00052683)*T^2

Total heat production (in W/kg) = 2.3818+ (-0.019182)*T+ (4.8258e-005)*T^2

where, T in degree C



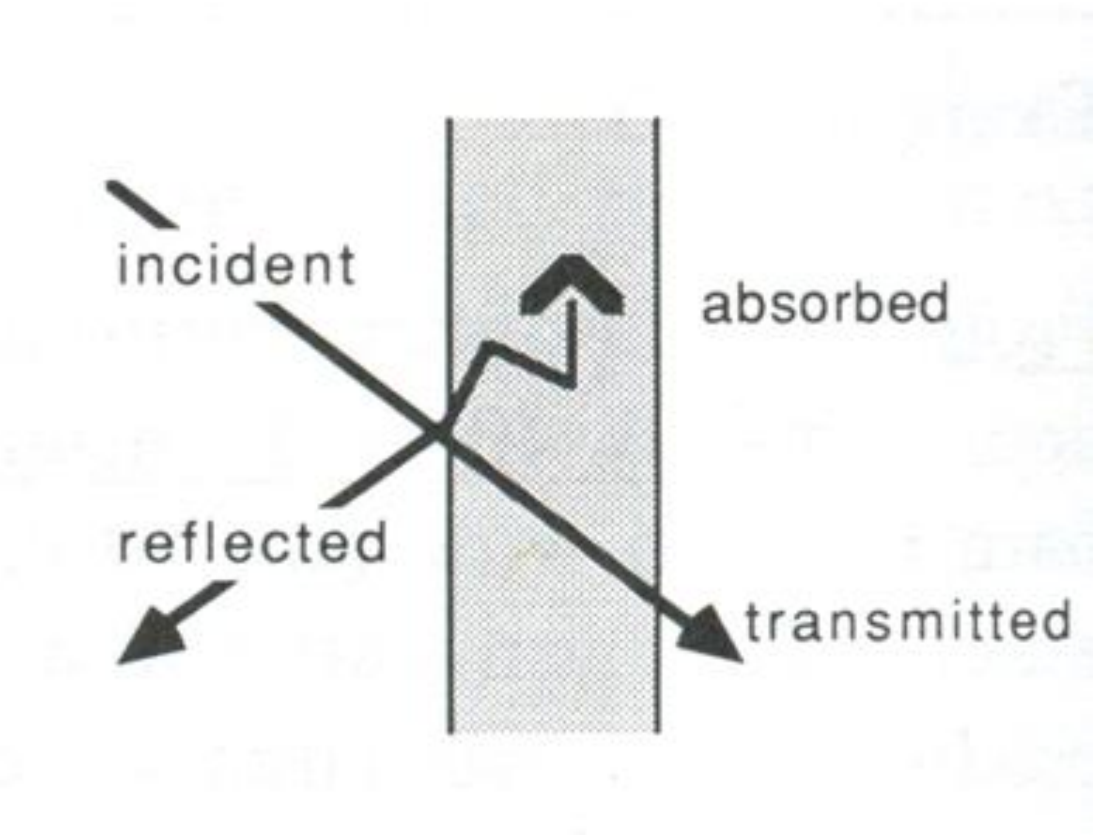
5-2.2 Mechanically Produced Heat, q_m

Ex. 5-3 某禽舍 12 m 寬、40 m 長，使用螢光燈管照明，每平方米地板面積使用 40 W，假設安定器需消耗額外的 20 % 功率。請估算來自燈光的顯熱產生速率。

Sol: 40 * 12 * 40 * 1.2 = 23000 W = 23 kW

5-2.3 Solar Heat Gain, q_{so}

吸收率 (absorptance, α)
反射率(reflectance, ρ)
穿透率(transmittance, τ)



Absorption

衰減係數(extinction coefficient, K, in mm^{-1})

穿透距離 (path length, L, in mm)

$-dI_\lambda = I_\lambda K_\lambda dx$ …eq.5-3

$\alpha = 1 - \exp(-KL)$ …eq.5-4

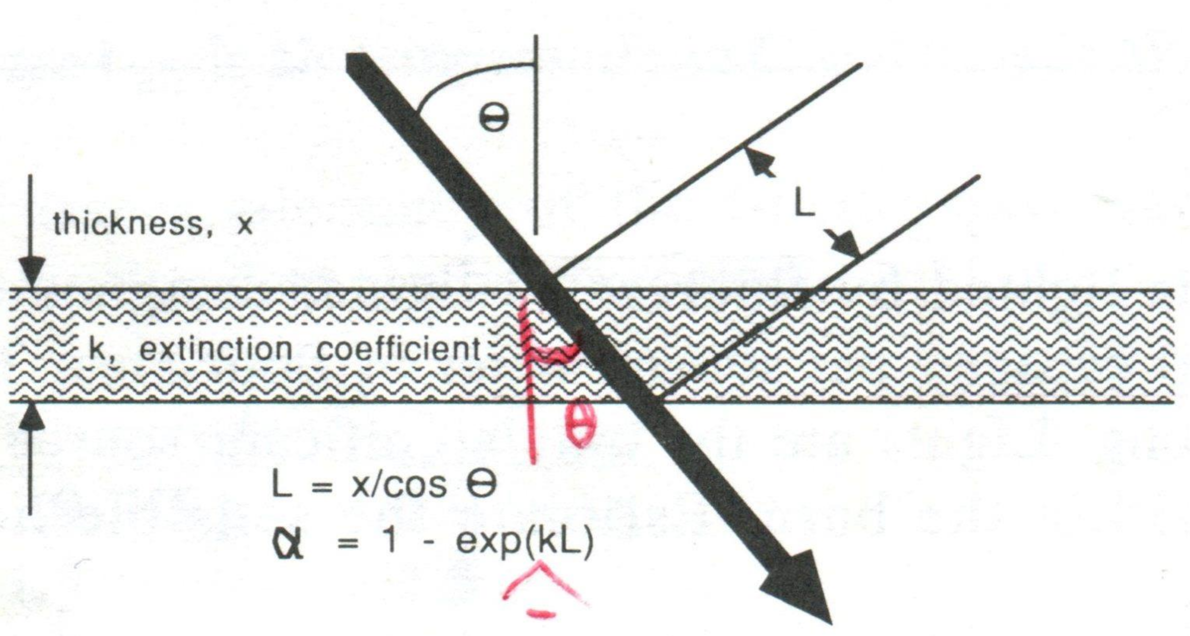


Table 5-1. Extinction coefficients for transparent materials.

Material	Extinction Coefficient, mm^{-1}
ordinary window glass	0.03 (approx.)
polyethylene	0.165
low-iron glass (<0.01% Fe_2O_3)	0.004 (approx.)
heat-absorbing glass	0.13 to 0.27
Tedlar[a] (polyvinyl fluoride)	0.14
Mylar[a] (polyethylene terephthalate)	0.205
Teflon[a] (fluorinated ethylene propylene)	0.06

[a]trademark of E. I. DuPont de Nemours, Wilmington, DE.

Ex. 5-4 請計算通過 3 mm 厚度一般玻璃的垂直入射光線的吸收率

Calculate the solar absorptance at normal incident angle for insolation passing through ordinary window glass 3 mm thick.

Sol:

由表 5-1 可知，衰減係數為 0.03 mm-1

由 eq 5-4, $\alpha = 1 - \exp(-KL) = 1 - \exp(-0.03 * 3) = 0.0861$

約 8.6 % 的光線經過玻璃時被吸收了。

Reflection 反射

折射率 (refractive index)

$$n = \sin\varphi / \sin\theta \qquad \text{...eq.5-5}$$

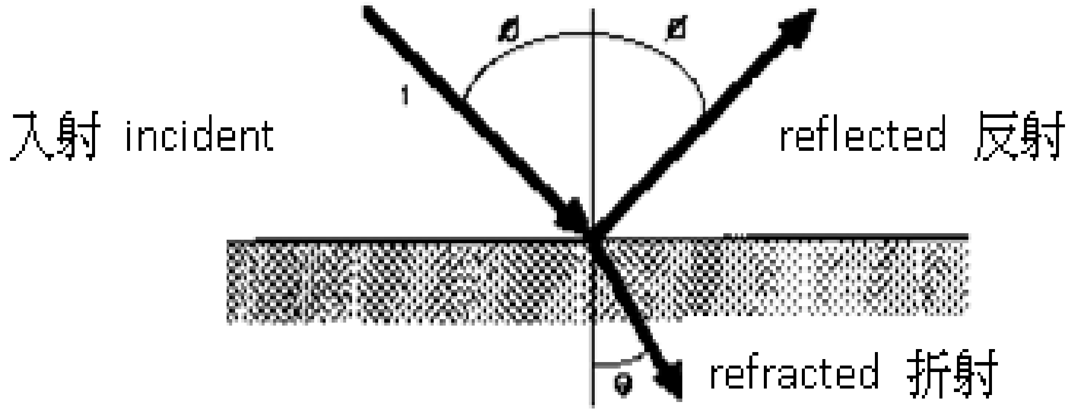


圖5-3. 光線照射到某透明材料時相關的入射、反射與折射角

Snell's law:

$$\rho_{parallel} = \sin^2(\varphi-\theta)/\sin^2(\varphi+\theta) \qquad \text{... eq.5-6a}$$

$$\rho_{perpendicular} = \tan^2(\varphi-\theta)/\tan^2(\varphi+\theta) \qquad \text{... eq.5-6b}$$

$$\rho_{average} = (\rho_{parallel} + \rho_{perpendicular})/2$$

Ex. 5-5 光線入射玻璃 (n=1.5) 時入射角為 50度，請計算水平與垂直方向的反射率

Determine the two components (parallel and perpendicular) of reflectance of light irradiating a glass surface at an angle of 50 degrees.

Table 5-2. Refractive indices for light in the visible waveband.

Material	Refractive Index
air	1.00
window glass	1.50 to 1.55
Tedlar[a] (polyvinyl fluoride)	1.45
Mylar[a] (polyethylene terephthalate)	1.64
Teflon[a] (fluorinated ethylene propylene)	1.34

[a]trademark of E.I. DuPont de Nemours, Wilmington, DE.

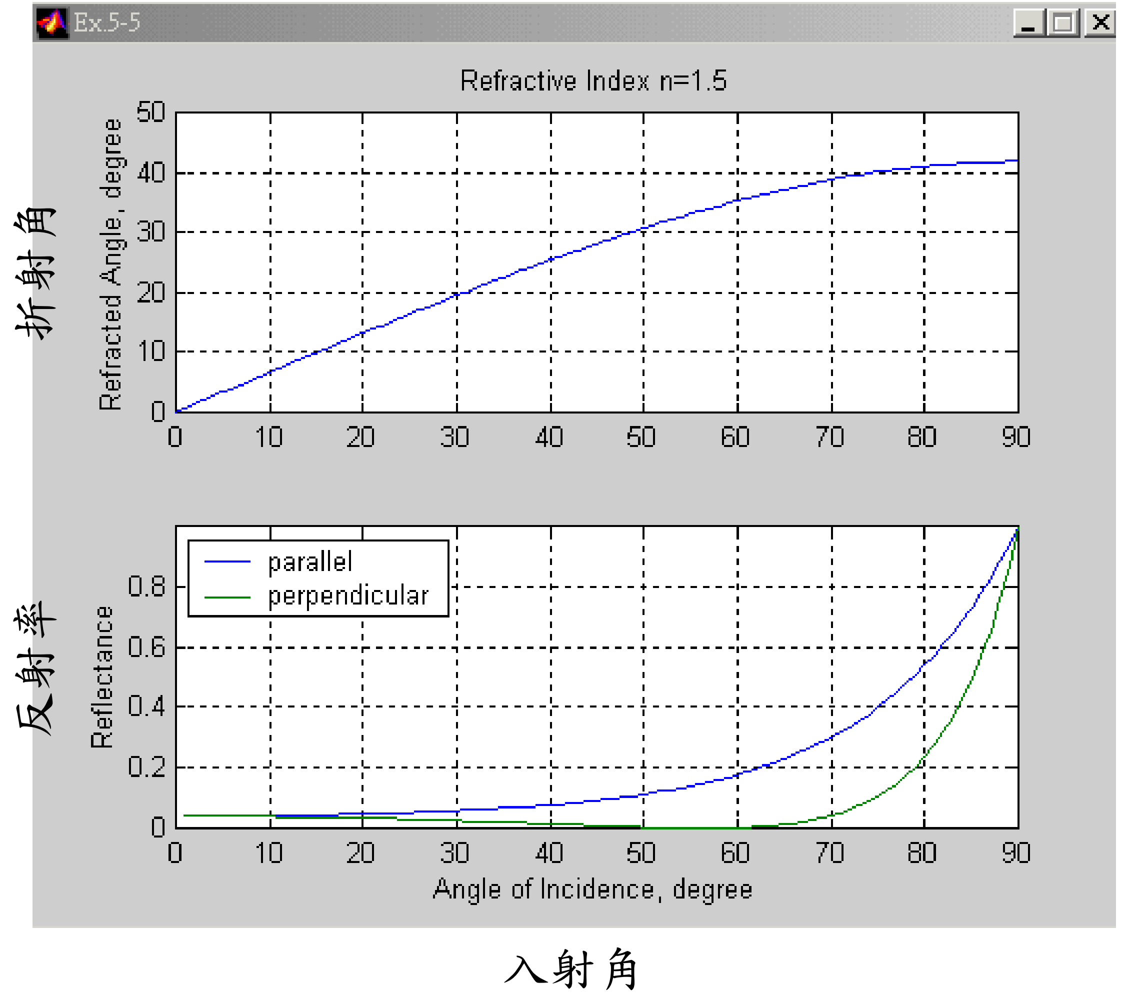
θ = arcsin (sin 50°/1.50) = 30.7° 折射角

$\rho_{parallel} = \sin^2(50 - 30.7) / \sin^2(50 + 30.7) = 0.112$

$\rho_{perpendicular} = \tan^2(50 - 30.7) / \tan^2(50 + 30.7) = 0.003$

$\rho_{average} = (0.112 + 0.003) / 2 = 0.058$

輸入 snell_law(2)，直接計算不同入射角下的反射率。產生視窗如下：



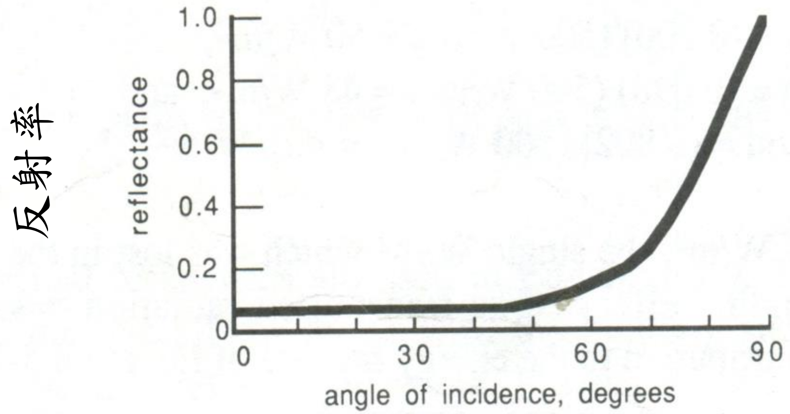
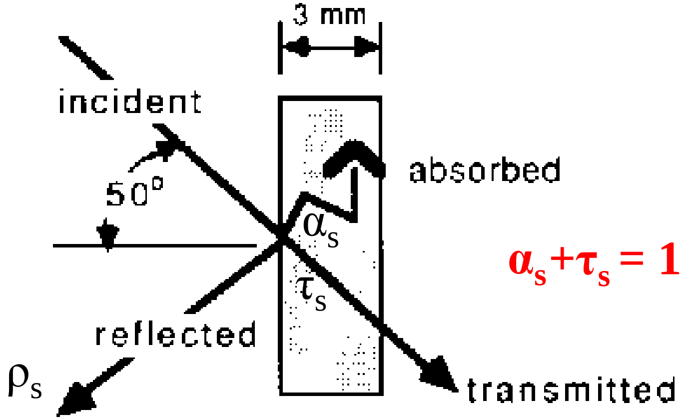


Figure 5-4. Reflectance (specular) for light incident on glass as a function of the angle of incidence.

Transmittance 穿透率



$\alpha_s + \tau_s = 1$

Stokes' equations

反射率

$$\rho_{actual} = \rho_s (1 + \tau_s \tau_{actual})$$ …eq.5-7a

穿透率

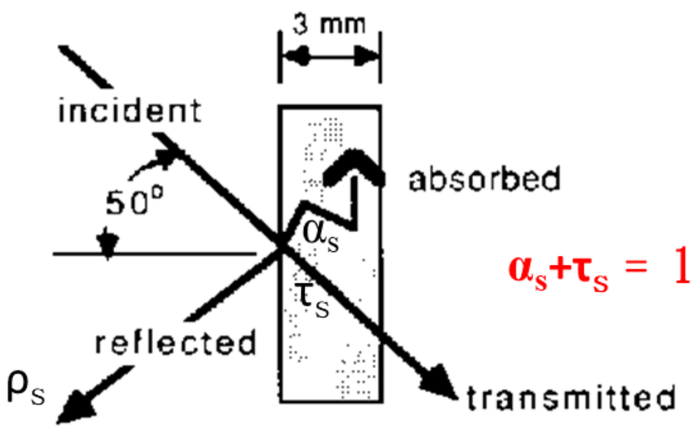
$$\tau_{actual} = \tau_s (1 - \rho_s)^2 / (1 - \rho_s^2 \tau_s^2)$$ …eq.5-7b

吸收率

$$\alpha_{actual} = 1 - \tau_{actual} - \rho_{actual}$$

$$= (1 - \rho_s)(1 - \tau_s)/(1 - \rho_s \tau_s)$$ …eq.5-7c

Ex. 5-6 入射角為50度，請計算太陽能為 500 W/m^2 的光線經過3 mm一般玻璃之後有多少被吸收、穿透與反射? 吸收率、穿透率與反射率各為何?



由 Ex.5-5 已知 $\rho_s = 0.058$

輸入 snell_law(3)，產生視窗如右下：

$$L = 3\ \text{mm}/\cos(30.7^\circ) = 3.49\ \text{mm}$$

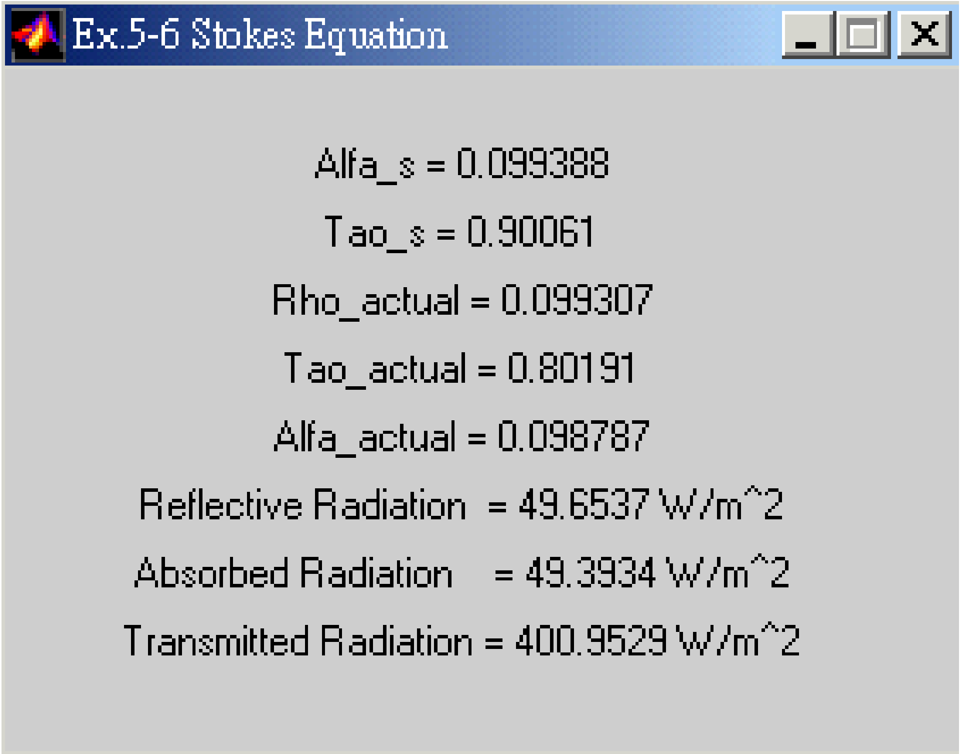
$$\alpha_s = 1 - \exp(-0.03\ \text{mm}^{-1} * 3.49\ \text{mm}) = 0.099$$

$$\tau_s = 1.0 - 0.099 = 0.901$$

$$\rho_{actual} = \overset{\rho_s}{0.058}\left(1 + \frac{0.901^2(1-0.058)^2}{1-0.058^2\,0.901^2}\right) = 0.100$$

$$\tau_{actual} = \overset{\tau_s}{0.901}\left(\frac{(1-0.058)^2}{1-0.058^2\,0.901^2}\right) = 0.802$$

$$\alpha_{actual} = 1.0 - 0.100 - 0.802 = 0.098$$



補充資料

多層透明被覆材料太陽能輻射性質之理論探討：I. 使用光跡追蹤法

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摘　要

本研究使用光跡追蹤法導出一系列的方程式可用來計算單、雙及多層透明被覆材料之透光率，吸收率及反射率。此些基本的太陽能輻射性質在太陽能與溫室被覆材料的研究上頗為重要。本研究導出之單層材料透光率之計算公式與前人推導者相同。雙層材料方面，本研究分兩方向進行。其一、有空氣在其間的雙層透明被覆材料：曾有部份學者有過類似的研究，但他們的方程式有著很大的限制，使得其可用性大為減低。其二、完全緊密接合的雙層透明被覆材料：在文獻中從未發現有類似研究發表。又，有關各種材料之衰減係數值方面，由於一般文獻中相關的記載很少且製造廠商也未能提供基本資料，實在有進一步研究之必要。本研究亦同時導出可用來求各種材料衰減係數之計算公式。

關鍵詞：透明被覆材料、太陽能輻射性質、光跡追蹤。

THEORETICAL INVESTIGATION OF SOLAR RADIATION PROPERTIES OF MULTI-LAYER GLAZINGS — PART I. USING RAY TRACING TECHNIQUE

More details

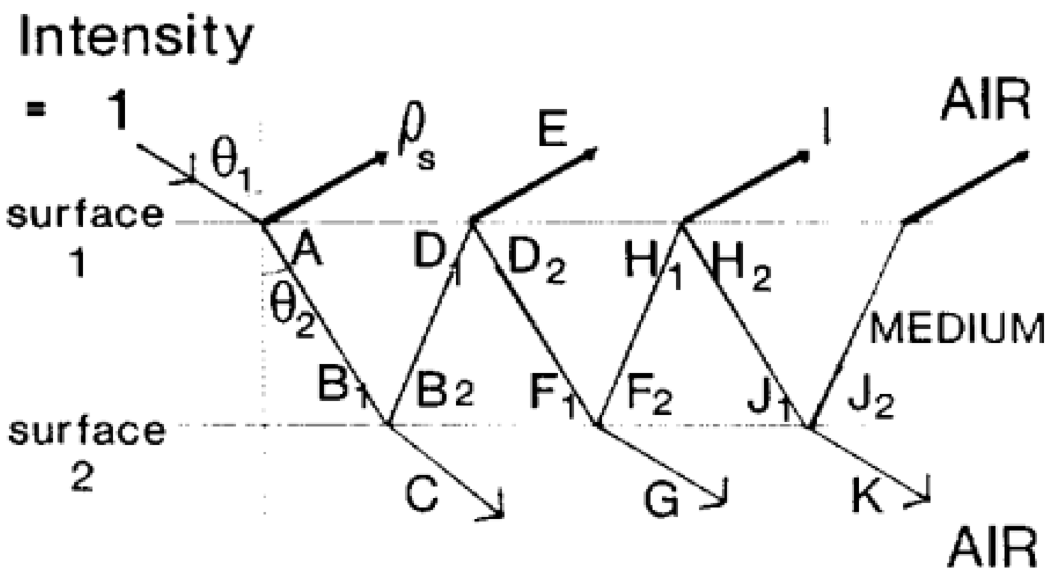


Figure 1 A schematic diagram of ray tracing technique on single layer glazing

$$A = 1 - \rho_s$$
$$B_1 = A(1-\alpha_s) = (1-\rho_s)\tau_s$$
$$B_2 = B_1\rho_s = \rho_s(1-\rho_s)\tau_s$$
$$C = B_1(1-\rho_s) = (1-\rho_s)^2\tau_s$$
$$D_1 = B_2(1-\alpha_s) = \rho_s(1-\rho_s)\tau_s^2$$
$$D_2 = D_1\rho_s = \rho_s^2(1-\rho_s)\tau_s^2$$
$$E = D_1(1-\rho_s) = \rho_s(1-\rho_s)^2\tau_s^2$$
$$F_1 = D_2(1-\alpha_s) = \rho_s^2(1-\rho_s)\tau_s^3$$
$$F_2 = F_1\rho_s = \rho_s^3(1-\rho_s)\tau_s^3$$
$$G = F_1(1-\rho_s) = \rho_s^2(1-\rho_s)^2\tau_s^3$$
$$H_1 = F_2(1-\alpha_s) = \rho_s^3(1-\rho_s)\tau_s^4$$
$$H_2 = H_1\rho_s = \rho_s^4(1-\rho_s)\tau_s^4$$
$$I = H_1(1-\rho_s) = \rho_s^3(1-\rho_s)^2\tau_s^4$$
$$J_1 = H_2(1-\alpha_s) = \rho_s^4(1-\rho_s)\tau_s^5$$
$$J_2 = J_1\rho_s = \rho_s^5(1-\rho_s)\tau_s^5$$
$$K = J_1(1-\rho_s) = \rho_s^4(1-\rho_s)^2\tau_s^5$$

$$\begin{aligned}\textit{Transmissivity } (\tau) &= (C + G + K + \dots)/1 \\ &= (1-\rho_s)^2\tau_s + \rho_s^2(1-\rho_s)^2\tau_s^3 + \rho_s^4(1-\rho_s)^2\tau_s^5 + \dots\dots \\ &= (1-\rho_s)^2\tau_s[1 + \rho_s^2\tau_s^2 + \rho_s^4\tau_s^4 + \dots] \\ &= \frac{(1-\rho_s)^2\tau_s}{1-\rho_s^2\tau_s^2} = \frac{(1-\rho_s)^2 e^{-KL}}{1-\rho_s^2 e^{-2KL}}\end{aligned}$$

$$\begin{aligned}\textit{Reflectivity } (\rho) &= (\rho_s + E + I + \dots)/1 \\ &= \rho_s + \rho_s(1-\rho_s)^2\tau_s^2 + \rho_s^3(1-\rho_s)^2\tau_s^4 + \dots \\ &= \rho_s + \frac{\rho_s(1-\rho_s)^2\tau_s^2}{1-\rho_s^2\tau_s^2} \\ &= \rho_s(1 + \tau_s\tau)\end{aligned}$$

$$\text{Absorptivity } (\alpha) = 1 - \tau - \rho$$

5-2.4. Heating System, q_h

5-2.5. Ventilation, q_{vi} and q_{vo}

$$q_{vo} - q_{vi} = 1006 * \rho * V * (t_i - t_o) \quad \text{…eq.5-8}$$

5-2.6. Structural Heat Loss, q_w

$$q_w = \Sigma (A/R) * (t_i - t_o) \quad \text{…eq.5-9}$$

5-2.7. Heat exchange with the floor, q_f

$$q_f = F * P * (t_i - t_o)$$

- 5-2.8. Evaporation, q_e

結構物	水分來源
barns	wash water, animal wastes and animal's respiration
greenhouses	floors and benches when water is spilled, from the surface of the potting medium, and from transpiration by plants.

As a rough rule, insolation which passes through the greenhouse cover can be partitioned into 5 categories. 進入溫室的太陽能可分成五大類：

50 %	Converted to sensible heat added to the air 轉換成顯熱
25 %	Added to the air as latent heat 轉換成潛熱
10 %	Reflected back to the outside 反射回溫室外
2~3 %	Used in photosynthesis 被植物利用
12~13 %	Stored in the intrinsic thermal mass to be released later 存於溫室內，稍後釋放

5-3. Uses of the Sensible Energy Balance

$q_s + q_m + q_{so} + q_h + q_{vi} = q_w + q_f + q_e + q_{vo}$ …eq.5-1

$q_s + q_m + q_{so} + q_h = \Sigma\ UA(t_i - t_o) + FP(t_i - t_o) + q_e + 1006\rho\ V\ (t_i - t_o)$ …eq.5-10

用於Animal housing，上式中有多項可簡化或取消：

$q_s = (\Sigma\ UA + FP + 1006\rho V)(t_i - t_o)$ …eq.5-11

$t_i = t_o + q_s / (\Sigma\ UA + FP + 1006\rho V)$ …eq.5-12

$V = [q_s - (\Sigma\ UA + FP)(t_i - t_o)] / [1006\rho(t_i - t_o)]$ …eq.5-13

Ex. 5-7 請計算在以下條件下所需要的通風風量率 (m^3/s) 以維持乳牛舍於 15 度C。
海拔 500 m，60 頭平均 580 kg 乳牛，牆、天花板、窗戶、門之面積依序為 274、520, 12, 15 m^2，熱阻依序為 2.05, 1.97, 0.3, 0.49 m^2K/W，周長 110 m，周長熱損因子 1.5 W/mK，室外溫度 -5度C，室內濕度 70%。假設燈光、馬達與透過窗戶進入室內的能量均可以忽略不計算。
The attic is well ventilated. The animal heat data for fairy cows in Appendix 5-1 reflect net sensible heat after latent heat conversion has been deducted.
Sol

$$\sum UA = \sum A/R = 274/2.05 + 520/1.97 + 12/0.3 + 15/0.49 = 470 \text{ W/K}$$

$$F*P = 15 * 110 = 165 \text{ W/K}$$

$$q_{s)500kg} = 1.2 \text{ W/kg at 15 degree C}$$

$$Qs = 60 * 1.2 * 500 * (580/500)^{0.734} = 40000 \text{ W} = 40 \text{ kW}$$

From eq. 5-13

$$\text{Ventilation rate} = [40000 – (470 + 165)*20] / [1006*1.14 * 20]$$

$$= 1.2 \text{ m}^3/\text{s} = 1.14 \text{ kg/m}^3 * 1.2 \text{ m}^3/\text{s} = 1.37 \text{ kg/s}$$

Ex. 5-8 續上題，假設最低需維持通風風量率0.9 m^3/s以維持動物體健康，請問室外的最低溫是多少時，室內將無法維持15度C。

$$t_o = t_i - q_s / (\Sigma UA + F P + 1006 \rho V) \quad \text{…eq.5-12b}$$

$$= 15 – 40000 / (470 + 165 + 1006*1.14*0.9)$$

$$= - 9\ ^oC$$

Ex. 5-9 續上題，假設通風風量率為 2 m^3/s，室內溫度會變成幾°C？

Sol: 本題 t_i 未知，q_s 無法求，需透過疊代計算

假設室內空氣密度 (ρ) 為 1.15 kg/m^3，動物體顯熱總產生量為 45 kW

$$t_i = -5 + 45000 / [470+165+1006*1.15*2] = 10.3\ ^oC$$

Now check the assumption

At indoor T = 10.3 °C, $q_s = 1.5 + (0.3/5)(1.2-1.5) = 1.48$ W/kg

$$Q_s = 60 * 1.48 * 500 * (580/500)^{0.734} = 49500\ W = 49.5\ kW$$

此值比假設值大，顯然假設有誤，ρ 與 顯熱總產生量都低估了

重新假設 ρ 為 1.16 kg/m^3，動物體顯熱總產生量為 48 kW

$$t_i = -5 + 48000 / [470+165+1006*1.15*2] = 11.2\ ^oC$$

Now check the assumption

At indoor T = 11.2 °C, $q_s = 1.5 + (1.2/5)(1.2-1.5) = 1.4$ W/kg

$$Q_s = 60 * 1.4 * 500 * (580/500)^{0.734} = 47000\ W = 47\ kW$$

此值比假設值小，顯然假設仍有誤， ρ 與 顯熱總產生量都高估了

經幾次疊代運算可求出室內溫度為 11 °C，ρ為 1.16 kg/m^3，動物體顯熱產生量為 47.5 kW

5-4. Components of the Mass Balance, Humidity

5-4.1. Moisture Production From Animals

Ex. 5-10 某豬舍內有 40, 60, 80 公斤的三種豬各100頭，室溫維持在 20 ^{o}C，請問在單位時間內需移除多少水分才能維持穩態。 (Appendix 5-1. p.403)

	Moisture Production	
Size, kg	mg/kg-s	mg/pig-s
40	0.61	24
60	0.47	28
80	0.39	31

$$100 * (24+28+31) / 10^6 = 0.0083 \text{ kg/s}$$

Ex. 5-11 牛舍內有100頭 570 kg的乳牛，請計算在10度C室溫下的水分產生率，這同時也是需被移除的速率以維持穩態？

Animal	Air Temperature	MP mg/kg s	LHP W/kg	SHP W/kg	THP W/kg
Dairy cow, 500 kg	-1 C	0.21	0.5	1.9	2.4
	10	0.28	0.7	1.5	2.2
	15	0.36	0.9	1.2	2.1
	21	0.36	0.9	1.1	2.0
	27	0.50	1.3	0.6	1.9

Moisture production rate = $0.28 * (570/500)^{0.734} = 0.31$ mg/kg.s

mp = 0.31 mg/kg.s (570 kg)(100 cows)(1.0×10^{-6} kg/mg) = 0.0157 kg/s

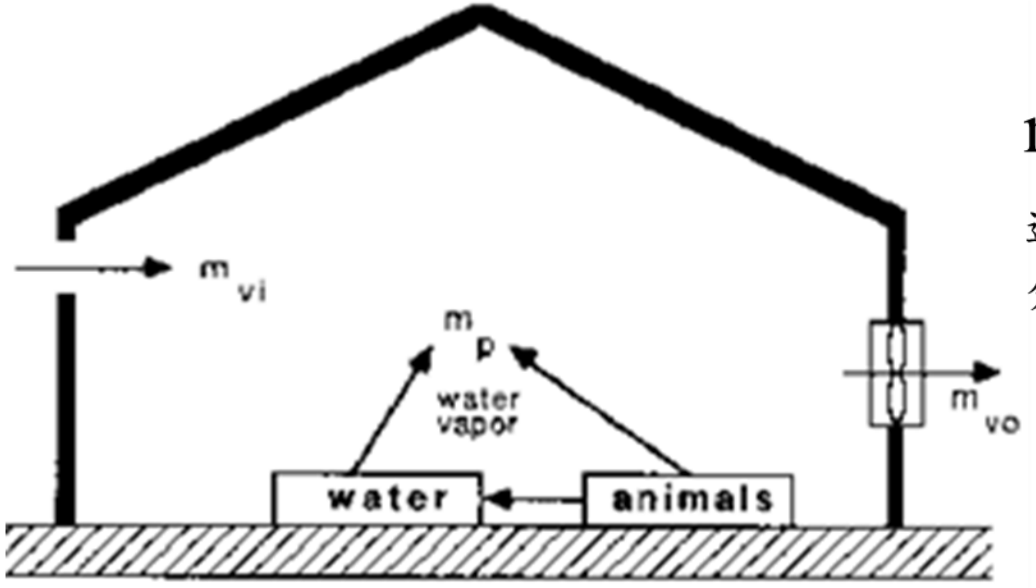
5-4.2. Ventilation, m_{vi} and m_{vo}

$$m_{vi} = \rho_o W_o \quad \text{...eq.5-14}$$

$$m_{vo} = \rho_i W_i \quad \text{...eq.5-15}$$

m_{vi}

透過通風**進入**空間的某成分(水汽、二氧化碳等)的質量



m_{vo}

透過通風**離開**空間的的某成分(水汽、二氧化碳等)的質量

5-5. Uses of the Mass Balance, Moisture

$$m_{air} = m_{water} / (W_i - W_o) \qquad \text{…eq.5-16}$$

Ex.5-12 某雞舍位於海拔1000 m，飼養3萬頭平均體重1.8 kg的來亨蛋雞，當室外溫、濕度為-20 ºC、55 %，欲維持室內為23 ºC、70 % 相對濕度時的通風風量率是多少？

Animal	Air Temperature	MP mg/kg s	LHP W/kg	SHP W/kg	THP W/kg
Laying hen, leghorn, 1.8 kg (a)	8	0.72	1.7	5.2	6.9
	12	0.82	2.0	4.6	6.6
	18	0.97	2.3	4.5	6.8
	28	1.19	2.9	3.7	6.6

At 23 ºC indoor, MP = (0.97 + 1.19)/2 = 1.08 mg/kg.s

m_{water} = 30000 * 1.8 * 1.08 = 58320 mg/s = 0.05832 kg/s

Wo = 0.000393 kg/kg DA at -20 ºC and 55% RH outdoor

Wi = 0.013919 kg/kg DA at 23 ºC and 70 % RH indoor

From eq. 5-16,

m_{air} = (0.05832)/(0.013919 – 0.000393) = 4.3 kg/s (Dry Air)

m_{air} = 4.3 * (1 + 0.013919) = 4.36 kg/s (Moist Air)

V_{air} = 4.36 kg/s / 1.03 kg/m^3 = 4.23 m^3/s

Extra topic: Moisture generated by fogging system and by plants

- Evapotranspiration = Evaporation + Transpiration
  - Moisture generated by Fogging
  - Moisture generated by plants

5-6. Components of the Mass Balance, Carbon Dioxide

5-6.1. Carbon Dioxide produced by Animals

ONE liter of CO_2 is produced, on the average, for every 24.6 kJ of total heat added to the environment by an animal. (1 L/s CO_2 = 24.6 kW)

5-7. Uses of the Mass Balance, Carbon Dioxide

1980 年代的大氣中的二氧化碳濃度約在345 ppm (parts per million, 體積比例)，相當於 345 x 1.519 = 524 mg of CO_2/kg of air.

現在 2022，大氣中的二氧化碳濃度約在 410 ppm

Ex.5-12 某雞舍位於海拔1000 m，飼養3萬頭平均體重1.8 kg的來亨蛋雞，當室外溫、濕度為-20 ºC、55 %，欲維持室內為23 ºC、70 % 相對濕度時的通風風量率是多少？

Ex. 5-13 續上例，計算風量率為 4.3 m^3/s下的室內CO_2含量

$$V_p + V_{vi} = V_{vo}$$

本例題的風量以體積為單位做計算

$$q_{total} = 30000 * 1.8 * (6.6+6.8)/2 = 361800 \text{ W} = 361.8 \text{ kW}$$

$$Vp = 361.8 / 24.6 = 14.7 \text{ L/s} = 0.0147 \text{ m}^3/\text{s}$$

$$0.0147 + [4.3 \text{ m}^3/\text{s} * 0.000345] = [4.3 \text{ m}^3/\text{s} * CO_{2indoor}]$$

$$CO_{2indoor} = 0.003764 = 3764 \text{ ppm}$$

This concentration of carbon dioxide is well below the 5000 ppm limit used by OSHA for human occupation. However, if research were to discover that a lower limit is preferred, a minimum ventilation rate might be based on carbon dioxide rather than moisture control.

UNITED STATES DEPARTMENT OF LABOR

Occupational Safety and Health Administration

Ex. 5-14 海拔為0 m體積為3000 m^3的溫室，因密閉不良導致的換氣率為0.75 ACH (air change per hour)，假設室內空氣溫度20 ºC，相對濕度70 %，溫室外CO_2濃度為345 ppm，溫室內補充CO_2濃度到 1000 ppm (1519 mg/kg) 以提升植物生長速率，請問CO_2的損失速率有多少 kg/s？假設 1 kg CO_2 為20 元，每天會損失多少錢?

Sol:

本例題的風量以重量為單位做計算

T_{air}@ 20 ºC, RH_{air}@ 70 % → 空氣密度 1.18 kg/m^3

m_{air} = 1.18 kg/m^3 * 3000 * 0.75 /3600 = 0.7375 kg/s

m_{vo} - m_{vi} = 0.7375 kg/s * 1.519 * (1000 – 345) = 733.8 mg/s = 2.64 kg/h

損失略低於 2.64 * 24 * 20 = 1267 元，因為暗期的呼吸作用會補回一些。

Extra topic: Carbon Dioxide consumed by plants and enriched by equipment

質量守恆(Mass Balance) 分析主要構成項

m_{vi}

透過通風**進入**空間的某成分(水汽、二氧化碳等)的質量

m_p

禽畜舍：空間中由**動物體**獲得的質量(CO_2, NH_3, H_2O...)

溫室：Vapor

植物體蒸散、水面蒸發

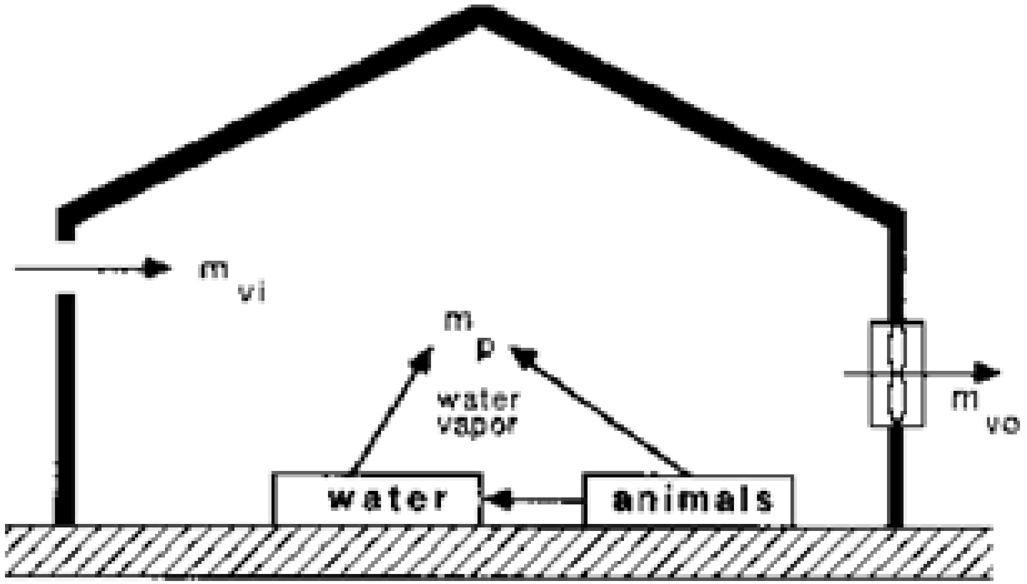
CO2

植物體光呼吸 (產生)

暗呼吸 (產生)

光合作用 (消耗)

設備 (補充)



質量守恆分析的主要構成項

m_{vo}

透過通風**離開**空間的的某成分(水汽、二氧化碳等)的質量

$$m_p + m_{vi} = m_{vo}$$

$$m_{vi} = m_{air} AH_o$$

$$m_{vo} = m_{air} AH_i$$

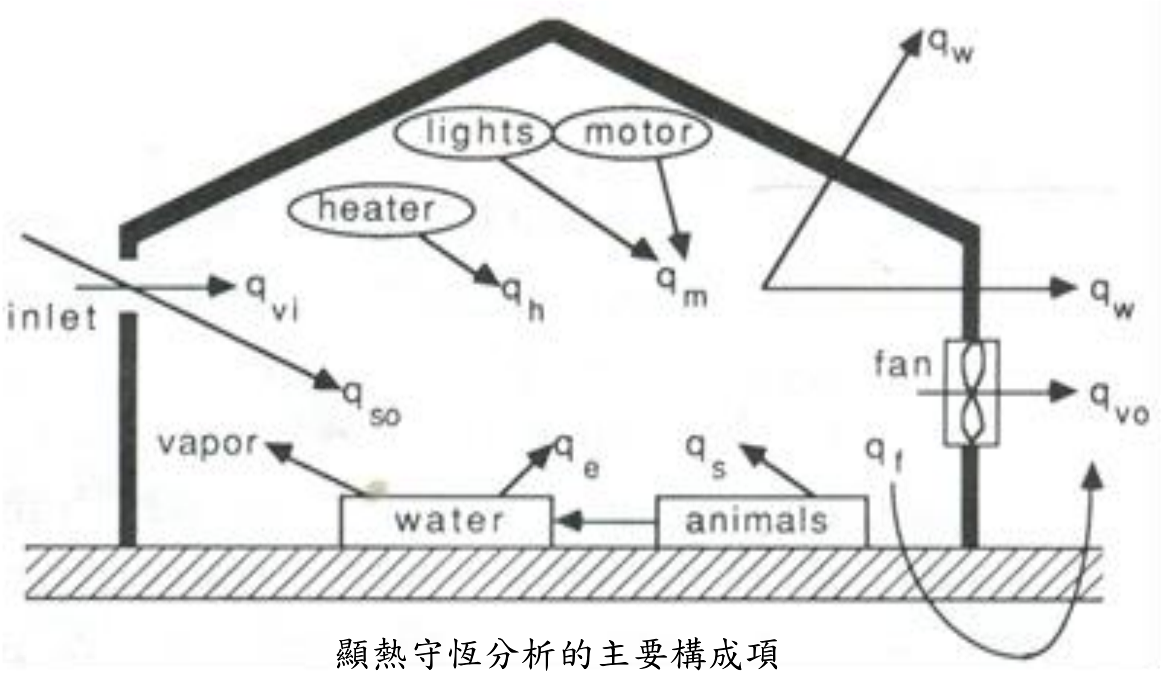
$$m_{air} = m_p / (AH_i - AH_o)$$

絕對溼度的差

顯熱守恆 (Sensible energy balance) 分析主要構成項：內外溫差 (temperature difference)

能量守恆 (Energy Balance) 分析主要構成項：內外焓差 (enthalpy difference)

q_s	空間中由動物體獲得的顯熱
q_m	空間中由機械元件獲得的顯熱
q_{so}	空間中由太陽獲得的顯熱
q_{vi}	透過通風進入空間的空氣(室外空氣)本身所含有的顯熱
q_h	空間中由加熱系統獲得或由冷氣系統扣除的顯熱



顯熱守恆分析的主要構成項

q_w	穿透結構體(牆、屋頂、窗、門地板、天花板等)所傳入或傳出的顯熱
q_f	穿透地板(主要發生在周邊)所傳入或傳出的顯熱
q_e	空間中顯熱轉換為潛熱的速率
q_{vo}	透過通風離開空間的空氣 (室內空氣)本身所含有的顯熱

Gains - Losses = Change of Storage

Steady state means no change of storage, thus, **Gains = Losses**

$$q_s + q_m + q_{so} + q_h + q_{vi} = q_w + q_f + q_e + q_{vo}$$

溫室的日間降溫

全密閉 $q_{vi} = q_{vo} = 0$

有通風

通風量 = m_{air} (kg/min)

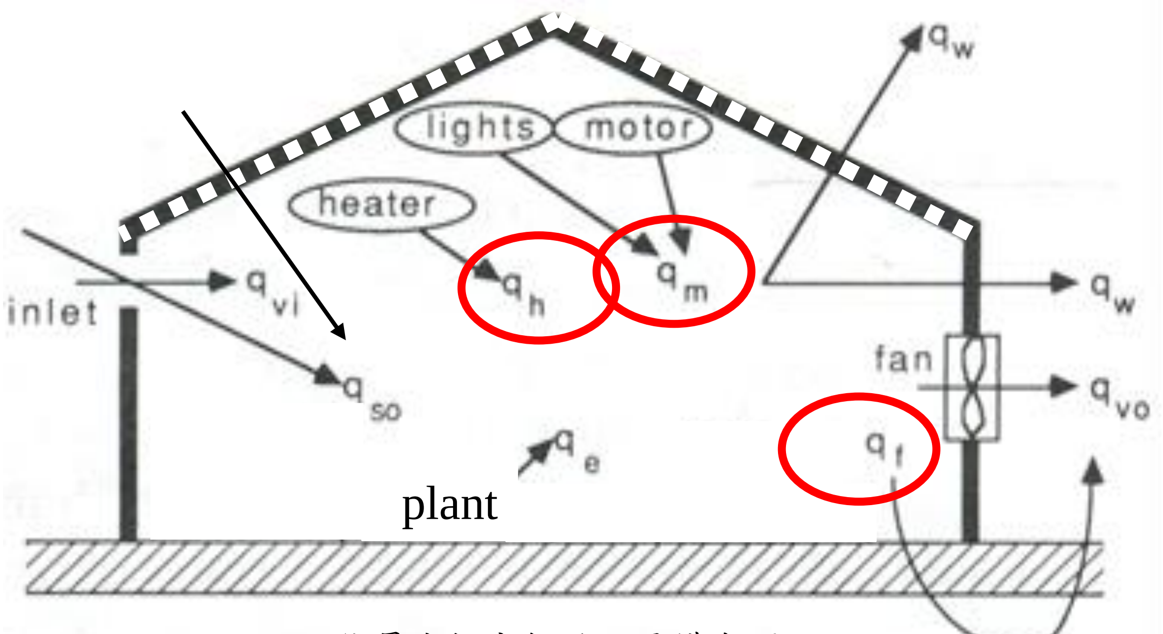
= ACM * Vol (m^3/min) / SV (m3/kg)

通風造成的能量差 (kJ/min)

= m_{air} * dh (kg/min * kJ/kg)

由屋頂、牆壁傳入/出的熱量

$$q_w = U * A * (T_i - T_o)$$



能量守恆分析的主要構成項

由地下傳入/出的熱量: q_f 忽略

由空調或熱泵除去或加入的熱量: q_h 忽略

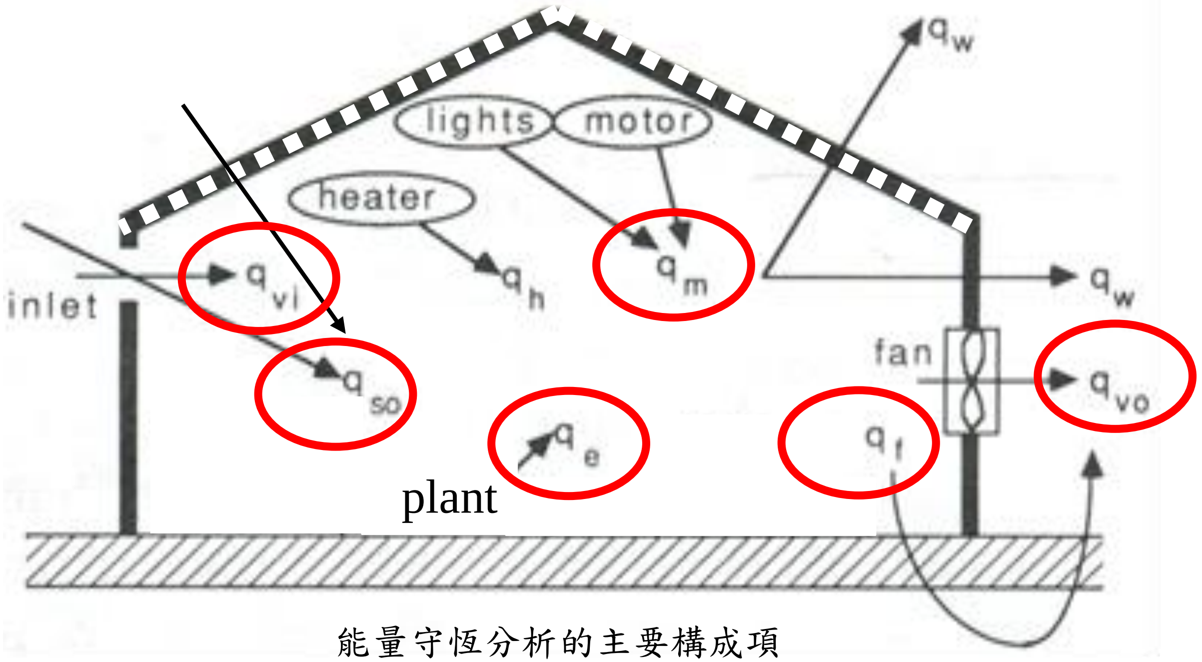
由馬達加入的熱量：q_m 忽略

$$\cancel{q_m} + q_{so} + \cancel{q_h} + q_{vi} = q_w + \cancel{q_f} + q_e + q_{vo}$$

進入溫室的太陽能轉換為顯熱

進入溫室的太陽能轉換為潛熱

溫室的夜間降溫



能量守恆分析的主要構成項

無太陽能 $q_{so} = 0$，無水分蒸發/蒸散 $q_e = 0$

如果開冷氣或熱泵，全密閉 $q_{vi} = q_{vo} = 0$

由屋頂、牆壁傳入/出的熱量

$$q_w = U * A * (T_i - T_o)$$

冷氣或熱泵的降溫或加溫負荷 ($T_1, RH_1 \rightarrow T_2, RH_2$)

$$q_h = \rho_{air} * V_{GH} * dh \ (kg * kJ/kg) = V_{GH} * dh \ (m^3 * kJ/m^3)$$

此處如果只考慮顯熱 (溫差)，$q_h = \rho_{air} * V_{GH} * Cp * dT$，會大幅低估所需的負荷

$$q_m + q_{so} + q_h + q_{vi} = q_w + q_f + q_e + q_{vo}$$

$$q_h - q_w = \rho_{air} V_{GH} * dh - U * A * (T_i - T_o) = 0$$

$$V_{GH} * dh - U * A * (T_i - T_o) = 0$$

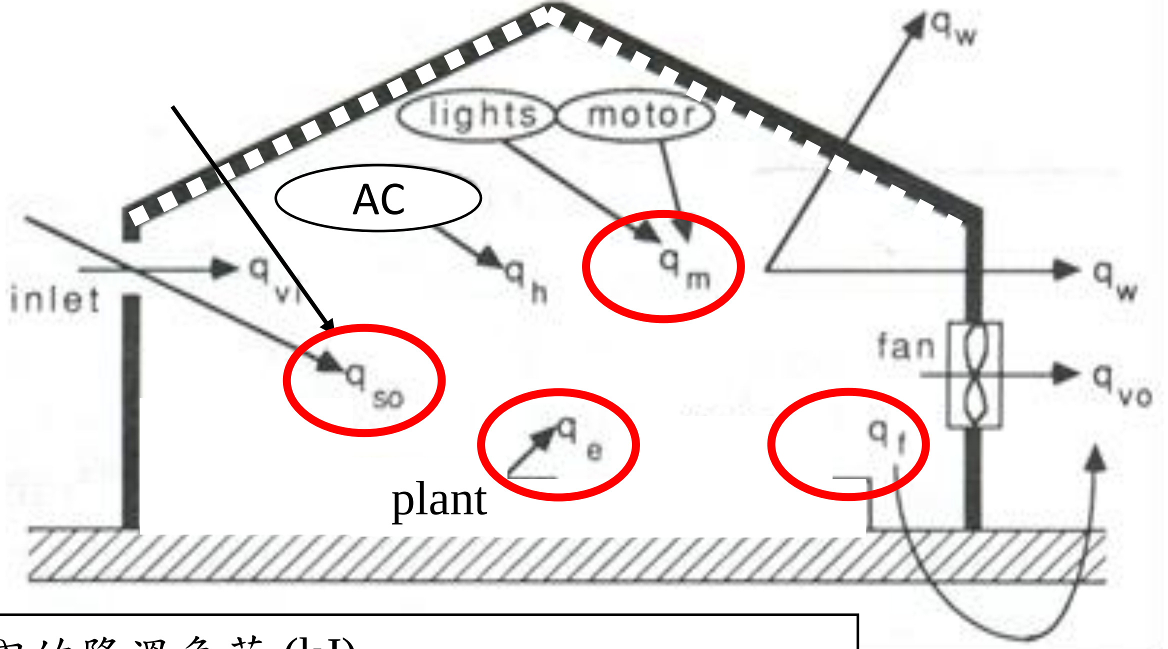
$$V_{GH} * dh + U * A * (T_o - T_i) = 0$$

Detail Info. of U value of ROOF

Suggested U value through various greenhouse glazing [P.V. Nelson]

Covering Materials (Glazing)	Heat Loss Coef. (U) Btu/ft^2/hr/F	W/m^2/K
Glass , single layer	1.13	6.42
Glass , double-layer, 1/4-in (6 mm) space	0.65	3.69
Glass , triple-layer, 1/4-in (6 mm) spaces	0.47	2.67
Polyvinyl Chloride (PVC)	0.92	5.22
Fiberglass-reinforced plastic (FRP)	1.2	6.81
Acrylic, single layer 1/8-in (3 mm)	1	5.68
Acrylic, double-layer pannel (16 mm thick)	0.58	3.29
Acrylic, double-layer pannel (8 mm thick)	0.64	3.63
Polycarbonate, double-layer pannel (16 mm thick)	0.58	3.29
Polycarbonate, double-layer pannel (6.5 mm thick)	0.69	3.92
Polyethylene (PE) film, single layer (2,4,6 mil)	1.15	6.53
Polyethylene (PE) film, double layer	0.8	4.54
Polyester film, Mylar	1.05	5.96
Polyvinyl fluoride (PVF), Tedlar, single layer film	1.05	5.96
Polyvinyl fluoride (PVF), double-layer film	0.76	4.32

溫室的夜間降溫



無太陽能 $q_{so} = 0$，無水分蒸發/蒸散 $q_e = 0$

開冷氣或熱泵，應盡量維持密閉 $q_{vi} = q_{vo} = 0$

但仍可能有漏縫，等同通風

通風增加的降溫負荷 (kJ/hr) , $q_{vi} - q_{vo}$

$= \rho_{air}\ ACH * V_{GH} * \triangle h$ (kJ/kg) or

$= ACH * V_{GH} * \triangle h$ (kJ/m³)

$\triangle h$: 室外熱焓 -室內熱焓

溫室內的降溫負荷 (kJ)

$q_h = \rho_{air}\ V_{GH} * dh$ (kg * kJ/kg)

$= V_{GH} * dh$ (m^3 * kJ/m^3)

dh: 室內空調啟動前後的熱焓差值

$T_1, RH_1 \rightarrow T_2, RH_2$

23 °C, 85%

h1=Enthalpy = 71.4

→

19 °C, 75%

h2=Enthalpy = 53.68

dh = 17.72 kJ/m³

由屋頂、牆壁傳入的熱量 (kJ/hr)

$q_w = U * A * (T_o - T_i)$

$= U * A * dT * 3.6$

dT: 室外溫度 - 室內溫度

冷氣的降溫負荷 = 三者相加

$= V_{GH} * (ACH * \triangle h + dh) + UA\ dT$

假設 $\triangle h = dh$

$= V_{GH} * (ACH + 1) * dh + UA\ dT$

NGP導入時 夜冷ランニングコスト試算表

1美制冷凍噸（RT） = 3024 kcal/h ≒ 12000 BTU ≒ 3.52 kW

2022年10月5日
Ver. 2.5 for Taiwan

皇基越南Apollo K1-K3 【夜冷】 19℃（17℃WB、85%RH）

温室条件	床面積	2,880 m^2 / 873 坪	表面積	4,662 m^2	設定温度	19 ℃	必要熱量(※1) / ディグリアワー	182.9 MWh / 1,737 ℃·h

- 由室外傳進來的熱量
  - Q = U*A*dT
  - U = 6.42 W/m^2K = 6.42 $J/(s.m^2.K)$
  - A = 4662 m^2
  - dT = 23-19 = 4
  - Q_1 = **6.42** * 4662 * 4 * 3.6 = 430992 kJ/h

溫室內因洩漏 (ACH = 2) 所增加的熱量

Q_2 = (ACH)* △h * (2880***5.5**)

= 2 * 17.72 (kJ/m^3) * 2880 * 5.5 (m^3) = 561,369 kJ/h

假設 △h = dh

溫室內降溫所需帶走的熱量

Q_3 = dh * (2880***5.5**) = 17.72 (kJ/m^3) * 2880 * 5.5 (m^3) = 280,684.8 kJ

空調設備在 n 小時內要達標，需要帶走 $Q = n * (Q_1 + Q_2) + Q_3$

空調設備的降溫負荷 = Q / n kJ/h = Q / (n*3600) kW = Q / (n*3600*3.52) RT

冷凍噸數需求

U	6.42	W/m2.K	single glass						
Asurface	4662	m2	area of all glazing (roof + walls)						
Afloor	2880	m2							
Height	5.5	m	GH_volumn	15840	m3				
Ti	19	deg.C	RHi	75	Hi	71.4			
To	23	deg.C	RHo	85	Ho	53.68	dH	17.72	kJ/m3
ACH due to leakage	0	1/hr	假設溫室有漏縫，以每小時 ACH 倍的室內體積計算						

Time to reach the target	1	1.5	2	h
Q1: UA*dT	430,993	646,489	861,985	kJ
Q2: heat due to leakage (ACH)	-	-	-	kJ
Q3: heat indoor (1 Vol)	280,685	280,685	280,685	kJ
Heat to removed = Q1+Q2+Q3	711,677	927,174	1,142,670	kJ
Required cooling load of AC	711,677	618,116	571,335	kJ/h
	198	172	159	kW
	56.2	48.8	45.1	RT

冷凍噸數需求

U	6.42	W/m2.K	single glass							
Asurface	4662	m2	area of all glazing (roof + walls)							
Afloor	2880	m2								
Height	5.5	m	GH_volumn	15840	m3					
Ti	19	deg.C	RHi	75	Hi	71.4				
To	23	deg.C	RHo	85	Ho	53.68		dH	17.72	kJ/m3
ACH due to leakage	0.4	1/hr	假設溫室有漏縫，以每小時 ACH 倍的室內體積計算							

Time to reach the target	1	1.5	2	h
Q1: UA*dT	430,993	646,489	861,985	kJ
Q2: heat due to leakage (ACH)	112,274	168,411	224,548	kJ
Q3: heat indoor (1 Vol)	280,685	280,685	280,685	kJ
Heat to removed = Q1+Q2+Q3	823,951	1,095,585	1,367,218	kJ
Required cooling load of AC	823,951	730,390	683,609	kJ/h
	229	203	190	kW
	65.0	57.6	53.9	RT

冷凍噸數需求

U	6.42	W/m2.K	single glass						
Asurface	4662	m2	area of all glazing (roof + walls)						
Afloor	2880	m2							
Height	5.5	m	GH_volumn	15840	m3				
Ti	19	deg.C	RHi	75	Hi	71.4			
To	23	deg.C	RHo	85	Ho	53.68	dH	17.72	kJ/m3
ACH due to leakage	0.6	1/hr	假設溫室有漏縫，以每小時 ACH 倍的室內體積計算						

Time to reach the target	1	1.5	2	h
Q1: UA*dT	430,993	646,489	861,985	kJ
Q2: heat due to leakage (ACH)	168,411	252,616	336,822	kJ
Q3: heat indoor (1 Vol)	280,685	280,685	280,685	kJ
Heat to removed = Q1+Q2+Q3	880,088	1,179,790	1,479,492	kJ
Required cooling load of AC	880,088	786,527	739,746	kJ/h
	244	218	205	kW
	69.5	62.1	58.4	RT

冷凍噸數需求

U	6.42	W/m2.K	single glass						
Asurface	4662	m2	area of all glazing (roof + walls)						
Afloor	2880	m2							
Height	5.5	m	GH_volumn	15840	m3				
Ti	19	deg.C	RHi	75	Hi	71.4			
To	23	deg.C	RHo	85	Ho	53.68	dH	17.72	kJ/m3
ACH due to leakage	0.8	1/hr	假設溫室有漏縫，以每小時 ACH 倍的室內體積計算						

Time to reach the target	1	1.5	2	h
Q1: UA*dT	430,993	646,489	861,985	kJ
Q2: heat due to leakage (ACH)	224,548	336,822	449,096	kJ
Q3: heat indoor (1 Vol)	280,685	280,685	280,685	kJ
Heat to removed = Q1+Q2+Q3	936,225	1,263,995	1,591,766	kJ
Required cooling load of AC	936,225	842,664	795,883	kJ/h
	260	234	221	kW
	73.9	66.5	62.8	RT

冷凍噸數需求

U	6.42	W/m2.K	single glass						
Asurface	4662	m2	area of all glazing (roof + walls)						
Afloor	2880	m2							
Height	5.5	m	GH_volumn	15840	m3				
Ti	19	deg.C	RHi	75	Hi	71.4			
To	23	deg.C	RHo	85	Ho	53.68	dH	17.72	kJ/m3
ACH due to leakage	1	1/hr	假設溫室有漏縫，以每小時 ACH 倍的室內體積計算						

Time to reach the target	1	1.5	2	h
Q1: UA*dT	430,993	646,489	861,985	kJ
Q2: heat due to leakage (ACH)	280,685	421,027	561,370	kJ
Q3: heat indoor (1 Vol)	280,685	280,685	280,685	kJ
Heat to removed = Q1+Q2+Q3	992,362	1,348,201	1,704,040	kJ
Required cooling load of AC	992,362	898,801	852,020	kJ/h
	276	250	237	kW
	78.3	70.9	67.2	RT

Chap. 5 Home Work

1. 沿用 p165-166 example 5-12的基本數據，分別計算要維持室內狀況為23℃或70%RH時所需之通風率 (ventilation rate)，並比較二者之大小。假設戶外溫度為10, 15, 20, 25, 30℃，濕度為50, 75, 90%。當外溫大於23℃時會啟動水牆，假設水牆效率為75%，請完成下表。(注意在某些溫濕度狀況下將無法達到需求的室內狀況，請註明"無法達成"，當此情況發生，改計算需除去多少熱或多少水份才能達到目標，使用另表說明)

Required Ventilation rate	相對濕度 50%				
	外溫10	外溫15	外溫20	外溫25	外溫30
a.溫度控制23℃					
b.濕度控制70%					
Max (a, b at 50%)					
Required Ventilation rate	相對濕度 75%				
	外溫10	外溫15	外溫20	外溫25	外溫30
a.溫度控制23℃					
b.濕度控制70%					
Max (a, b at 75%)					
Required Ventilation rate	相對濕度 90%				
	外溫10	外溫15	外溫20	外溫25	外溫30
a.溫度控制23℃					
b.濕度控制70%					
Max (a, b at 90%)					

2. 將上題所完成的表格中的Max(a,b)值 針對外溫(10-30°C)予以繪圖，隨濕度不同應有三條曲線。

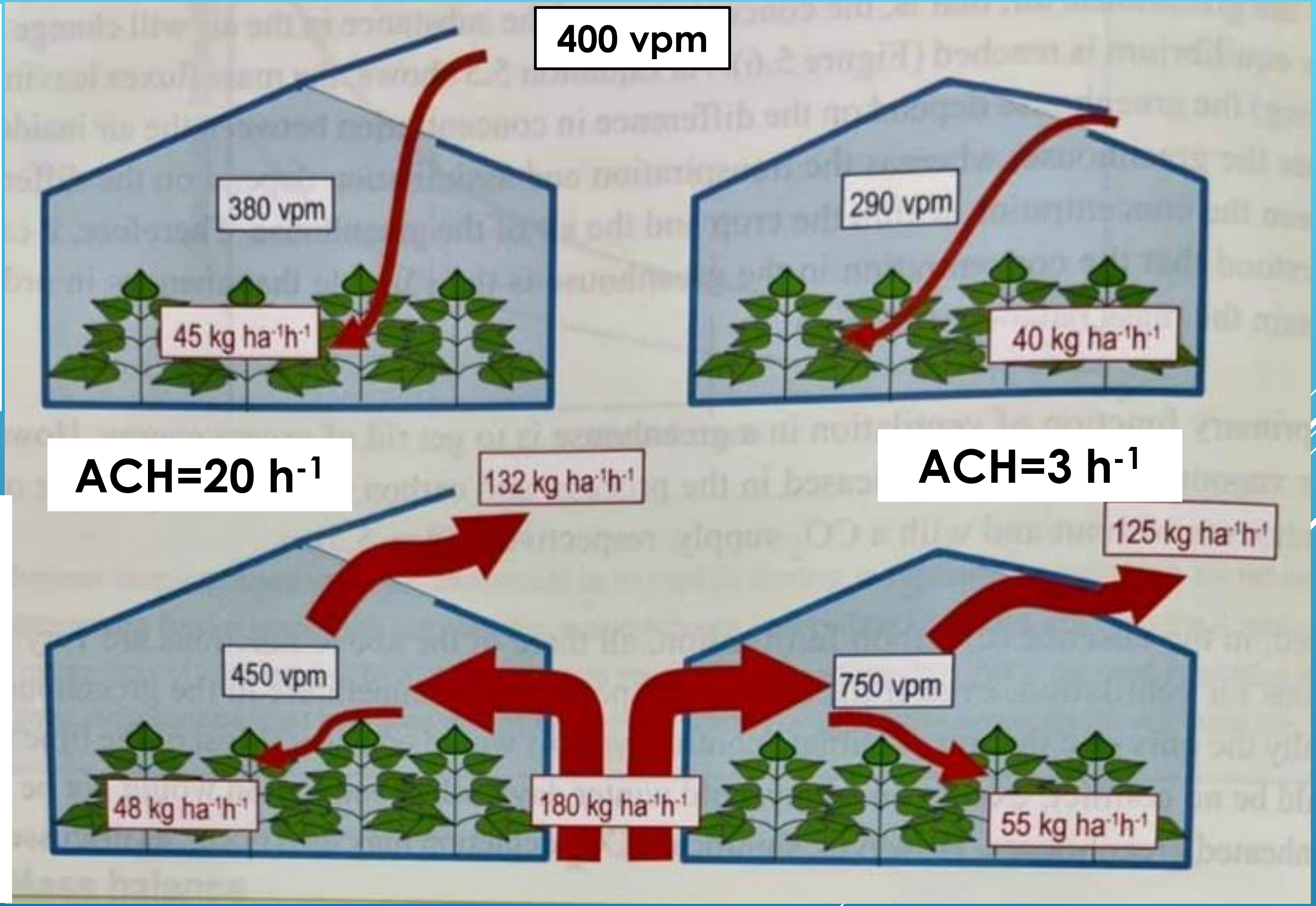
3. Text Book ex 5-9 改用 Matlab 撰寫程式 (直接解Ti).

4. Text Book ex 5-12 改用 Matlab 撰寫程式 (使用 psy.m 中的functions 求解 Humidity ratio).

Crop Assimilation / Net Photosynthesis

無CO_2施肥時，ACH=20 較佳
室內可維持較高 CO_2 濃度
(380 > 290 vpm)
可保持較高的同化速率
(45 > 40 kg ha^{-1} h^{-1})

有CO_2施肥時，ACH=3 較佳
市內可維持較高的 CO_2濃度
(750 > 450 vpm)
可保持較高的同化速率
(55 > 48 kg ha^{-1} h^{-1})



溫室通風口高度: 6 m, 最大同化速率: 72 kg ha^{-1}h^{-1}(2 mg m^{-2} s^{-1})
室外 CO_2 濃度: 400 vpm

Pn = f(Ci)

Stanghellini *et.al.*, 2008

Pn = Pmax * Ci/(Ci+230)			where Pmax = 72	
Exact Pn	Ci	Ci/(Ci+230)	Pn	
55	750	0.765	55.1	
48	450	0.662	47.6	
45	380	0.623	44.9	
40	290	0.558	40.2	

求解穩態質量守恆問題

共計八項參數

1. 溫室高度 h (6 m)
2. 室外 CO_2濃度 Co (400 ppm x 1.519→ mg CO_2/kg air)
3. 植物光合速率 Pmax (72 kg/ha/h)

4. 換氣率 ACH (3, 20 h^{-1})
5. CO_2 補充速率 Cs (0, 180 kg/ha/h)

6. 室內 CO_2濃度 Ci (ppm x 1.591 → mg/kg)
7. 植物光合速率 Pn (kg/ha/h)
8. CO_2 散失速率 Cexit (kg/ha/h)

已知參數1~5的數值，求參數 6~8 的值