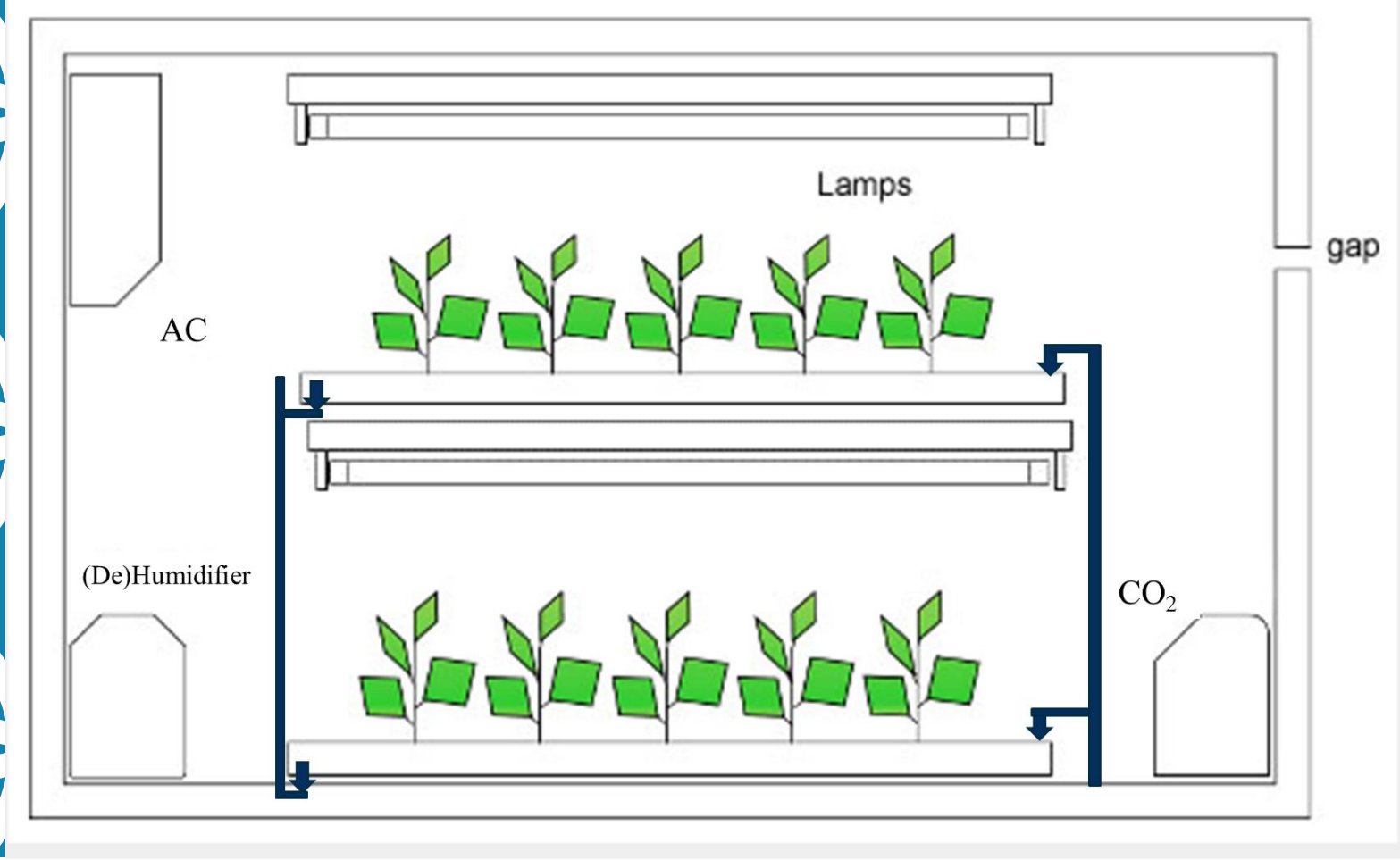

SIMULATOR OF PLANT FACTORY WITH ARTIFICIAL LIGHTING (PFAL)

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大綱

- 簡介：全人工光型植物工廠
- 植物、環境與燈光配置
- 質能平衡：CO_2, 水分,能源
- PFAL Simulator - Excel 版

簡介：PFAL

全人工光型植物工廠 (PFAL) 在密閉的環控室內栽培作物，幾乎不受天候與蟲害的影響，生產風險大幅降低。

PFAL 使用人工光，不導入日光，減少了日光每日變化與季節性變化的影響；使用保溫的外牆，也隔絕了室外溫度的影響，因此環境的調控變單純。

維持較高的氣密性 (ACH < 0.01) 可讓較低溫且較高二氧化碳濃度的室內空氣得以維持在室內，節省二氧化碳與冷氣的成本

維持較高的氣密性可減少受室外溫、溼度影響

需要高效率 (高 µmol/J) 的人工光源

如萵苣或菠菜等，PPFD為200~300 µmol/m^2/s

PFAL內需要補充二氧化碳

PFALs 通常比溫室小，CO_2施肥不透過燃燒天然氣，通常使用液態CO_2鋼瓶，透過電磁閥控制並隨時監測CO_2濃度。

在PFAL 中 CO_2 濃度通常維持在 1000 ppm

在PFAL 中 的室內溫度通常透過空調 AC 來控溫。

室內的溫、濕度通常維持在光合作用與植物生長或發育最適當的溫、濕度範圍。

溫度通常維持在定值並保持固定的日/夜溫差

PFAL中使用多層的栽培架

- 通常至少會有 5 至 10 層來極大化單位土地面積的產能
- 燈光安裝在每一層
- 營養液透過循環系統輸送到每一層

營養液是含有水溶性礦物質的水溶液，植物透過根系吸收營養液，並將水分與營養成分 (溶於水中的陰陽離子) 輸送全株，最終由葉片的蒸散作用將水分送往空氣中。

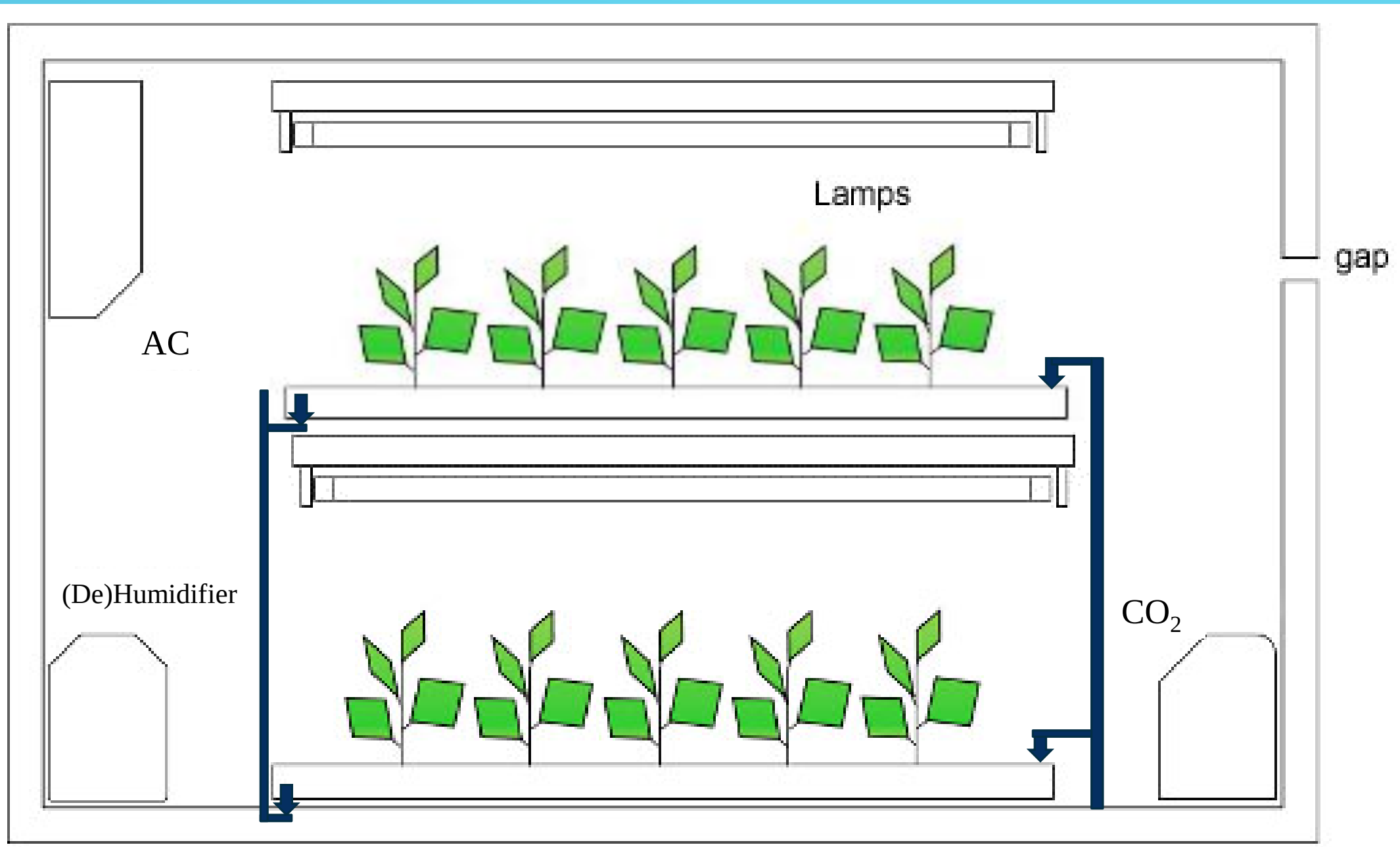
- 因為蒸散作用，室內空氣的相對濕度Relative humidity/水蒸氣密度water vapor density/絕對溼度absolute humidity/水蒸汽壓water vapor pressure 增加。

- 在PFAL中，有時除溼設備是必要的，雖然空調設備啟動時，除溼會一併進行。但當溫度達設定值時，空調設備停機，但濕度可能仍高。

- 空調設備所冷凝的水分可導入水槽中重複使用。這是PFAL 的栽培用水量遠比溫室或田間栽培少很多的主因。

廠房：必備設施

1. Thermally insulated walls with very low ACH (nearly air tight)
2. AC with reused of condensed water
3. Multi-layer cultural bench
   - Artificial light for each layer
   - Circulating nutrient solution delivered to each layer
4. CO_2 enrichment
5. (De)humidifier
6. Monitoring and control


Lamps
gap
AC
(De)Humidifier
CO_2

Culture room								
Room length	10	m	space utilization	0.5		Leaf area/plant	0.1	m2/plt
Room width	10	m	No. of layers	4		Number of plants	6000	plt/room
Room height	4	m	Culture area	200	m2	Total leaf area	600	m2
Room volume	400	m3	Cropping density	30	plts/m2	LAI	3	

環控室體積 = 長x寬 x 高 = 10 x 10 x 4 = 400 m^3

栽培面積 = 室內面積 x 空間利用率 x 栽培層數 = 100 x 0.5 x 4 = 200 m^2

室內總株數 = 栽培面積 / 栽培密度 = 200 x 30 = 6000 株

總葉面積 = 單株葉片面積 x 總株數 = 0.1 x 6000 = 600 m^2

葉面積指數 (LAI) = 總葉面積 / 栽培面積 = 600 / 200 = 3

密度

空氣、CO_2 都視為 理想氣體

$$PV = nRT = mRT / M$$

一大氣壓下

$$V/m = RT/M$$

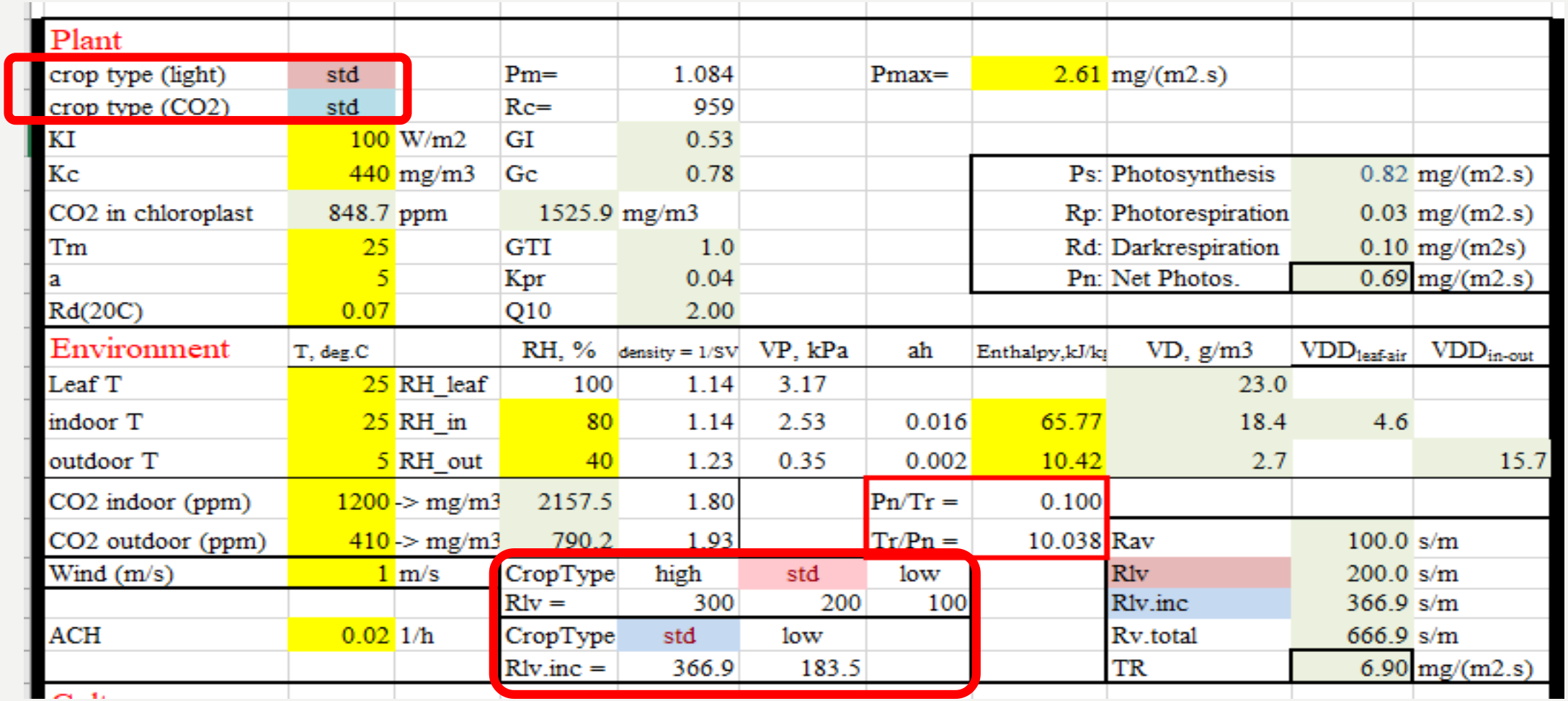
$$Density = m/V = M/RT$$

28/0.0821/(273.15+25) = 1.14
28/0.0821(273.15+5) = 1.23

Environment	T, deg.C		RH, %	density = 1/SV
Leaf T	25	RH_leaf	100	1.14
indoor T	25	RH_in	80	1.14
outdoor T	5	RH_out	40	1.23
CO2 indoor (ppm)	1200	-> mg/m3	2157.5	1.80
CO2 outdoor (ppm)	410	-> mg/m3	790.2	1.93

44.01/0.0821/(273.15+25) = 1.7979
44.01/0.0821(273.15+5) = 1.927

植物與環境



Plant										
crop type (light)	std		Pm=	1.084		Pmax=	2.61	mg/(m2.s)		
crop type (CO2)	std		Rc=	959						
KI	100	W/m2	GI	0.53						
Kc	440	mg/m3	Gc	0.78			Ps:	Photosynthesis	0.82	mg/(m2.s)
CO2 in chloroplast	848.7	ppm	1525.9	mg/m3			Rp:	Photorespiration	0.03	mg/(m2.s)
Tm	25		GTI	1.0			Rd:	Darkrespiration	0.10	mg/(m2s)
a	5		Kpr	0.04			Pn:	Net Photos.	0.69	mg/(m2.s)
Rd(20C)	0.07		Q10	2.00						
Environment	T, deg.C		RH, %	density = 1/SV	VP, kPa	ah	Enthalpy,kJ/kg	VD, g/m3	$VDD_{leaf-air}$	VDD_{in-out}
Leaf T	25	RH_leaf	100	1.14	3.17			23.0		
indoor T	25	RH_in	80	1.14	2.53	0.016	65.77	18.4	4.6	
outdoor T	5	RH_out	40	1.23	0.35	0.002	10.42	2.7		15.7
CO2 indoor (ppm)	1200	-> mg/m3	2157.5	1.80		Pn/Tr =	0.100			
CO2 outdoor (ppm)	410	-> mg/m3	790.2	1.93		Tr/Pn =	10.038	Rav	100.0	s/m
Wind (m/s)	1	m/s	CropType	high	std	low		Rlv	200.0	s/m
			Rlv =	300	200	100		Rlv.inc	366.9	s/m
ACH	0.02	1/h	CropType	std	low			Rv.total	666.9	s/m
			Rlv.inc =	366.9	183.5			TR	6.90	mg/(m2.s)

光量與二氧化碳濃度都會影響氣孔阻力

作物的氣孔對前者分三種類型的反應： high、std.、low

作物的氣孔對後者分兩種類型的反應： std.、low

作物的氣孔對輻射量分三種類型的反應： high、std.、low

high
=IF(PAR>80,300,1400-PAR*(1400-300)/80)

std
=IF(PAR>80,200,1200-PAR*(1200-200)/80)

low
=IF(PAR>80,100,1000-PAR*(1000-100)/80)

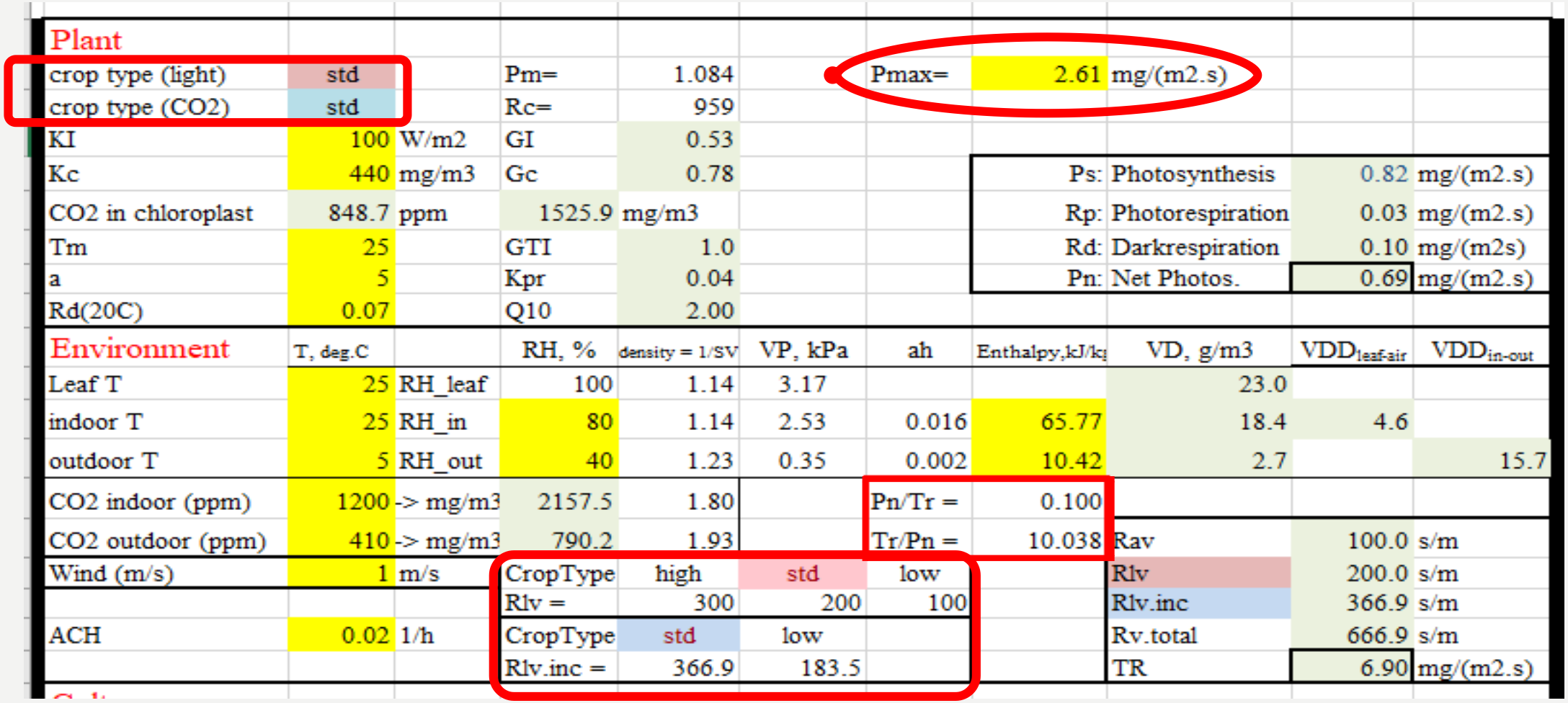
PAR閥值 = 80 W m^{-2} = 80 * 4.6 = 368 μmol m^{-2} s^{-1}

作物的氣孔對CO_2濃度分兩種類型的反應： std.、low

std
=IF(CO2in_mg>=2352,400,400*CO2in_mg/2352)

low
=IF(CO2in_mg>=2352,200,200*CO2in_mg/2352)

CO_2閥值 = 2352 mg m^{-3} = 1200 ppm * density of CO_2



Plant										
crop type (light)	std		Pm=	1.084		Pmax=	2.61	mg/(m2.s)		
crop type (CO2)	std		Rc=	959						
KI	100	W/m2	GI	0.53						
Kc	440	mg/m3	Gc	0.78			Ps:	Photosynthesis	0.82	mg/(m2.s)
CO2 in chloroplast	848.7	ppm	1525.9	mg/m3			Rp:	Photorespiration	0.03	mg/(m2.s)
Tm	25		GTI	1.0			Rd:	Darkrespiration	0.10	mg/(m2s)
a	5		Kpr	0.04			Pn:	Net Photos.	0.69	mg/(m2.s)
Rd(20C)	0.07		Q10	2.00						
Environment	T, deg.C		RH, %	density = 1/SV	VP, kPa	ah	Enthalpy,kJ/kg	VD, g/m3	$VDD_{leaf-air}$	VDD_{in-out}
Leaf T	25	RH_leaf	100	1.14	3.17			23.0		
indoor T	25	RH_in	80	1.14	2.53	0.016	65.77	18.4	4.6	
outdoor T	5	RH_out	40	1.23	0.35	0.002	10.42	2.7		15.7
CO2 indoor (ppm)	1200	-> mg/m3	2157.5	1.80		Pn/Tr =	0.100			
CO2 outdoor (ppm)	410	-> mg/m3	790.2	1.93		Tr/Pn =	10.038	Rav	100.0	s/m
Wind (m/s)	1	m/s	CropType	high	std	low		Rlv	200.0	s/m
			Rlv =	300	200	100		Rlv.inc	366.9	s/m
ACH	0.02	1/h	CropType	std	low			Rv.total	666.9	s/m
			Rlv.inc =	366.9	183.5			TR	6.90	mg/(m2.s)

蒸散效率 Transpiration Efficiency, Pn / Tr = 0.1

此數值偏高，應該是 Pmax 的預設值高估

光合能力：最大光合速率

- 光合能力代表最大光合速率

  Photosynthetic capacity (P_{max}) is a measure of the maximum rate at which leaves are able to fix carbon during photosynthesis.

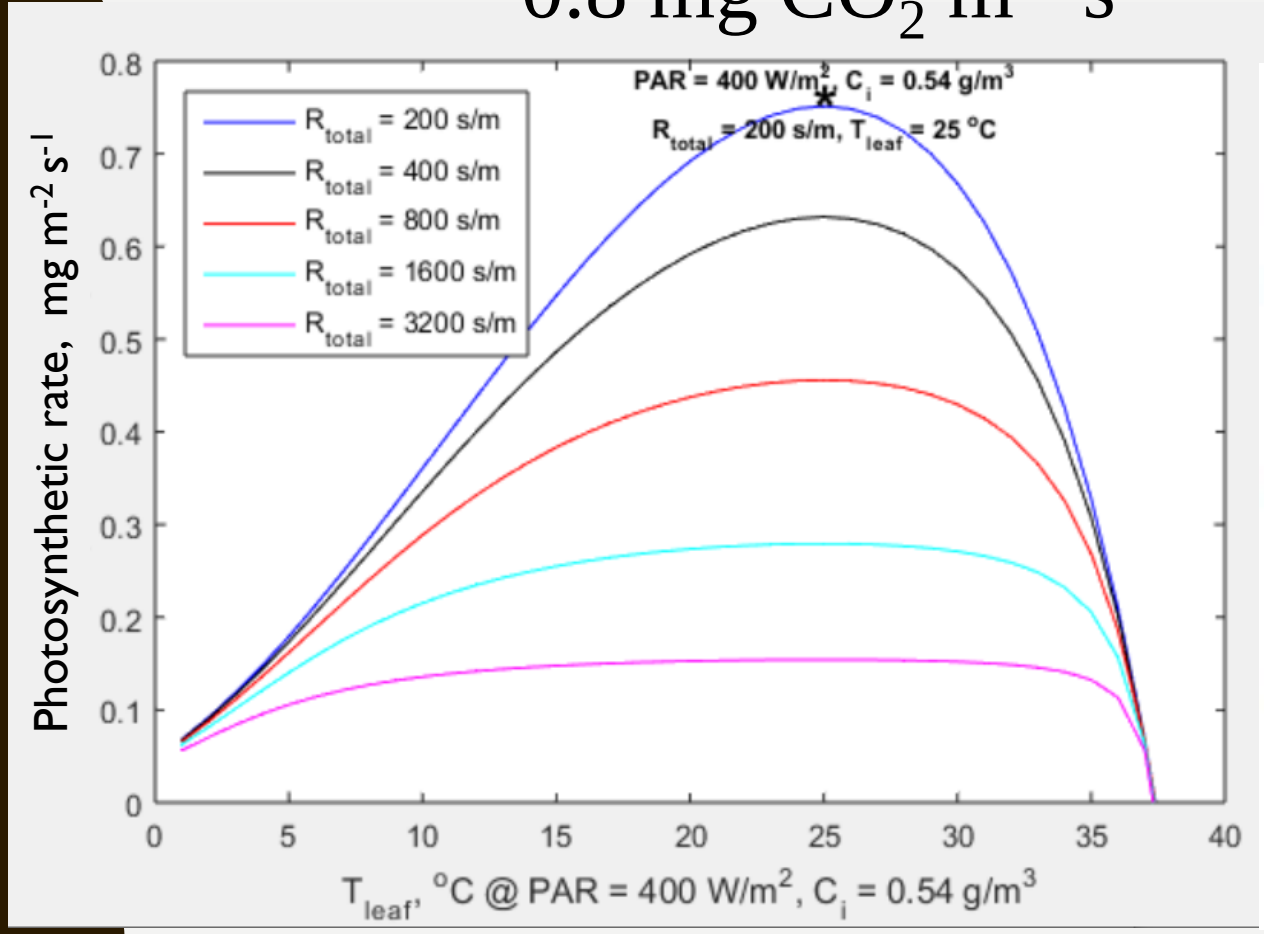
- 常用單位： the amount of carbon dioxide that is fixed per meter squared per second, for example as μmol m^{-2} sec^{-1}.

- 增加葉片上的氣孔數量可以提升光合能力

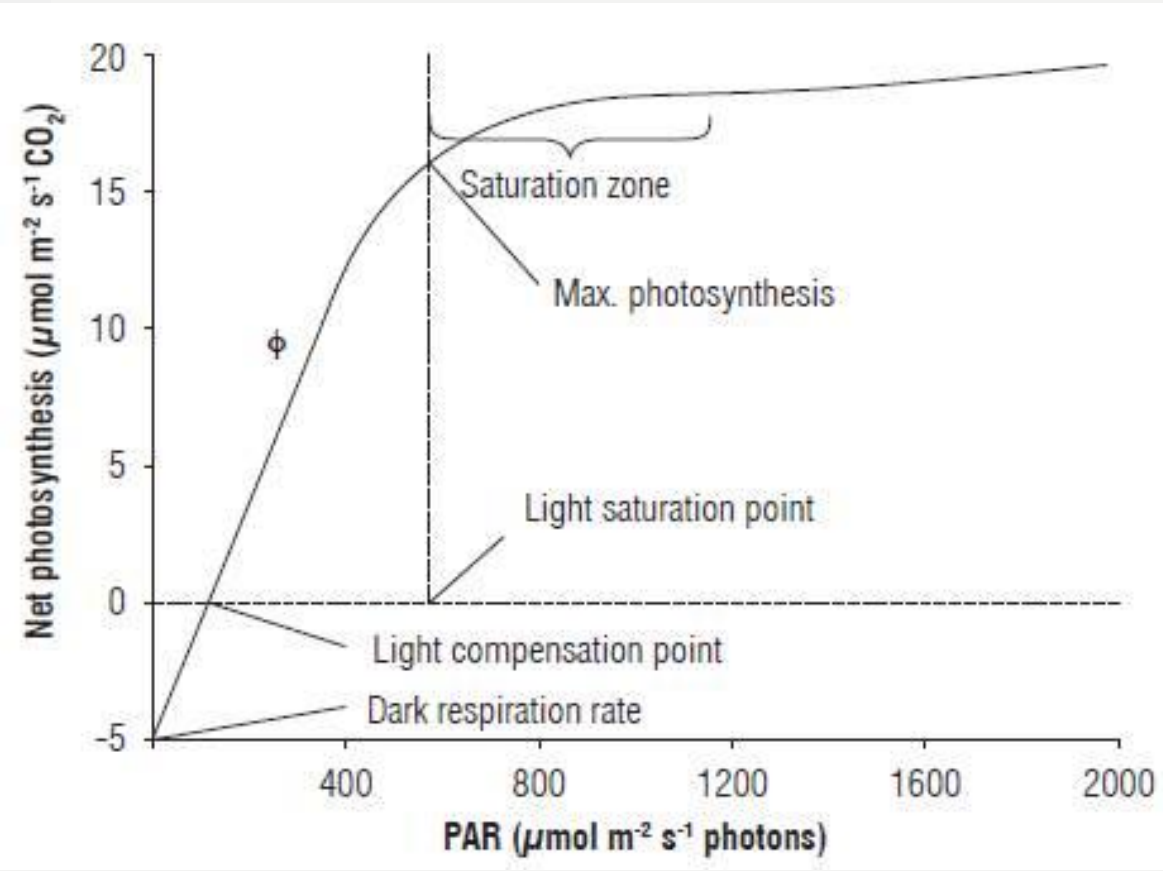
  Tanaka, Y., S. S. Sugano, T. Shimada, and I. Hara-Nishimura. 2013. Enhancement of leaf photosynthetic capacity through increased stomatal density in *Arabidopsis*. New Phytologist **198**: 757–764.

光合能力：最大光合速率

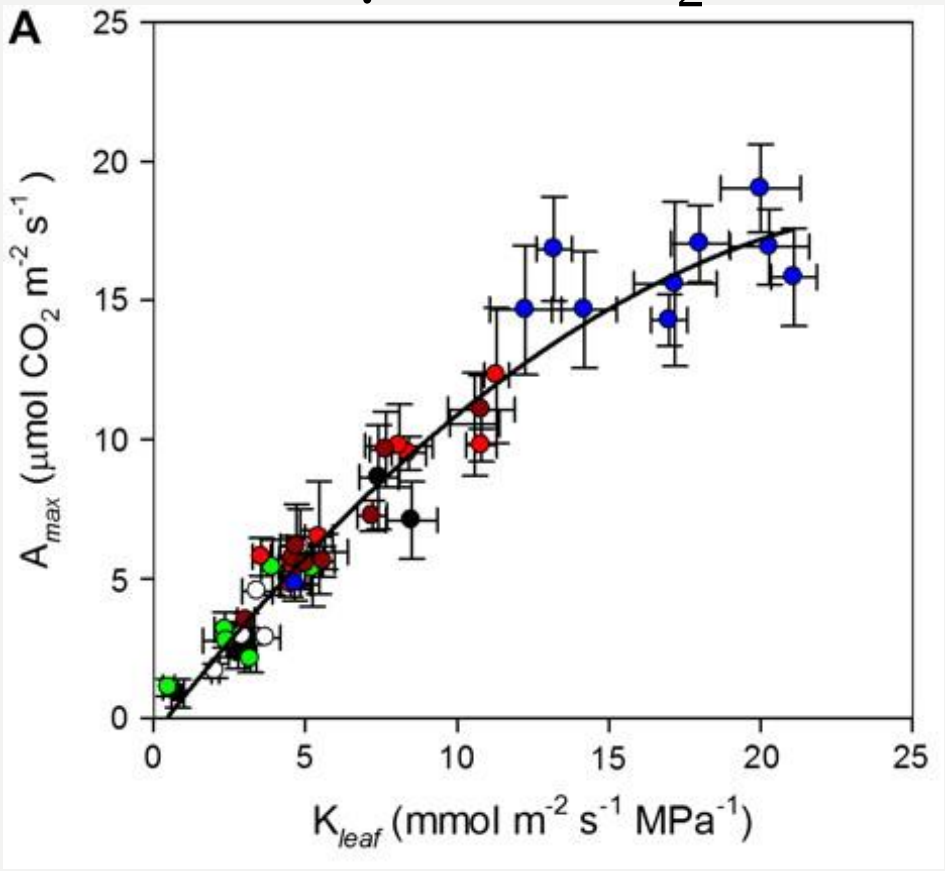
0.8 mg CO_2 m^{-2} s^{-1}

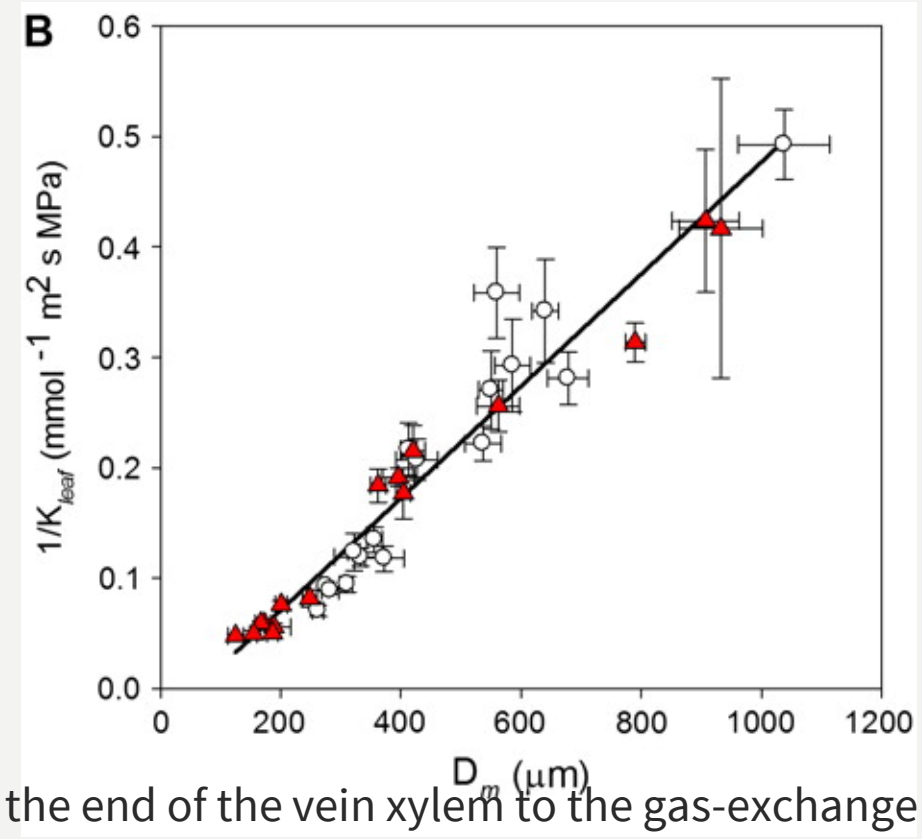


20 µmol CO_2 m^{-2} s^{-1}



20 μmol CO_2 m^{-2} s^{-1} = 0.88 mg CO_2 m^{-2} s^{-1}

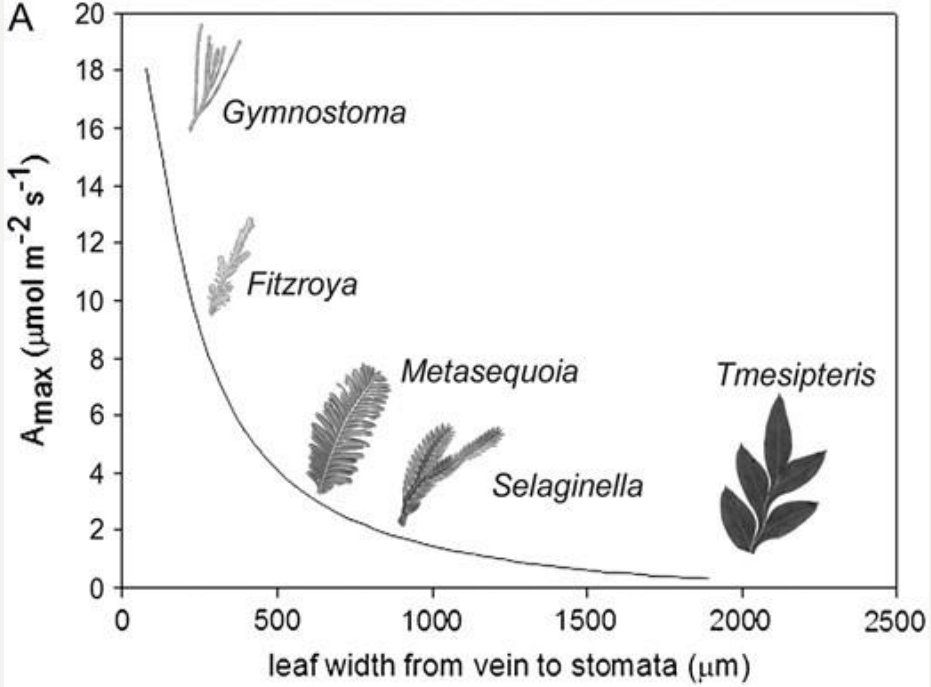


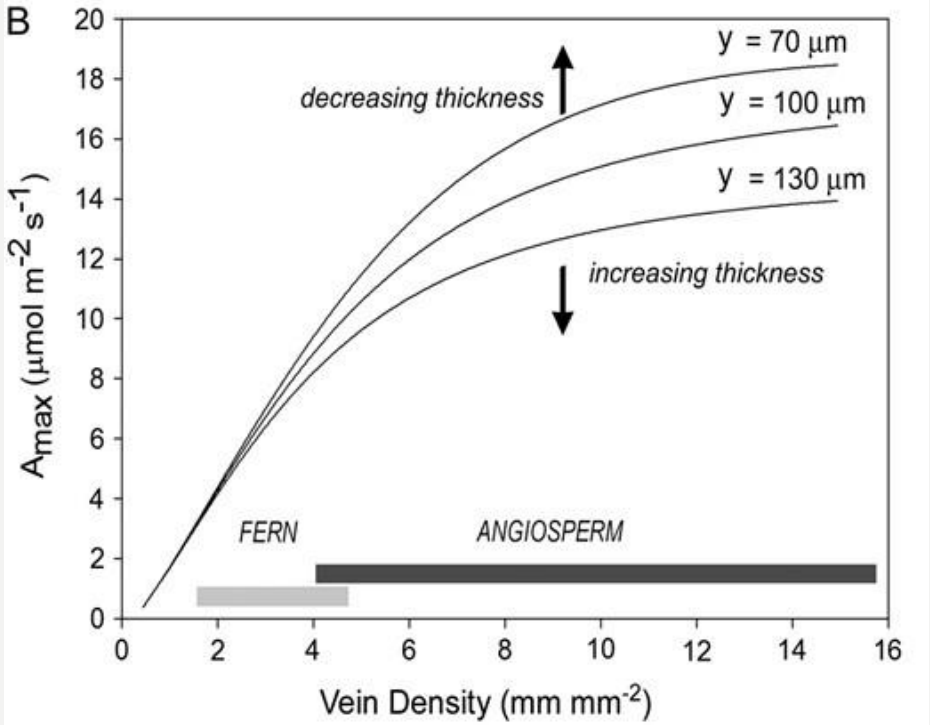


from the end of the vein xylem to the gas-exchange epidermis

Across the diverse range of land plant diversity sampled, an intimate association between light-saturated net CO_2 assimilation rate (A_{max}) and the hydraulic conductance (K_{leaf}) of whole leaves was found

Tim J. Brodribb, Taylor S. Feild, Gregory J. Jordan. 2007. **Leaf Maximum Photosynthetic Rate and Venation Are Linked by Hydraulics 葉片水力學.** *Plant Physiology*, Volume 144, Issue 4, August 2007, Pages 1890-1898, https://doi.org/10.1104/pp.107.101352





A. 單脈葉中A_{max}對葉寬的敏感性

A_{max}隨著葉變窄而增加

只有從葉脈到氣孔的最大距離
小於幾百微米的物種才能實現高光合速率

圖中顯示了五個代表性物種的大致位置

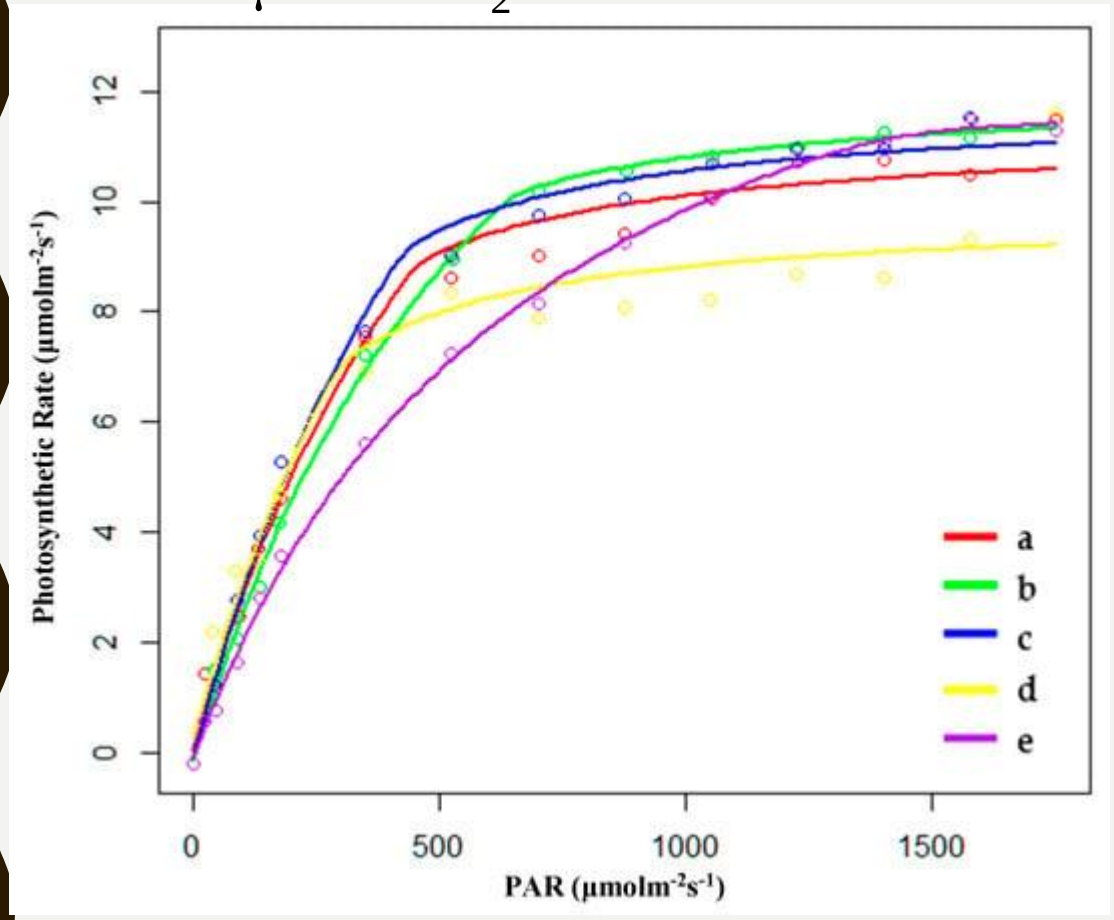
B. 葉脈密度對葉片A_{max}的影響

從葉脈到表皮的葉厚度為 70、100 和 130 μm

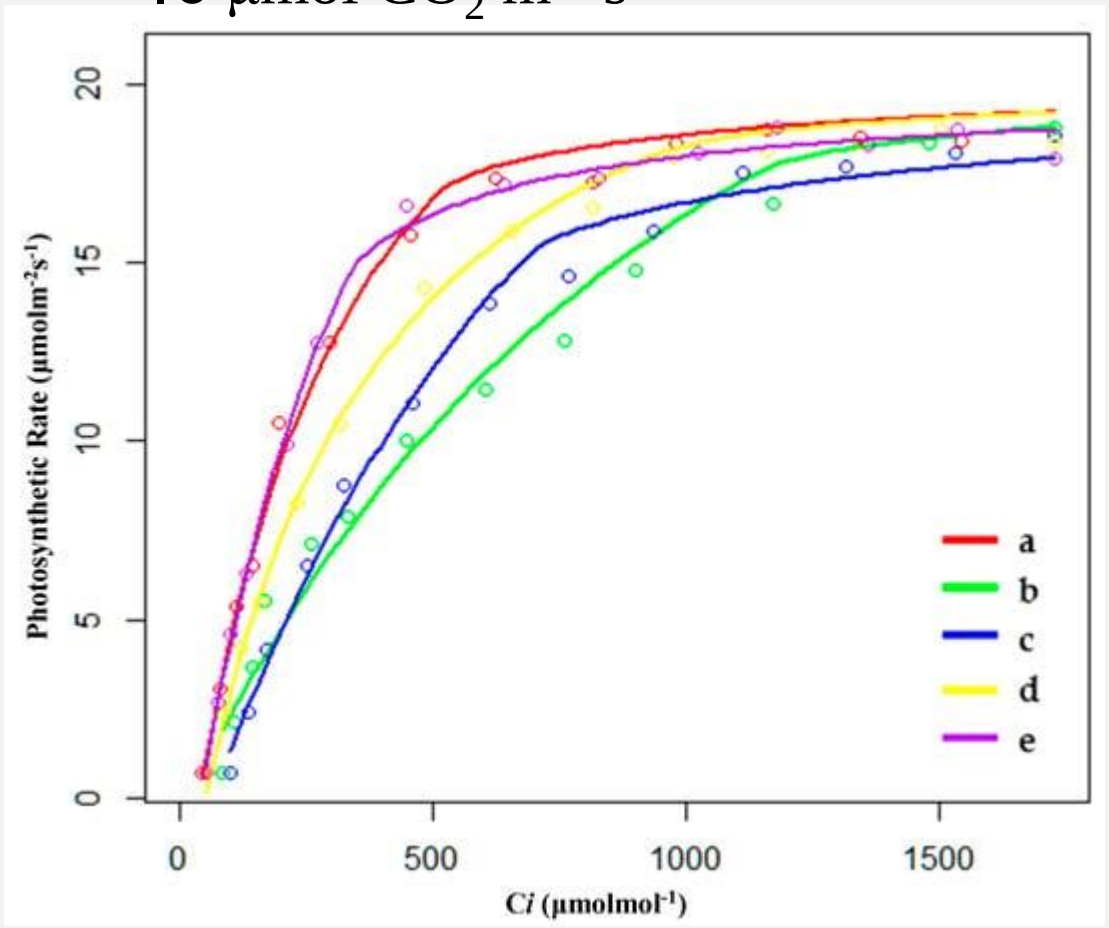
A_{max}隨著葉片變薄而增加

光合能力：最大光合速率

12 μmol CO_2 m^{-2} s^{-1}



18 μmol CO_2 m^{-2} s^{-1}



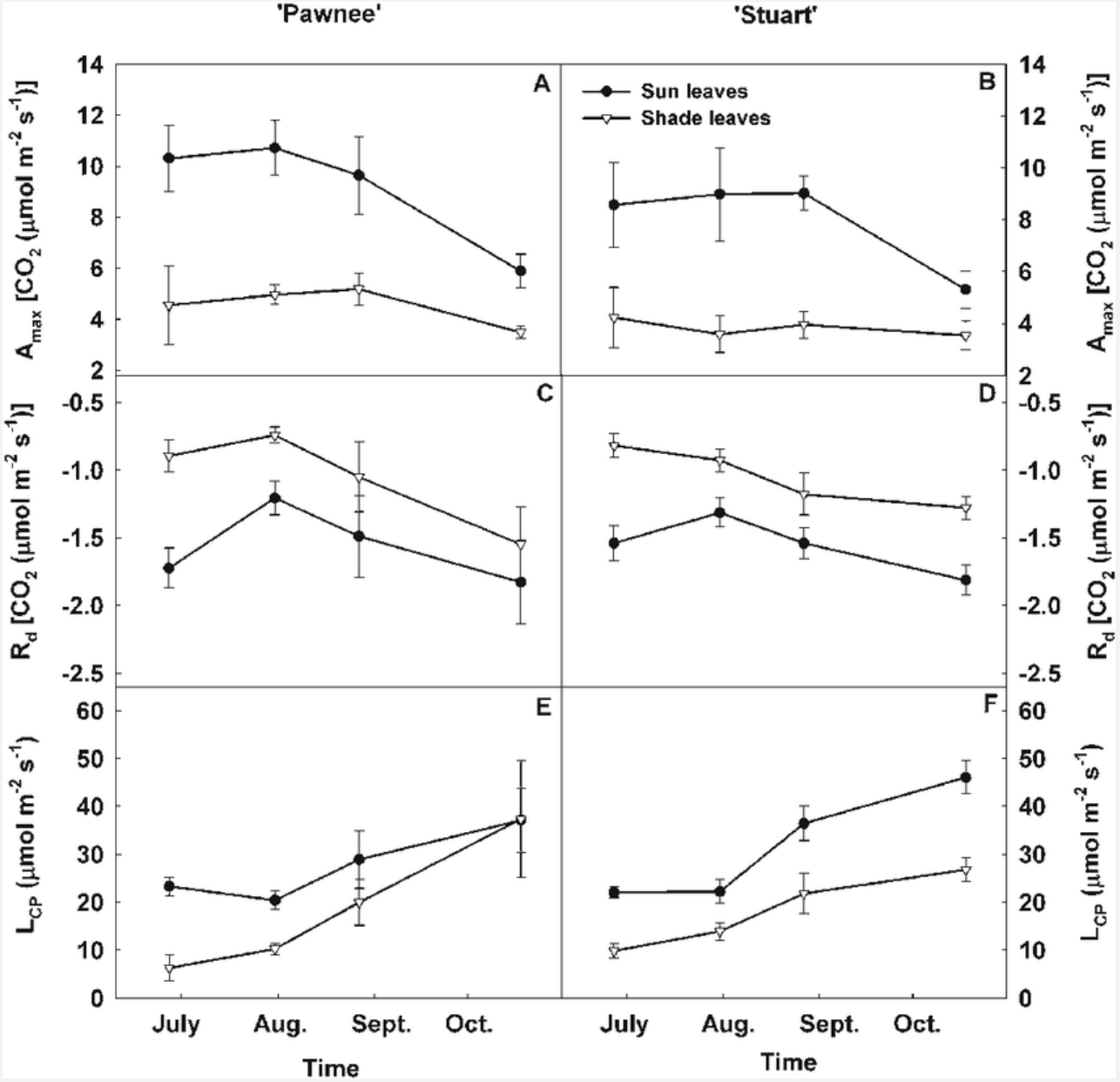
光合能力
最大光合速率

Sun leaves:

10 μmol CO_2 m^{-2} s^{-1}

Shade leaves:

6 μmol CO_2 m^{-2} s^{-1}



蒸散效率 Transpiration Efficiency (TE)

TE = Pn / Tr　　又稱 CO_2/vapor exchange rate

TE 隨著 PPFD 與 CO_2 濃度增加而增加
應該是因為氣孔阻力增加之故

VPD 較低 (1.1 kPa) 時的 TE 高於VPD 較高 (2.2 kPa) 時的 TE，前者約是後者的 1.37倍

番茄葉片的TE 範圍大致在 0 ~ 0.03 $mg/m^2/s$

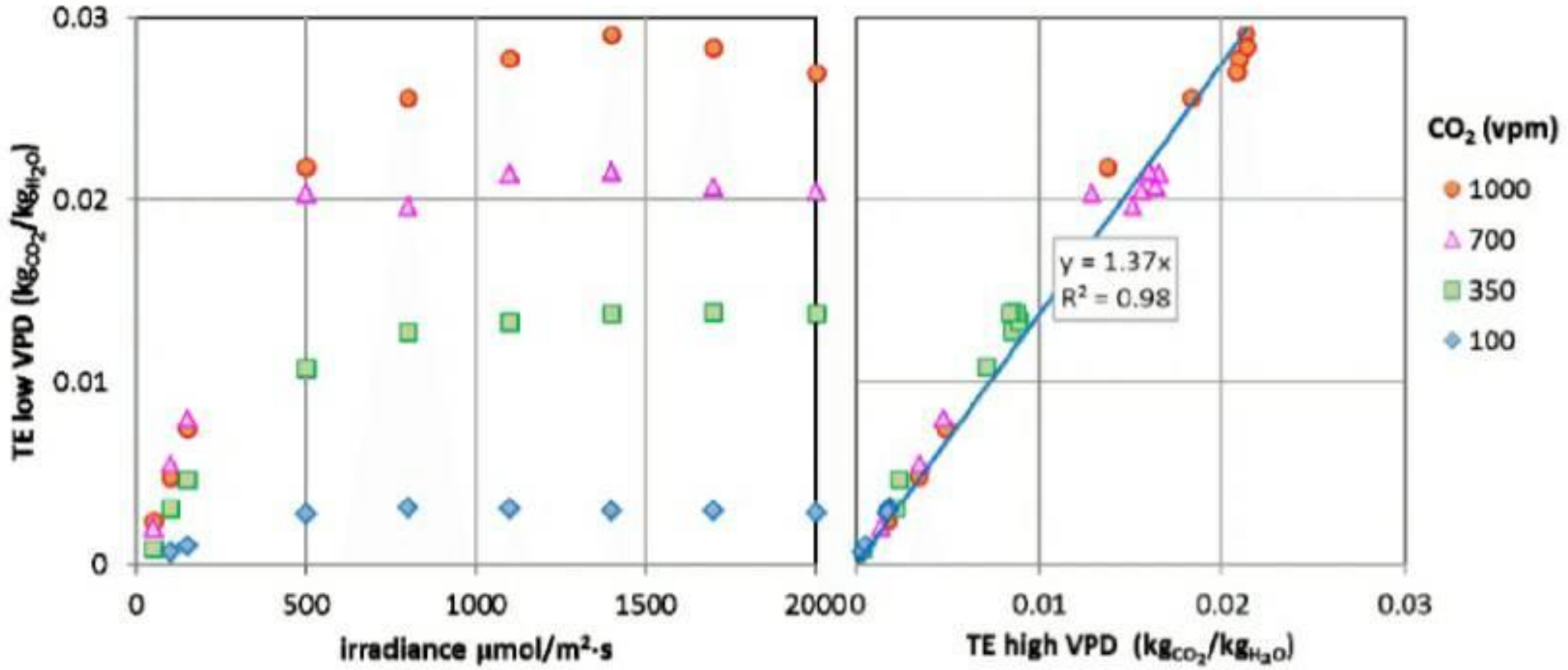


Fig. 2. Effect of ambient conditions on transpiration efficiency (TE) of tomato leaves (ratio of weight of assimilated CO_2 to weight of transpired water). Left panel: effect of light (Photosynthetic Photon Flux Density, x-axis) and CO_2 concentration (symbols at right), measured at 25°C leaf temperature and 1.1 kPa vapour pressure deficit. Right panel: effect of humidity. On the y-axis are the measurements shown at left, on the x-axis are the corresponding measurements done at a VPD of 2.2 kPa.

最大光合作用速率 (Pmax) 一般 < 20 μmol m^{-2} s^{-1} (0.88 mg m^{-2} s^{-1})

更改此參數值為0.88

Plant										
crop type (light)	std		Pm=	0.365		Pmax=	0.88	mg/(m2.s)		
crop type (CO2)	std		Rc=	959						
KI	100	W/m2	GI	0.53						
Kc	440	mg/m3	Gc	0.78			Ps:	Photosynthesis	0.30	mg/(m2.s)
CO2 in chloroplast	848.7	ppm	1525.9	mg/m3			Rp:	Photorespiration	0.01	mg/(m2.s)
Tm	25		GTI	1.0			Rd:	Darkrespiration	0.10	mg/(m2s)
a	5		Kpr	0.04			Pn:	Net Photos.	0.18	mg/(m2.s)
Rd(20C)	0.07		Q10	2.00						
Environment	T, deg.C		RH, %	density = 1/SV	VP, kPa	ah	Enthalpy,kJ/kg	VD, g/m3	$VDD_{leaf-air}$	VDD_{in-out}
Leaf T	25	RH_leaf	100	1.14	3.17			23.0		
indoor T	25	RH_in	80	1.14	2.53	0.016	65.77	18.4	4.6	
outdoor T	5	RH_out	40	1.23	0.35	0.002	10.42	2.7		15.7
CO2 indoor (ppm)	1200	-> mg/m3	2157.5	1.80		Pn/Tr =	0.0268			
CO2 outdoor (ppm)	410	-> mg/m3	790.2	1.93		Tr/Pn =	37.370	Rav	100.0	s/m
Wind (m/s)	1	m/s	CropType	high	std	low		Rlv	200.0	s/m
			Rlv =	300	200	100		Rlv.inc	366.9	s/m
ACH	0.02	1/h	CropType	std	low			Rv.total	666.9	s/m
			Rlv.inc =	366.9	183.5			Tr	6.90	mg/(m2.s)

蒸散效率 Transpiration Efficiency, Pn / Tr = 0.0268

更改 作物對光量與二氧化碳濃度的反應類型
兩者都改為 low, R_{lv} 與 $R_{lv.inc}$ 均下降

Plant										
crop type (light)	low		Pm=	0.365		Pmax=	0.88	mg/(m2.s)		
crop type (CO2)	low		Rc=	562						
KI	100	W/m2	GI	0.53						
Kc	440	mg/m3	Gc	0.78				Ps: Photosynthesis	0.30	mg/(m2.s)
CO2 in chloroplast	848.7	ppm	1525.9	mg/m3				Rp: Photorespiration	0.01	mg/(m2.s)
Tm	25		GTI	1.0				Rd: Darkrespiration	0.10	mg/(m2s)
a	5		Kpr	0.04				Pn: Net Photos.	0.19	mg/(m2.s)
Rd(20C)	0.07		Q10	2.00						
Environment	T, deg.C		RH, %	density = 1/SV	VP, kPa	ah	Enthalpy,kJ/kg	VD, g/m3	$VDD_{leaf-air}$	VDD_{in-out}
Leaf T	25	RH_leaf	100	1.14	3.17			23.0		
indoor T	25	RH_in	80	1.14	2.53	0.016	65.77	18.4	4.6	
outdoor T	5	RH_out	40	1.23	0.35	0.002	10.42	2.7		15.7
CO2 indoor (ppm)	1200	-> mg/m3	2157.5	1.80		Pn/Tr =	0.0157			
CO2 outdoor (ppm)	410	-> mg/m3	790.2	1.93		Tr/Pn =	63.898	Rav	100.0	s/m
Wind (m/s)	1	m/s	CropType	high	std	low		Rlv	100.0	s/m
			Rlv =	300	200	100		Rlv.inc	183.5	s/m
ACH	0.02	1/h	CropType	std	low			Rv.total	383.5	s/m
			Rlv.inc =	366.9	183.5			Tr	12.00	mg/(m2.s)

Pn 微幅增加 (0.18 → 0.19, +5.5%)，Tr 大幅增加 (6.9 → 12, +74%)

結果：Pn/Tr 大幅降低 (0.0268 → 0.0157, -41.4%)

更改 作物對光量與二氧化碳濃度的反應類型
前者改為 high，後者維持 std

Plant										
crop type (light)	high		Pm=	0.327		Pmax=	0.88	mg/(m2.s)		
crop type (CO2)	std		Rc=	1099						
KI	100	W/m2	GI	0.48						
Kc	440	mg/m3	Gc	0.78			Ps:	Photosynthesis	0.26	mg/(m2.s)
CO2 in chloroplast	848.7	ppm	1525.9	mg/m3			Rp:	Photorespiration	0.01	mg/(m2.s)
Tm	25		GTI	1.0			Rd:	Darkrespiration	0.10	mg/(m2s)
a	5		Kpr	0.04			Pn:	Net Photos.	0.15	mg/(m2.s)
Rd(20C)	0.07		Q10	2.00						
Environment	T, deg.C		RH, %	density = 1/SV	VP, kPa	ah	Enthalpy,kJ/kg	VD, g/m3	$VDD_{leaf-air}$	VDD_{in-out}
Leaf T	25	RH_leaf	100	1.14	3.17			23.0		
indoor T	25	RH_in	80	1.14	2.53	0.016	65.77	18.4	4.6	
outdoor T	5	RH_out	40	1.23	0.35	0.002	10.42	2.7		15.7
CO2 indoor (ppm)	1200	-> mg/m3	2157.5	1.80		Pn/Tr =	0.0258			
CO2 outdoor (ppm)	410	-> mg/m3	790.2	1.93		Tr/Pn =	38.735	Rav	100.0	s/m
Wind (m/s)	1	m/s	CropType	high	std	low		Rlv	300.0	s/m
			Rlv =	300	200	100		Rlv.inc	366.9	s/m
ACH	0.02	1/h	CropType	std	low			Rv.total	766.9	s/m
			Rlv.inc =	366.9	183.5			Tr	6.00	mg/(m2.s)

Pn 降低 (0.18 → 0.15, -16.7%)，Tr 也降低 (6.9 → 6.0, -13%)，但幅度較小

結果：Pn/Tr 微幅降低 (0.0268 → 0.0258, -3.7%)

當輻射量低於低限 (80 W m^{-2})，R_{lv} 氣孔阻力會大幅增加 (300 → 767.5)

Plant										
crop type (light)	high		Pm=	0.215		Pmax=	0.88	mg/(m2.s)		
crop type (CO2)	std		Rc=	1753						
KI	100	W/m2	GI	0.32						
Kc	440	mg/m3	Gc	0.78			Ps:	Photosynthesis	0.17	mg/(m2.s)
CO2 in chloroplast	848.7	ppm	1525.9	mg/m3			Rp:	Photorespiration	0.01	mg/(m2.s)
Tm	25		GTI	1.0			Rd:	Darkrespiration	0.10	mg/(m2s)
a	5		Kpr	0.04			Pn:	Net Photos.	0.07	mg/(m2.s)
Rd(20C)	0.07		Q10	2.00						
Environment	T, deg.C		RH, %	density = 1/SV	VP, kPa	ah	Enthalpy,kJ/kg	VD, g/m3	$VDD_{leaf-air}$	VDD_{in-out}
Leaf T	25	RH_leaf	100	1.14	3.17			23.0		
indoor T	25	RH_in	80	1.14	2.53	0.016	65.77	18.4	4.6	
outdoor T	5	RH_out	40	1.23	0.35	0.002	10.42	2.7		15.7
CO2 indoor (ppm)	1200	-> mg/m3	2157.5	1.80		Pn/Tr =	0.0182			
CO2 outdoor (ppm)	410	-> mg/m3	790.2	1.93		Tr/Pn =	55.051	Rav	100.0	s/m
Wind (m/s)	1	m/s	CropType	high	std	low		Rlv	767.5	s/m
			Rlv =	767.5	625	482.5		Rlv.inc	366.9	s/m
ACH	0.02	1/h	CropType	std	low			Rv.total	1234.4	s/m
			Rlv.inc =	366.9	183.5			Tr	3.73	mg/(m2.s)

Pn 大幅降低 (0.18 → 0.07, -61%)，Tr 大幅降低 (6.9 → 3.73, -46%)

結果：Pn/Tr 降低 (0.0268 → 0.0182, -32%)

當CO_2高於上限 (1200 ppm)，$R_{lv.inc}$ 氣孔阻力小幅增加 (366.9 → 400)

Plant											
crop type (light)	high		Pm=	0.215		Pmax=	0.88	mg/(m2.s)			
crop type (CO2)	std		Rc=	1800							
KI	100	W/m2	GI	0.32							
Kc	440	mg/m3	Gc	0.78				Ps:	Photosynthesis	0.18	mg/(m2.s)
CO2 in chloroplast	848.7	ppm	1525.9	mg/m3				Rp:	Photorespiration	-0.01	mg/(m2.s)
Tm	25		GTI	1.0				Rd:	Darkrespiration	0.10	mg/(m2s)
a	5		Kpr	-0.04				Pn:	Net Photos.	0.09	mg/(m2.s)
Rd(20C)	0.07		Q10	2.00							
Environment	T, deg.C		RH, %	density = 1/SV	VP, kPa	ah	Enthalpy,kJ/kg	VD, g/m3		$VDD_{leaf-air}$	VDD_{in-out}
Leaf T	25	RH_leaf	100	1.14	3.17			23.0			
indoor T	25	RH_in	80	1.14	2.53	0.016	65.77	18.4		4.6	
outdoor T	5	RH_out	40	1.23	0.35	0.002	10.42	2.7			15.7
CO2 indoor (ppm)	1400	-> mg/m3	2517.1	1.80		Pn/Tr =	0.0238				
CO2 outdoor (ppm)	410	-> mg/m3	790.2	1.93		Tr/Pn =	41.944	Rav		100.0	s/m
Wind (m/s)	1	m/s	CropType	high	std	low		Rlv		767.5	s/m
			Rlv =	767.5	625	482.5		Rlv.inc		400.0	s/m
ACH	0.02	1/h	CropType	std	low			Rv.total		1267.5	s/m
			Rlv.inc =	400.0	200.0			Tr		3.63	mg/(m2.s)

Pn 大幅增加 (0.07 → 0.09, +28.5%)，Tr 小幅降低 (3.73 → 3.63, -2.68%)

蒸散效率(TE) Pn/Tr 大幅增加 (0.0182 → 0.0238, +30.7%)

燈光配置與光量

Lighting								
W per LEDtube	20	W/lamp	Number of LEDtubes	1818		PAR	80	W/m2
No.LEDtube/layer	6		PPFD	370	μmol/m^2/s	DLI	21.312	mol/m2/day
Bench area per layer	0.66	m2	Light Period	16	h/day	Power consumpti	181.82	W/m2
Total W of other equip (W_e)			80	W/room		Total W of lamps	36360.00	W/room

PAR (W m^{-2}) = PPFD / 4.6 → PPFD 大於 370, PAR 大於 80 此為 R_{lv} 的閥值

DLI = PPFD (μmol m^{-2}s^{-1}) x LP (給光時數L) x 3.6 / 1000 = 14.4 mol m^{-2}day^{-1}

總燈管數 = 栽培面積x每層安裝燈管數/單層面積 = 200 x 6 / 0.66 = 1818

總耗電量 = 總燈管數 x 單支燈管耗電量 = 1818 x 20 = 36360 W

單位面積耗電量 = 36360 / 200 = 181.8 W m^{-2}

質量守恆

CO_2 BALANCE

CO2 balance		
LA per plant	0.1	m2/plant
Number of plants	6000	plants/room
Pn	0.7	mg/m2/s
ACH	0.1	1/h
Room volumn	400	m3

	ppm	mg/m3
CO_2 in	1200	2157.5
CO_2 out	410	790.2

C_N per room	412.5	mg/s/room
CO_2 absorbed by plants		
C_V per room	15.2	mg/s/room
CO_2 loss by ventilation		
C_S per room	427.6	mg/s/room
CO_2 supply to room		

$$C_s = C_v + C_N$$

lation | CO2 balance | Water balance | Energy balance | ⊕

$C_N = P_N \times L$ = P_N x LA.plt x Num.plt

PN : Net photosynthesis rate per leave area, mg/(m2s)

L : Total leaf area in a room, m2/room

$C_N = 1 * (0.02*100) = 2$ mg/(s.room)

$$C_V = A \times (\rho\ ca_{in} - \rho\ ca_{out}) \times V_r$$

A : Ventilation rate, 1/h

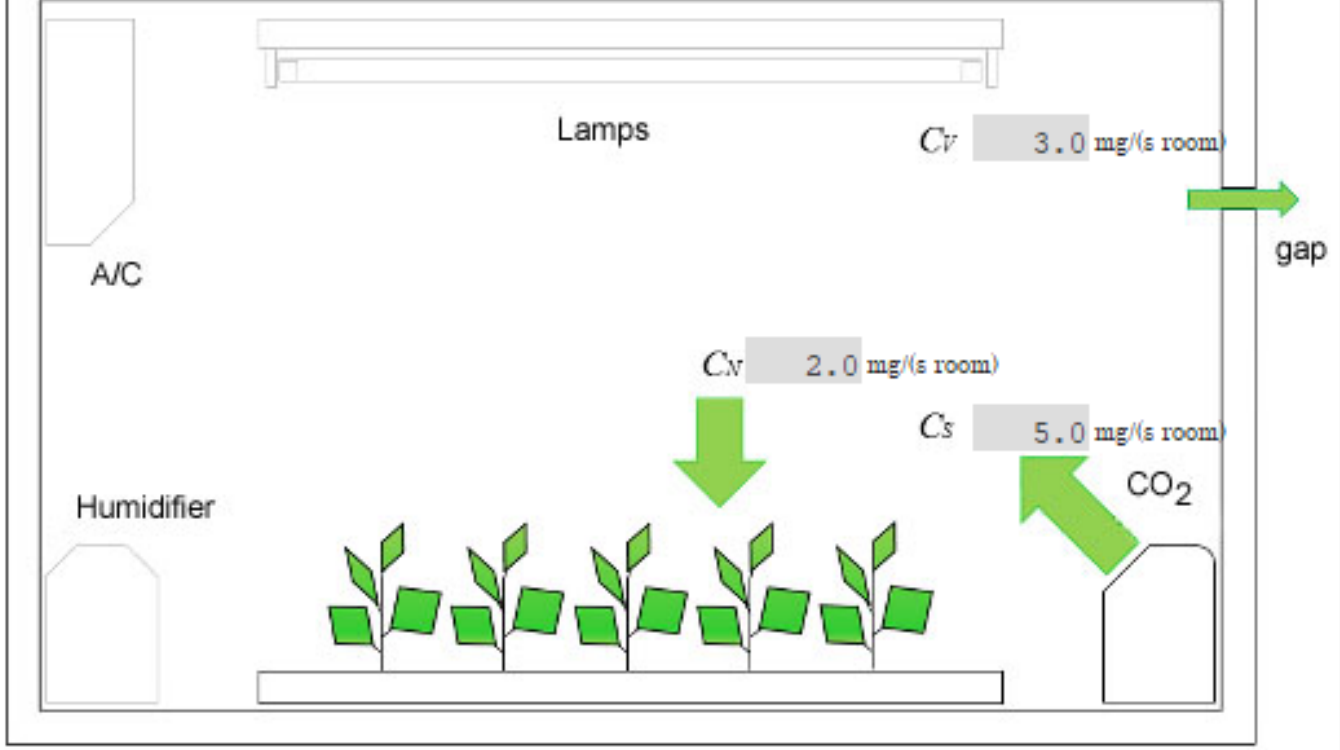
Vr : Interior Volume

ρca in : Inside CO2 concentration, mg/m3

ρca out : Outside CO2 concentration, mg/m3

$Cv = 0.02*(1799.5-733)*500 / 3600$
$= 2.9625$ mg/s

$C_s = C_v + C_N = 2 + 2.96 = 4.96$ mg/s



Simulation

LA per plant	0.02	m²/plant			Num. of plants	100 plants/room
Room length	10	m	Room width	10 m	Room height	5 m
Room volume	500.0	m³/room			A	0.02 1/h
1) Room net photos. rate(CN)				2.0	mg/(s room)	
Net photos. rate per unit leaf area				1.0	mg/(m² s)	
2) CO2 loss by ventiration(CV)				3.0	mg/(s room)	
CO2 conc. in				1000	ppm	1799.5 mg/m3
CO2 conc. out				380	ppm	733.0 mg/m3
3) CO2 supply to room(CS)				5.0	mg/(s room)	

質量守恆

WATER BALANCE

	deg.C		%	density	VP, kPa	ah, kg/kg	Enthalpy,kJ/kg	VD, g/m3	$VDD_{leaf-air}$	VDD_{in-out}
T_leaf	25	RH_leaf	100	1.14	3.17			23.01		
T_in	25	RH_in	80	1.14	2.53	0.016	65.77	18.41	4.602	
T_out	5	RH_out	40	1.23	0.35	0.002	10.42	2.72		15.69

Water balance		
LAperPlt	0.1	m2/plant
NoofPlts	6000	plants/room
Tr	5.3	mg/m2/s
ACH	0.02	1/h
Room volumn	400	m3

$T_R + H = V_W$, or $H = Vw - T_R$

T_R = Tr*LAperPlt*NoofPlts

Vw=VolofRoom*ACH*(Vdin-Vdout)*1000/3600

T_R per room	3191.1	mg/s/room
Vapor transpired by plants		
V_W per room	34.9	mg/s/room
Vapor loss by ventilation		
(De)H needed	-3156.2	mg/s/room

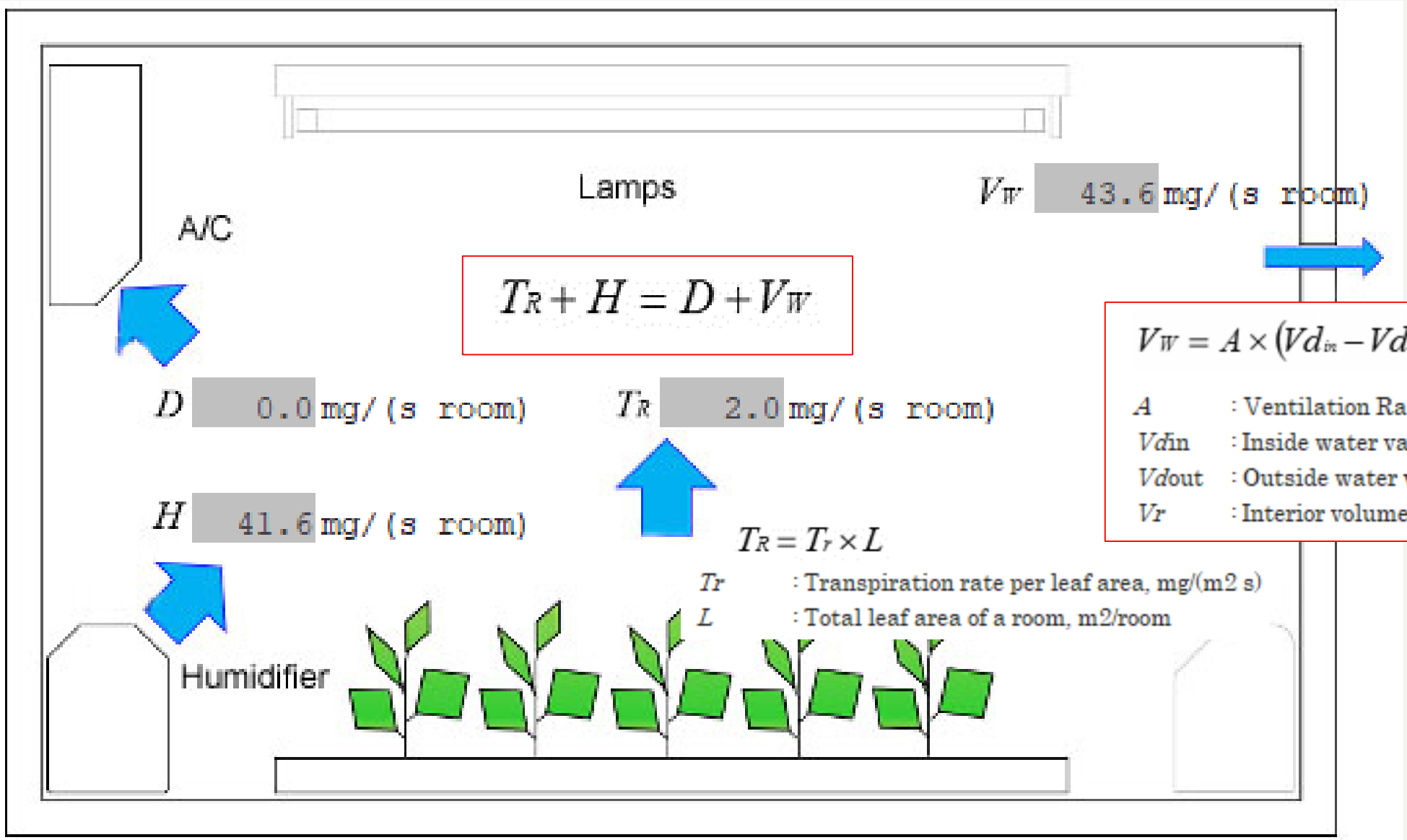
Value > 0 means Humidification

Value < 0 means Dehumidification

PF simulation | CO2 balance | Water balance | Energy balance

蒸散產生的水汽量（3191.1）遠大於換氣的排濕量（34.9）

此時則需要啟動除濕機才能維持設定的室內濕度



蒸散產生的水汽量（2）小於換氣的排濕量（43.6），
此時則需要啟動加濕機才能維持設定的室內濕度

Simulation

Temp. in	25	C	RH in	80	%	Vds in	18.4	g/m3
Temp. out	5	C	RH out	40	%	Vds out	2.7	g/m3
LA per plant	0.02	m2/plant				Num. of plants	100	plants/room
Room length	10	m	Room width	10	m	Room height	5	m
Room volume	500.0	m2/room				A	0.02	1/h

= 23.01 * 0.8

= 6.79 * 0.4

1) Transpiration rate of room(TR)	2.0	mg/(s room)
TR per unit leaf area	1.0	mg/(m2 s)
2) Water loss by ventiration(VW)	43.6	mg/(s room)
3) Humidfication(H)	41.6	mg/(s room)
4) Dehumidification(D)	0.0	mg/(s room)

Relative humidity, %	Temperature,C					
	0	5	10	15	20	25
0	0.00	0.00	0.00	0.00	0.00	0.00
20	0.97	1.36	1.88	2.56	3.45	4.60
40	1.94	2.72	3.76	5.13	6.91	9.20
60	2.91	4.08	5.64	7.69	10.36	13.81
80	3.87	5.43	7.51	10.25	13.82	18.41
100	4.84	6.79	9.39	12.82	17.27	23.01

$$T_R = Tr * L = 1 * 2 = 2 \text{ mg/(s.room)}$$

$$V_w = 0.02*(18.41-2.72)*500/3600 = 0.0436 \text{ g/(s.room)} = 43.6 \text{ mg/(s.room)}$$

TR + H = D + Vw, 2 + H = D + 43.6, D=0 (no dehumidification), H = 43.6 – 2 = 41.6

能量守恆

ENERGY BALANCE

進入溫室的熱量以潛熱(Q_L)+顯熱(Q_S)兩種方式呈現

- 荷蘭的相對濕度低，Q_L 占比較低，但也有近半 1000/1900 = 52.63%, 其餘為Qs 900/1900 = 47.37%
- 南歐如西班牙濕度高，Qs 占比更低 350/2000 = 17.5%, Q_L 占比高 1650/2000 =82.5%

台灣的天氣與南歐相近，濕度都偏高，尤其是在夜間，特別是沒有加熱的溫室內。換言之，空調作用於除溼的比例頗高。氣密性不高的 PFAL，也存在這種困擾。

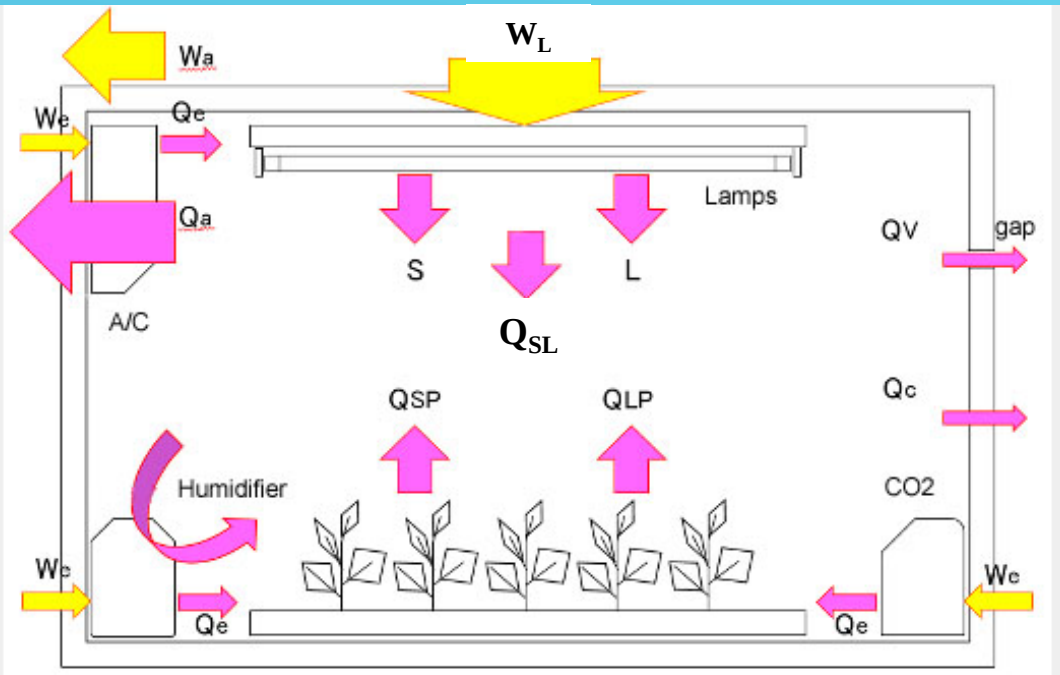
	deg.C		%	density	VP, kPa	ah, kg/kg	Enthalpy,kJ	VD, g/m3	$VDD_{leaf-air}$	VDD_{in-out}
T_leaf	25	RH_leaf	100	1.14	3.17			23.01		
T_in	25	RH_in	80	1.14	2.53	0.016	65.77	18.41	4.602	
T_out	5	RH_out	40	1.23	0.35	0.002	10.42	2.72		15.69
Room dimension		Lg	10	Wd	10.00	Hgh	4.00 m			
Room volume	**400**	**m3**	ACH	0.02		**k_w (conductivity of walls) =**			0.10	

Energy balance

$W_L + W_e = Qv + Qc + Qa$

Total W of lamps (W_L)	36360.0	W/room, Total W of other equip. (We)	80.0	W/room
Heat loss by ventilation (Qv)	140.7	W/room		
Qv = (Enth_in - Enth_out) * Density_in * VolofRoom * ACH / 3.6				
Heat loss by conduction (Qc)	720.0	W/room		
Qc = 2*(Lg*Wid+Wid*Hgh+Lg*Hgh) * Kw * (Tin - Tout)				
Heat carry away by AC (Qa)	35579.3	W/room		
Qa = W_L + W_e - Qv - Qc				

PF simulation | CO2 balance | Water balance | Energy balance



Simulation

Temp. in	25	C	RH in	80	% LA per plant	0.02	m2/plant
Temp. out	5	C	RH out	40	% Num. of plants	100	plants/room
Lamp type	INF				Total W of lamps	8000	W/room
Room length	10	m	Room width	10	m Room height	5	m
Room volume	500.0	m³ /room			A	0.02	1/h

Heat production by lamps(QSL)	5118.7	J/(s room)
Short wave radiation(S)	1231.1	J/(s room)
Long wave radiation(L)	1650.2	J/(s room)
eat loss by ventiration(QV)	176.0	J/(s room)
Heat loss by conduction(QC)	800.0	J/(s room)
Heat carried away by AC(QA)	7024.0	J/(s room)

此三個數值與所選擇的燈具有關
但最後納入其它計算的是
燈具的總耗電 (WL)

所以就算選用的燈具種類不同
也不影響模式的實用性

濕空氣所含的熱量可分兩部分計算，兩者合計即為熱焓值(enthalpy):

1. 顯熱 Sensible heat of 1 kg air

$$Hs \text{ (in J/kg)} = T * Cp$$

2. 潛熱 Latent heat of 1 kg air:

$$H_L \text{ (in J/kg)} = Wx * Vd / \rho_{air} = Wx * AH$$

HS	: Sensible Heat, J/kg	
T	: Temperature, C	
* Conversion from J/g to J/kg is 1000 g/kg		
HL	: Latent Heat, J/kg	
Wx	: Vaporization Heat of Water, J/kg	
Vd	: Water Vapor Density, kg/m3	
ρair	: Air Density, kg/m3	

假設室內溫、濕度均高於室外，Hs 與 H_L 透過牆壁與孔隙對外傳出。

室內的熱量主要來自燈光與其他設備的電力消耗 (W_L and W_e)，一般假設電能消耗量等於傳入的熱量。當室溫維持定值，能量守恆式如下：

$$W_L + W_e = Q_v + Q_c + Q_a$$

	Temperatu	RH		density = 1/SV	Vps	ah	enthalpy,kJ/kg			
Leaf (oC)	25	RHleaf,%	100	1.14	3.17			Vds leaf	23.0	g/m3
indoor (oC)	25	RHin,%	80	1.14	3.17	0.016	65.77	Vd in	18.4	g/m3
outdoor (°C)	5	RHout,%	40	1.23	0.87	0.002	10.42	VDD	4.6	g/m3

Hs = 25 * 1006 J/kg.K = 25.15 kJ/kg

Wx = 2441.7 kJ/kg vapor @ 25 °C

H_L =2441.7* 0.016 kg vapor/kg air = 39.06 kJ/kg air

Hs + H_L = 64.21 kJ/kg 此即為室內空氣的熱焓值

但此二數值並不是前頁提到的 S 與 L

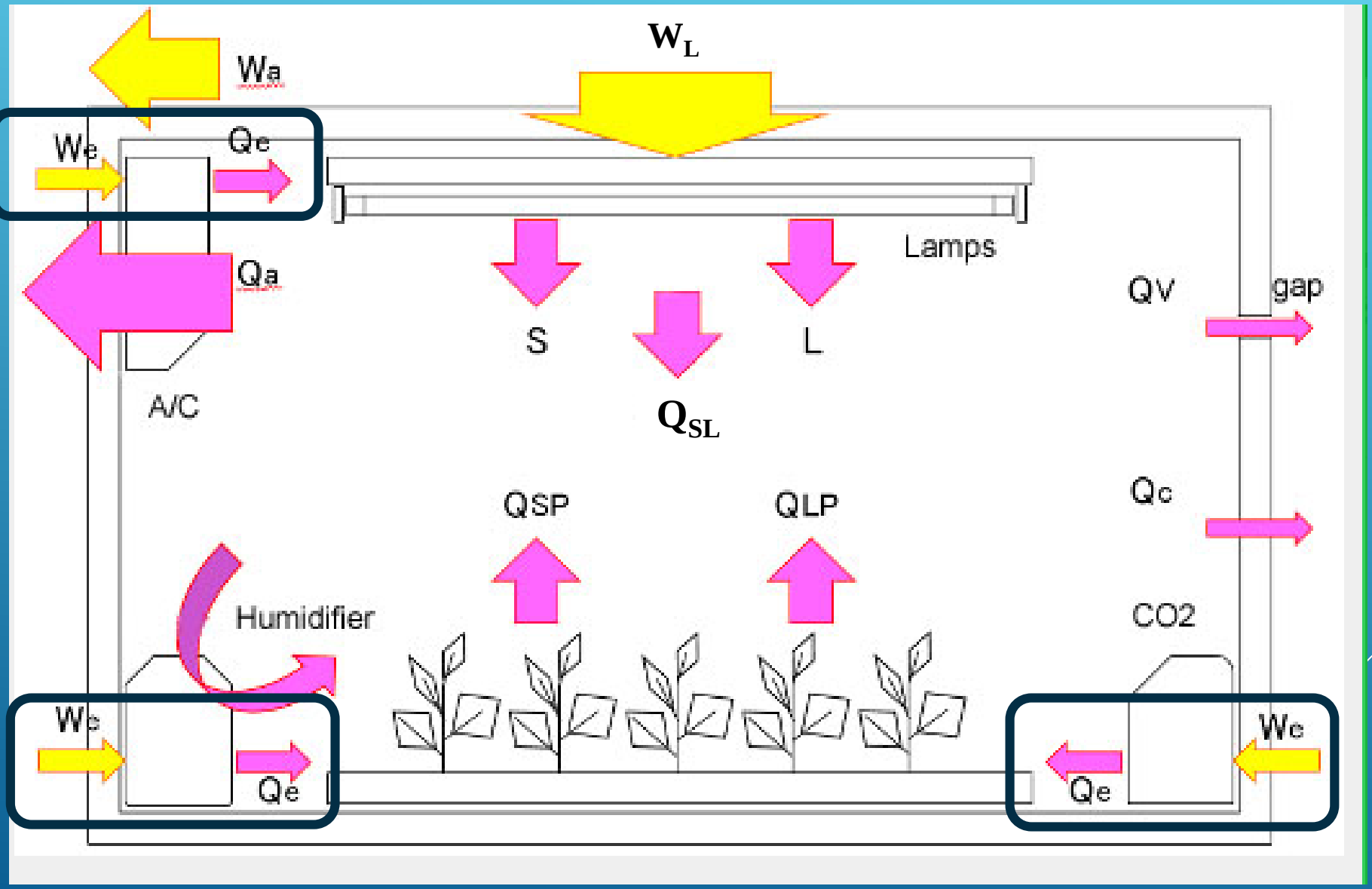
mperature	Vapor pressure	Heat of vaporization, ΔHvap			
[°C]	[kPa] [100*bar]	[J/mol]	[kJ/kg]	[Wh/kg]	[Btu(IT)/lb$_m$]
0.01	0.61165	45054	2500.9	694.69	1075.2
2	0.70599	44970	2496.2	693.39	1073.2
4	0.81355	44883	2491.4	692.06	1071.1
10	1.2282	44627	2477.2	688.11	1065.0
14	1.5990	44456	2467.7	685.47	1060.9
18	2.0647	44287	2458.3	682.86	1056.9
20	2.3393	44200	2453.5	681.53	1054.8
25	3.1699	43988	2441.7	678.25	1049.7
30	4.2470	43774	2429.8	674.94	1044.6

WL	: Electrical energy supplied to lamps, J/s
We	: Electrical energy supplied to other equipment in a room, J/s
Qv	: Heat by ventilation, J/s
Qc	: Conduction heat, J/s
Qa	: Exhaust heat from air conditioners, J/s

其它的電力設備產生的熱量 We → Qe

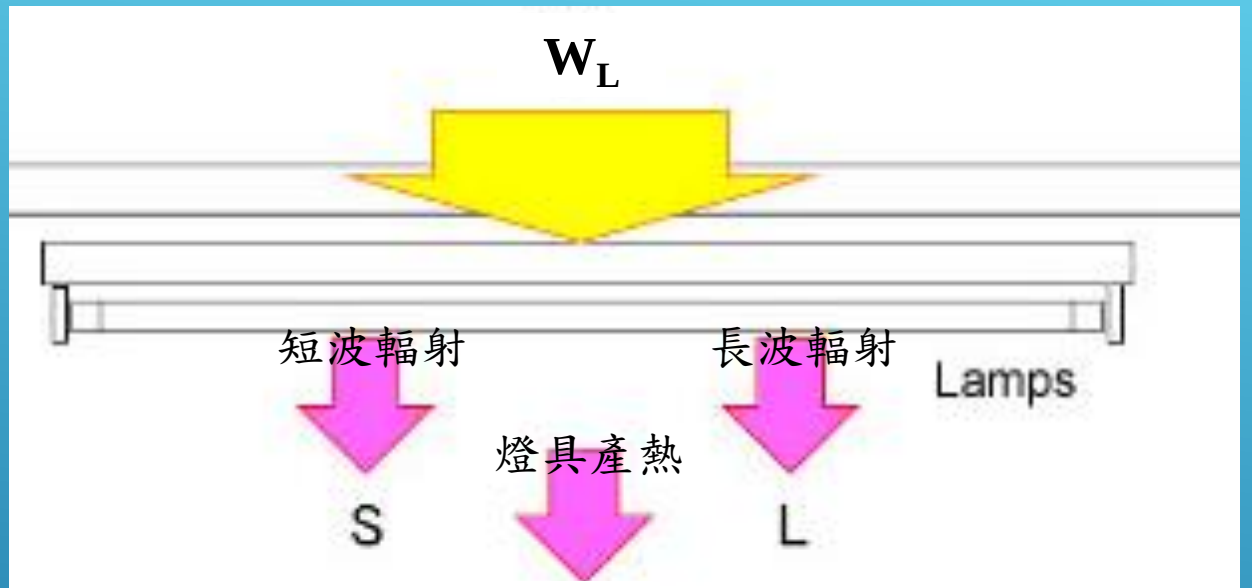
AC系統有室內、外機，只需考量室內機的風扇所消耗的電力

除濕機非長時間運轉，CO_2施肥如使用鋼瓶，都可忽略



通常以此些設備的耗電量估算產生的熱量

圖中未包括營養液循環系統的馬達等



燈光的耗電量 = 產生的總熱量

$$W_L = Q_{SL} + S + L$$

Q_{SL} : Amount of heat production by lamps, J/s

S : Amount of energy of shortwave radiation, J/s

L : Amount of energy of long-wave radiation, J/s

$$Q_V = (E_{in} - E_{out}) \times \rho_{air} \times A \times V_r$$

Ein : Inside enthalpy, J/kg

Eout : Outside enthalpy, J/kg

A : Ventilation rate, 1/h

Vr : Volume of a room, m3

透過孔隙換氣排出的熱量

$$Q_c = (T_{in} - T_{out}) \times K_W \times A_r$$

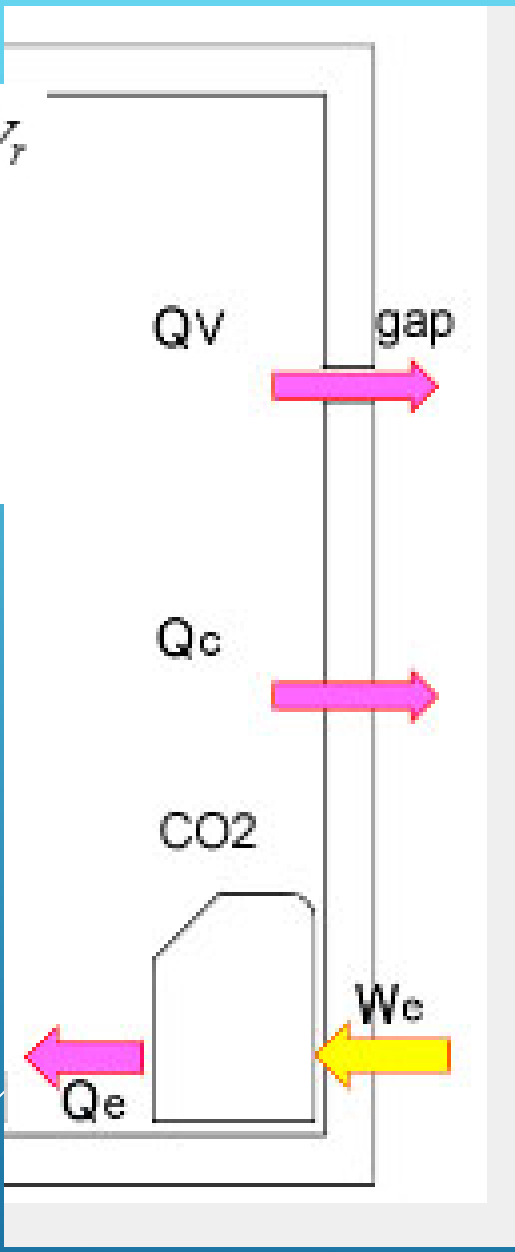
Tin : Inside temperature, C

Tout : Outside temperature, C

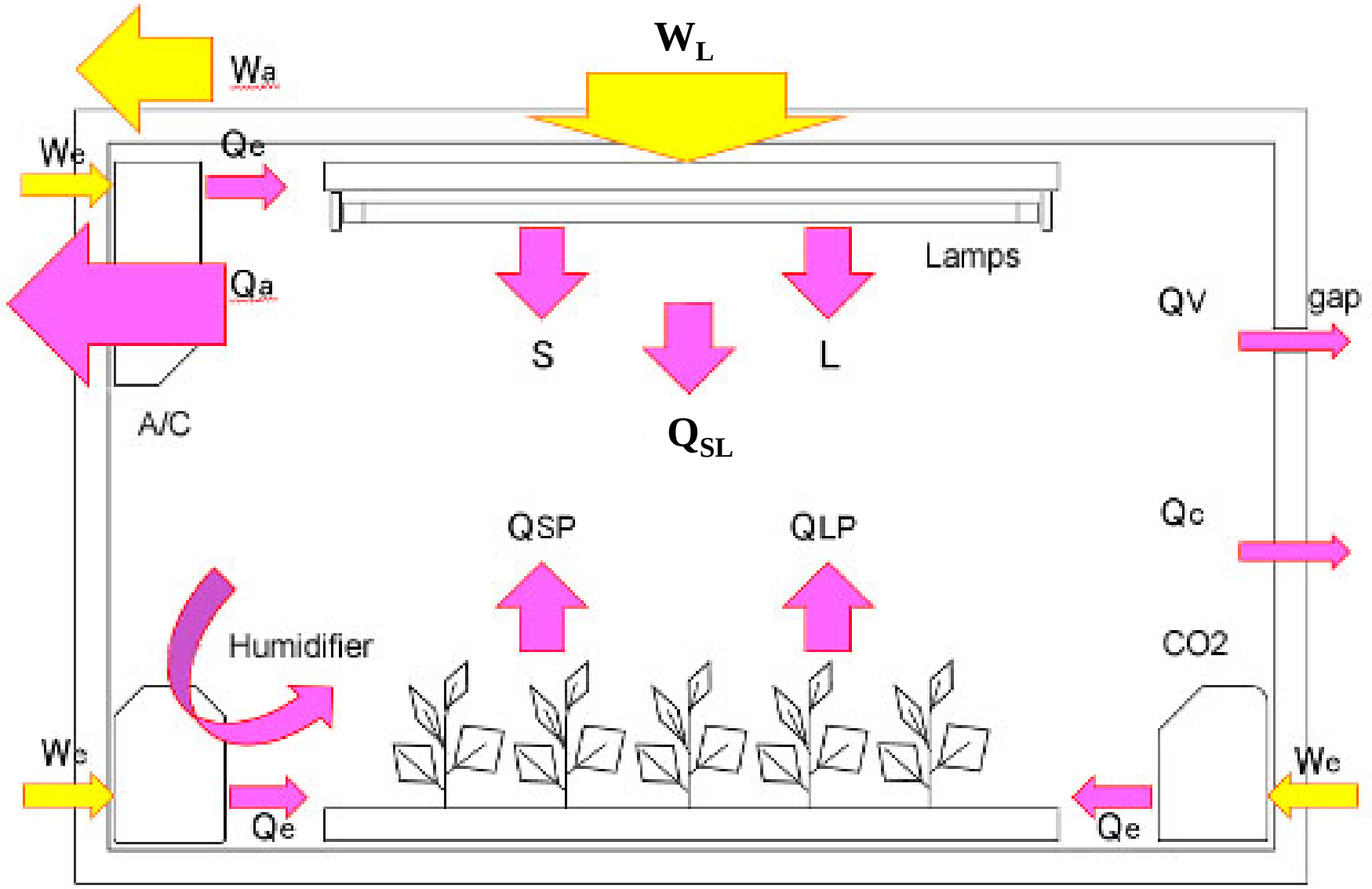
Kw : Heat conduction coefficient, J/(s m2 C)

Ar : wall, ceiling, and floor area, m2

透過牆壁傳導傳出的熱量



當 Q_V 與 Q_C不足以傳出所有的熱(Q_{SL}+S+L+Q_e)時



就需要
空調設備
Q_a來散熱

空調的降
溫負荷可
由此計算

Simulation

Temp. in	25 C	RH in	80 %	LA per plant	0.02	m2/plant	
Temp. out	5 C	RH out	40 %	Num. of plants	100	plants/room	
Lamp type	INF			Total W of lamps	8000	W/room	
Room length	10 m	Room width	10 m	Room height	5	m	
Room volume	500.0 m³ /room			ACH	0.02	1/h	

$$W_L = Q_{SL} + S + L$$

Heat production by lamps(QSL)	5118.7 J/(s room)
Short wave radiation(S)	1231.1 J/(s room)
Long wave radiation(L)	1650.2 J/(s room)
Heat loss by ventilation (QV)	176.0 J/(s room)
Heat loss by conduction(QC)	800.0 J/(s room)
Heat carried away by AC(QA)	7024.0 J/(s room)

Inside enthalpy (h) = 65.81
Outside h = 10.42 kJ/kg
dh = 65.81 – 10.42 = 55.39
Q_v = dh*1.14*500*0.02/3.6 =
178 J/s = W
Qc=(25-5)* k *(400) = 800 W
假設熱導係數 k =0.1
空調降溫負荷Q_a=
8000-178-800 = 7022 W

$$W_L + W_e = Q_V + Q_c + Q_a$$

PFAL Simulator

左側為資料輸入區

Plant									
crop type (light)	std		Pm=	0.241		Pmax=	0.88	mg/(m2.s)	
crop type (CO2)	std		Rc=	1408		Photosynthetic Capacity			
KI	100	W/m2	GI	0.35					
Kc	440	mg/m3	Gc	0.78		Ps:	Photosynthesis	0.19	mg/(m2.s)
CO2 in chloroplast	848.7	ppm	1525.9	mg/m3		Rp:	Photorespiration	0.01	mg/(m2.s)
Tm	25		GTI	1.0		Rd:	Darkrespiration	0.10	mg/(m2s)
a	15		Kpr	0.04		Pn:	Net Photos.	0.09	mg/(m2.s)
Rd(20C)	0.07		Q10	2.00					

Environment	T, deg.C		RH, %	density = 1/SV	VP, kPa	ah	Enthalpy,kJ/kg	VD, g/m3	$VDD_{leaf-air}$	VDD_{in-out}
Leaf T	25	RH_leaf	100	1.14	3.17			23.0		
indoor T	25	RH_in	80	1.14	2.53	0.016	65.77	18.4	4.6	
outdoor T	5	RH_out	40	1.23	0.35	0.002	10.42	2.7		15.7
CO2 indoor (ppm)	1200	-> mg/m3	2157.5	1.80		Pn/Tr =	0.0189	= Transpiration Efficiency (TE)		
CO2 outdoor (ppm)	410	-> mg/m3	790.2	1.93		Tr/Pn =	53.012	Rav	100.0	s/m
Wind (m/s)	1	m/s	CropType	high	std	low		Rlv	520.7	s/m
			Rlv =	652.7174	520.6522	388.587		Rlv.inc	366.9	s/m
ACH	0.02	1/h	CropType	std	low			Rv.total	987.6	s/m
			Rlv.inc =	366.9	183.5			Tr	4.66	mg/(m2.s)

Culture room								
Room length	10	m	space utilization	0.5		Leaf area/plant	0.1	m2/plt
Room width	10	m	No. of layers	4		Number of plants	6000	plt/room
Room height	4	m	Culture area	200	m2	Total leaf area	600	m2
Room volume	400	m3	Cropping density	30	plts/m2	LAI	3	

Lighting								
W per LEDtube	20	W/lamp	Number of LEDtubes	1818		PAR	54	W/m2
No.LEDtube/layer	6		PPFD	250	$\mu mol/m^2/s$	DLI	14.4	mol/m2/day
Bench area per layer	0.66	m2	Light Period	16	h/day	Power consump. / cural area	181.82	W/m2
Total W of other equip (W_e)			80	W/room		Total W of lamps	36360.00	W/room

右側為計算結果

CO2 balance		
CO_2 supply to room (C_S)	55.78	mg/(s.room)
Net photos. rate in room (C_N)	52.74	mg/(s.room)
CO_2 loss by ventilation (C_V)	3.04	mg/(s.room)
$C_S = C_N + C_V$		

Water balance		
Transpiration rate of room (T_R)	2795.9	mg/(s.room)
(De)Humidification (H)	-2761.0	mg/(s.room)
Water loss by ventilation (V_W)	34.9	mg/(s.room)
$T_R + H = V_W$		

Energy balance		
k (conductivity of walls) =	0.1	
Total W of lamps (W_L)	36360.0	W/room
Total W of other equipment (W_e)	80	W/room
Heat loss by ventilation (Qv)	140.7	W/room
Heat loss by conduction (Qc)	720	W/room
Heat carry away by AC (Qa)	35579.3	W/room
$W_L + W_e = Qv + Qc + Qa$		

CO2 Price					kg CO2	cost,NT$	Ratio
20		CO2 used	per day		3.21	64	2.32 %
NT$/kg			/day/plant		0.0005	0.0107	
			/day/m2 roon		0.0321		
			per month		96.39	1928	
			per year		1172.69	23,454	
Elec.fee: Light						cost,NT$	
3.5		Light elec	36.44	kW/room			
NT$/kWh			583	kWh per day		2041	73.7 %
	Light Period		0.097	kWh /day/plant			
	16		5.83	kWh/day/m2 room			
			17491	kWh per month		61,219	
			212810	kWh per year		744,834	
Elec.fee: AC						cost,NT$	
3		AC_elec	11.86	kW/room			
COP			190	kWh per day		664	24.0 %
			0.032	kWh/day/plant			
			1.898	kWh/day/m2 room			
			5693	kWh per month		19924	
			69261	kWh per year		242,414	
Capacity of AC required			10.108	RT, Note: 3.52 kW per Refri. Ton			

Operating cost (CO2 + AC & Light Elec)						
	Ratio of OP cost			per day	2769	NT$
ACH	CO2	Light elec	AC elec	per month	83,071	NT$
0.02	2.32%	73.7%	24.0%	per year	1,010,701	NT$

EY	100	g/kWh
Yield	58.3	kg/day
	1749	kg/month
	20989	kg/year

PF simulation | CO2 balance | Water balance | Energy balance

四個工作表單

整廠模擬的輸出結果 (ACH = 0.01, indoor CO_2 = 800 ppm, COP = 3)

CO2 balance		
CO2 supply to room (C_S)	26.78	mg/(s.room)
Net photos. rate in room (C_N)	26.06	mg/(s.room)
CO2 loss by ventilation (C_V)	0.72	mg/(s.room)
$C_S = C_N + C_V$		

Water balance		
Transpiration rate of room (T_R)	3191.1	mg/(s.room)
(De)Humidification (H)	-3173.7	mg/(s.room)
Water loss by ventilation (V_W)	17.4	mg/(s.room)
$T_R + H = V_W$		

Energy balance		
k (conductivity of walls) =	0.1	
Total W of lamps (W_L)	36360.0	W/room
Total W of other equipment (W_e)	80	W/room
Heat loss by ventilation (Qv)	70.3	W/room
Heat loss by conduction (Qc)	720	W/room
Heat carry away by AC (Qa)	35649.7	W/room
$W_L + W_e = Qv + Qc + Qa$		

CO2 Price		CO2 used		kg CO2	cost,NT$	Ratio
20			per day	1.54	31	1.13%
NT$/kg			/day/plant	0.0003	0.0051	
			/day/m2 roon	0.0154		
			per month	46.27	925	
			per year	562.94	11,259	

Elec.fee: Light					cost,NT$	
3.5		Light elec	36.44	kW/room		
NT$/kWh			583	kWh per day	2041	74.6%
	Light Period		0.097	kWh /day/plant		
	16		5.83	kWh/day/m2 room		
			17491	kWh per month	61,219	
			212810	kWh per year	744,834	

Elec.fee: AC					cost,NT$	
3		AC_elec	11.88	kW/room		
COP			190	kWh per day	665	24.3%
			0.032	kWh/day/plant		
			1.901	kWh/day/m2 room		
			5704	kWh per month	19964	
			69398	kWh per year	242,893	

Capacity of AC required	10.128	RT, Note: 3.52 kW per Refri. Ton

Operating cost (CO2 + AC & Light Elec)						
	Ratio of OP cost			per day	2737	NT$
ACH	CO2	Light elec	AC elec	per month	82,108	NT$
0.01	1.13%	74.6%	24.3%	per year	998,985	NT$

EY	100	g/kWh
Yield	58.3	kg/day
	1749	kg/month
	20989	kg/year

整廠模擬的輸出結果 (ACH = 0.01, indoor CO_2 = 800 ppm, COP = 5.5)

CO2 balance		
CO2 supply to room (C_S)	26.78	mg/(s.room)
Net photos. rate in room (C_N)	26.06	mg/(s.room)
CO2 loss by ventilation (C_V)	0.72	mg/(s.room)
$C_S = C_N + C_V$		
Water balance		
Transpiration rate of room (T_R)	3191.1	mg/(s.room)
(De)Humidification (H)	-3173.7	mg/(s.room)
Water loss by ventilation (V_W)	17.4	mg/(s.room)
$T_R+H = V_W$		
Energy balance		
k (conductivity of walls) =	0.1	
Total W of lamps (W_L)	36360.0	W/room
Total W of other equipment (W_e)	80	W/room
Heat loss by ventilation (Qv)	70.3	W/room
Heat loss by conduction (Qc)	720	W/room
Heat carry away by AC (Qa)	35649.7	W/room
$W_L + W_e = Qv + Qc + Qa$		

CO2 Price		CO2 used		kg CO2	cost,NT$	Ratio
20			per day	1.54	31	1.27%
NT$/kg			/day/plant	0.0003	0.0051	
			/day/m2 room	0.0154		
			per month	46.27	925	
			per year	562.94	11,259	
Elec.fee: Light					cost,NT$	
3.5		Light elec	36.44	kW/room		
NT$/kWh			583	kWh per day	2041	83.8%
	Light Period		0.097	kWh /day/plant		
	16		5.83	kWh/day/m2 room		
			17491	kWh per month	61,219	
			212810	kWh per year	744,834	
Elec.fee: AC					cost,NT$	
5.5		AC_elec	6.48	kW/room		
COP			104	kWh per day	363	14.9%
			0.017	kWh/day/plant		
			1.037	kWh/day/m2 room		
			3111	kWh per month	10889	
			37853	kWh per year	132,487	
Capacity of AC required			10.128	RT, Note: 3.52 kW per Refri. Ton		

Operating cost (CO2 + AC & Light Elec)						
	Ratio of OP cost			per day	2434	NT$
ACH	CO2	Light elec	AC elec	per month	73,034	NT$
0.01	1.27%	83.8%	14.9%	per year	888,579	NT$

EY	100	g/kWh
Yield	58.3	kg/day
	1749	kg/month
	20989	kg/year

整廠模擬的輸出結果
(ACH = 0.01, indoor CO_2 = 800 ppm, COP = 5.5)

日產能 (Daily Yield, DY, in kg)

DY = EY x DPC / 1000

栽培作物的能源產能 (Energy Yield, EY, in $g.kWh^{-1}$)
日總耗電 (Daily Power Consumption, DPC, in $kWh.day^{-1}$)

EY = 100 $g.kWh^{-1}$、DPC = 583 $kWh.day^{-1}$
DY = 58.3 kg,day^{-1} = 1.749 噸/month = 21 噸/Year

更多學習

第7章：蒸散

第8章：淨光合速率

光呼吸、暗呼吸、光合速率

栽培面積的計算導入栽培層數與空間利用率的概念，
栽培株數以單位面積的栽培密度為基準，
由此算出全場的總株數，也增加 LAI 的計算

Cultivation Room

Room length	10	m	space utilization	0.5		Leaf area/plant	0.1	m2/plt
Room width	10	m	No. of layers	4		Number of plants	6000	plt/room
Room height	4	m	Culture area	200	m2	Total leaf area	600	m2
Room volume	400	m3	Cropping density	30	plts/m2	LAI	3	

Tr = 6.9, Leaf area/plant = 0.1, No. of plants = 6000

T_R = 6.9 x 0.1 x 6000 = 4140 mg/s/room

燈光所涉及熱能的計算方式

增加輸入每日光照時數，允許光照成本的計算
燈管使用數量的計算，以單位面積使用的燈管數量為計算基礎

Lighting									
W per LEDtube	20	W/lamp	Number of LEDtubes	1818			PAR	54	W/m2
No.LEDtube/layer	6		PPFD	250	µmol/m^2/s		DLI	14.4	mol/m2/day
Bench area per layer	0.66	m2	Light Period	16	h/day	Power consump. / cural area		181.82	W/m2
Total W of other equip (W_e)			80	W/room			Total W of lamps	36360.00	W/room

栽培面積 200 m^2，No. LEDs = 6 * 200 / 0.66 = 1818 支燈管
單位栽培面積耗電瓦數 = 6 x 20 / 0.66 = 181.82 W/m^2
燈光耗電總瓦數 = 20 x 1818 = 36360 W/room

CO2 balance	C_N = 0.71 x 0.1 x 6000 = 426 mg/s/room		
	CO2 supply to room (C_S)	443.67	mg/(s.room)
	Net photos. rate in room (C_N)	428.48	mg/(s.room)
	CO2 loss by ventilation (C_V)	15.19	mg/(s.room)
	$C_S = C_N + C_V$		
Water balance	T_R = 6.9 x 0.1 x 6000 = 4140 mg/s/room		
	Transpiration rate of room (T_R)	4140.1	mg/(s.room)
	(De)Humidification (H)	-3965.8	mg/(s.room)
	Water loss by ventilation (V_W)	174.3	mg/(s.room)
	$T_R+H = V_W$	V_w = 0.1 * 15.7 * 400 / 3.6 = 174.4	
Energy balance			
	k (conductivity of walls) =	0.1	
	Total W of lamps (W_L)	36363.6	W/room
	Total W of other equipment (W_e)	80	W/room
	Heat loss by ventilation (Qv)	703.4	W/room
	Heat loss by conduction (Qc)	720	W/room
	Heat carry away by AC (Qa)	35020.2	W/room
	Qv = 0.1 * 400 * 55.35 * 1.14 / 3.6 = 701 W		
	$W_L + W_e = Qv + Qc + Qa$		
	Qc = 0.1 * 2*(10*10+20*4) * (25-5)= 720 W		

分析結果分三部分彙整

二氧化碳平衡：

可求所需提供的二氧化碳施肥速率
可進而求出二氧化碳施肥成本

水分平衡：

可求出所需除溼機的除溼能力與耗電
可進而求出除溼機的耗電成本

能量平衡：

可求出空調設備的降溫能力與耗電
可進而求出空調設備的耗電成本

增加三項輸入參數

二氧化碳的成本
每kWh 的電價
空調設備的性能係數 COP

所需空調的冷卻能力

三項設備的單日、每月與年操作成本的彙整與占比的比較
單日單株成本、單位用地面積成本

CO2 Price				kg CO2	cost,NT$	Ratio
20		CO2 used	per day	36.95	739	21.52%
NT$/kg			/day/plant	0.0062	0.1232	
			/day/m2 roon	0.3695		
			per month	1108.46	22169	
			per year	13486.23	269,725	
Elec.fee: Light					cost,NT$	
3.5		Light elec	36.44	kW/room		
NT$/kWh			583	kWh per day	2041	59.4%
	Light Period		0.097	kWh /day/plant		
	16		5.83	kWh/day/m2 room		
			17491	kWh per month	61,219	
			212810	kWh per year	744,834	
Elec.fee: AC					cost,NT$	
3		AC_elec	11.67	kW/room		
COP			187	kWh per day	654	19.0%
			0.031	kWh/day/plant		
			1.868	kWh/day/m2 room		
			5603	kWh per month	19609	
			68166	kWh per year	238,580	
Capacity of AC required			9.948	RT, Note: 3.52 kW per Refri. Ton		

Operating cost (CO2 + AC & Light Elec)						
	Ratio of OP cost			per day	3433	NT$
ACH	CO2	Light elec	AC elec	per month	102,998	NT$
0.1	21.52%	59.4%	19.0%	per year	37,594,135	NT$

CO2 balance

CO2 supply to room (C_S)	26.78	mg/(s.room)
Net photos. rate in room (C_N)	26.06	mg/(s.room)
CO2 loss by ventilation (C_V)	0.72	mg/(s.room)
$C_S = C_N + C_V$		

Water balance

Transpiration rate of room (T_R)	3191.1	mg/(s.room)
(De)Humidification (H)	-3173.7	mg/(s.room)
Water loss by ventilation (V_W)	17.4	mg/(s.room)
$T_R + H = V_W$		

Energy balance

k (conductivity of walls) = 0.1

Total W of lamps (W_L)	36360.0	W/room
Total W of other equipment (W_e)	80	W/room
Heat loss by ventilation (Qv)	70.3	W/room
Heat loss by conduction (Qc)	720	W/room
Heat carry away by AC (Qa)	35649.7	W/room
$W_L + W_e = Qv + Qc + Qa$		

CO2 Price				kg CO2	cost,NT$	Ratio
20		CO2 used	per day	1.54	31	1.13%
NT$/kg			/day/plant	0.0003	0.0051	
			/day/m2 room	0.0154		
			per month	46.27	925	
			per year	562.94	11,259	

Elec.fee: Light					cost,NT$	
3.5		Light elec	36.44	kW/room		
NT$/kWh			583	kWh per day	2041	74.6%
	Light period		0.097	kWh /day/plant		
	16		5.83	kWh/day/m2 room		
			17491	kWh per month	61,219	
			212810	kWh per year	744,834	

Elec.fee: AC					cost,NT$	
3		AC_elec	11.88	kW/room		
COP			190	kWh per day	665	24.3%
			0.032	kWh/day/plant		
			1.901	kWh/day/m2 room		
			5704	kWh per month	19964	
			69398	kWh per year	242,893	

Capacity of AC required: 10.128 RT, Note: 3.52 kW per Refri. Ton

Operating cost (CO2 + AC & Light Elec)						
	Ratio of OP cost			per day	2737	NT$
ACH	CO2	Light elec	AC elec	per month	82,108	NT$
0.01	1.13%	74.6%	24.3%	per year	998,985	NT$

EY	100	g/kWh
Yield	58.3	kg/day
	1749	kg/month
	20989	kg/year

除濕機的規格與電費尚未納入

此部分與空調的除濕有部分重疊

HW：以預設數值為基準

- 室內的二氧化碳濃度由400 提高到1200 ppm，成本會增加多少，光合速率會增加多少?
- ACH 由0.01 提高到 0.2，二氧化碳施肥的成本會提高多少?
- 室內維持20 ºC，室外溫度由 5 提高到25 ºC ，同時ACH 由0.01 至0.2，換氣影響的成本又會如何?
- 其它 …

THE END

兩個版本的比較

千葉大學 vs. 台大

Plant

Plant type (light)	Std.		Plant type (CO2)	Std.			
Kl	100		GI	0.10			
Kc	440	mg/m³	Gc	0.79			
CO2 in chloroplast	848.7	ppm =	1663.4	mg/m³			
Tm	25	˚C	GTl	1.00	Photosynthesis	0.16	mg/(m²s)
a	5		Kpr	0.12	Photorespiratio	0.02	mg/(m²s)
Rd (20C)	0.07	mg/(m²s)	Rd	0.10	mg/(m²s) Net Photos.	0.04	mg/(m²s)

千葉大學的版本

Environment

Temp. in	25	˚C	RH in	80	%	Vds in	18.4	g/m3
Temp. out	5	˚C	RH out	40	%	Vds out	2.7	g/m3
CO2 in	1000	ppm	1799.5	mg/m³		Rlv	1059.7	s/m
CO2 out	380	ppm	733.0	mg/m³		Rav	100.0	s/m
Wind	1	m/s				Inc. of Rlv	306.0	s/m
						TR	3.14	mg/(m²s)

Culture room

Room length	10	m	Room width	10	m	Room height	5	m
Room volume	500.0	m3/room	Culture area	200	m2	A	0.02	1/h
LA per plant	0.02	m2/plant	Num. of plants	100	plants/room			

Lighting

Lamp type	INF		Num. of lamps	200	lamps/room	PPF	51.5	μmol/(m2 s)
W per lamp	40	W/lamp	U	0.8		PAR	11.2	W/m²
F	3500	lm/lamp	M	0.8		Total W of lamp	8000	W/room
We	80	W/room						

CO2 Balance

CO2 supply to room(CS)	3.0	mg/(s room)
Net photos. rate in a room(CN)	0.1	mg/(s room)
CO2 loss by ventiration(CV)	3.0	mg/(s room)

$$Cs = C_N + C_V$$

Water Balance

3.14 * 0.02 * 100 = 6.28 mg/s/room

Transpiration rate of room(TR)	6.3	mg/(s room)
Humidification(H)	37.3	mg/(s room)
Water loss by ventiration(VW)	43.6	mg/(s room)
Dehumidification(D)	0.0	mg/(s room)

$$T_R + H = D + V_W$$

Energy Balance

Total W of lamps	8000	W/room
Total W of other equipment	80	W/room
Heat loss by ventiration(QV)	176	J/(s room)
Heat loss by conduction(QC)	800	J/(s room)
Heat carried away by AC(QA)	7104	J/(s room)

$$W_L + W_e = Q_V + Q_c + Q_a$$

主要差異

台大版本

- ✓ 增加全廠栽培株數的計算
- ✓ 更改燈光配置與能耗計算方式
- ✓ 增加葉溫的輸入

  計算蒸散時使用的VDD，以 葉片內與空氣的水汽密度差為準，不是以飽和空氣與空氣的水氣密度差為基準。千葉大學版本假設 葉溫 = 氣溫，所以不需輸入葉溫。
- ✓ 增加 TE 效率 與 LAI 的計算
- ✓ 增加燈光、空調、二氧化碳成本的計算與成本占比的比較

- It is always important to know what kind of lights will be used and how many of them are necessary.
- What are the light quality, duration and intensity required?
- Factors affecting light intensity on the surface of plants:
  1. Distance between lights and plants.
  2. Presence of light reflectors.
  3. Performance of light reflectors
  4. Surrounding environment, such as spacing among plants, color of walls or ceilings, distance of plants and walls, etc.
- An empirical equation is used in the area of architecture or lighting which calculate the light intensity with various light sources or room shapes.

燈光在此僅作為室內照明
不見得適用於植物栽培

$$E = \frac{F \times U \times M \times n}{R_A}$$

由 lux 計算適合嗎?

E : Average light intensity, lx
F : Luminous outputs per lamp, lm
U : Coefficient of utilization
M : Maintenance factor
n : Number of lamps, number
RA : Culture area, m2

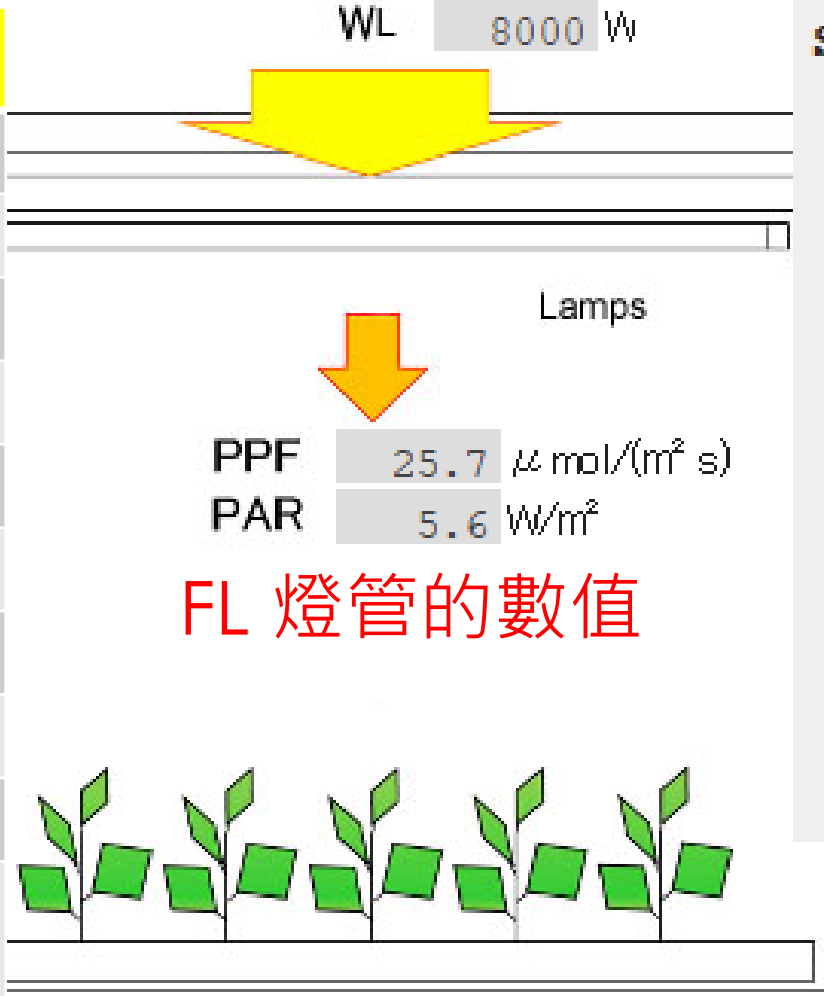
Coefficient of utilization can be obtained froma chart of coefficient of utilization with given room index and reflection ratio.

$$R = \frac{R_L \times R_W}{R_H \times (R_L + R_W)}$$

R : Room index

R_L, R_W, R_H: Room length, width, height, m

2240 lux =	PPFD
Fluorescent lamp 5000K	**30.22**
Natural daylight	**39.65**
Halogen lamp 3000K	**77.47**
High CRI LED 6500K	**38.6**
High CRI LED 4000K	**39.92**
HPS 2000K	**29.06**
Red LED 650 nm	**172.14**
Blue LED 450 nm	**258.84**
Red+Blue LED	**198.76**
Red+Blue+White LED 450+650nm+3500K	**57.54**



FL 燈管的數值

Simulation

W per lamp	40	W/lamp
F	3500	lm/lamp
Num. of lamps	200	lamps/room
U	0.8	
M	0.8	
Culture area	200	m2
PPF	25.7	μmol/(m2 s)
PAR	5.6	W/m2
Total W of lamps	8000	W/room

The coefficient of utilization (U): The % of light irradiated from light sources reaches the surface of plants. It is estimated 70% in efficient PAL.

The maintenance factor (M) accounts for deterioration of light sources by aging. A number of 60% for fluorescent lamps that have been used for a few year.

Fluorescent lamp only

由 lux 轉換為光量子數與輻射能，可信嗎?

assumed that 87 lx is equal to 1 μmol/(m2 s) or 0.218 W/m2.

WL (total W of lamps)= W/lamp*n

= 40 *200=8000 W

$E = (F\ U\ M\ n)/R_A$

= 3500*0.8*0.8*200/200

= 2240 lm/m^2 = 2240 lux

PPF = E/**87** = 25.7 $\mu mol/m^2/s$

PAR=PPF/**4.589** = 5.6 W/m^2

台大版本增加葉溫輸入功能，允許空氣溫度與葉溫不同的計算，蒸散的計算改成以葉溫為準

Environment

	Temperatu	RH		density = 1/SV	Vps	ah	enthalpy,kJ/kg			
Leaf (oC)	25	RHleaf,%	100	1.14	3.17			Vds leaf	23.0	g/m3
indoor (oC)	25	RHin,%	80	1.14	3.17	0.016	65.77	Vd in	18.4	g/m3
outdoor (°C)	5	RHout,%	40	1.23	0.87	0.002	10.42	VDD	4.6	g/m3
CO2 indoor (ppm)	1200	-> mg/m3	2157.5	1.80				Vd out	2.7	g/m3
CO2 outdoor (ppm)	410	-> mg/m3	790.2	1.93				Rav	100.0	s/m
Wind (m/s)	1	m/s	CropType	high	std	low		Rlv	200.0	s/m
			Rlv =	300	200	100		Rlv.inc	366.9	s/m
ACH	0.02	1/h	CropType	std	low			Rv.total	666.9	s/m
			Rlv.inc =	366.9	183.5			TR	6.90	mg/(m2.s)

dh = 65.77 – 10.42 = 55.35 kJ/kg
Vol = 400, ACH = 0.02, density = 1.14
dh per room = 0.02 * 400 * 55.35 * 1.14 / 3.6 = 140.22
If ACH = 0.1, dh per room = 140.22 * 5 = 701 W/room

dVd = (18.4 – 2.7) = 15.7 g/m3, ACH = 0.1
Water loss by ventilation = 0.1 * 15.7 * 400 / 3.6 = 174.4 mg/s/room

允許選擇不同作物種類：針對輻射量有三個選項，針對二氧化碳濃度有兩個選項
程式可自動選擇計算使用的參數值