Ch. 4 Steady state thermal analysis
穩態熱傳分析

Steady-state thermal analysis is evaluating the thermal equilibrium of a system in which the temperature remains constant over time. In other words, it involves assessing the equilibrium state of a system subject to constant heat loads and environmental conditions

方煒 Wei FANG
NTU_BME and Global ATGS
National Taiwan University

前言

本章旨在介紹農業建築的各個組成單元的穩態熱傳計算，包括**透過**

牆面/天花板/窗/門/地板/地下室牆面與地面的熱傳導

各種牆面

Appendix 4-1, at p399

APPENDIX 4-1

SKETCHES OF COMMON WALL CONSTRUCTION TYPES

Taken in part from the 1985 ASHRAE Handbook of Fundamentals,

American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA

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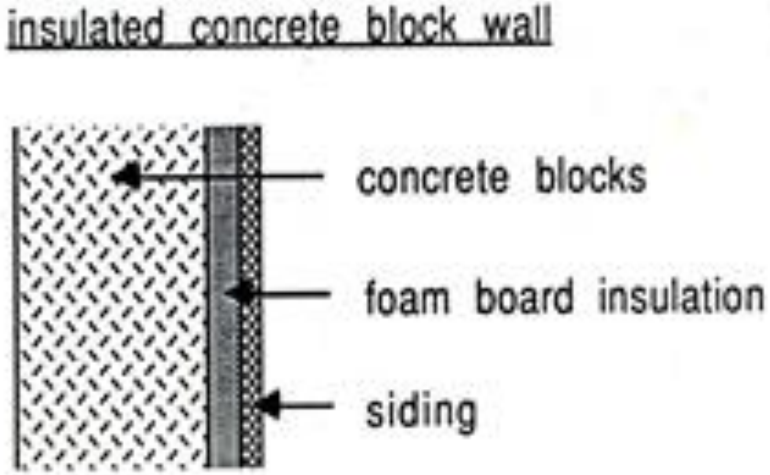
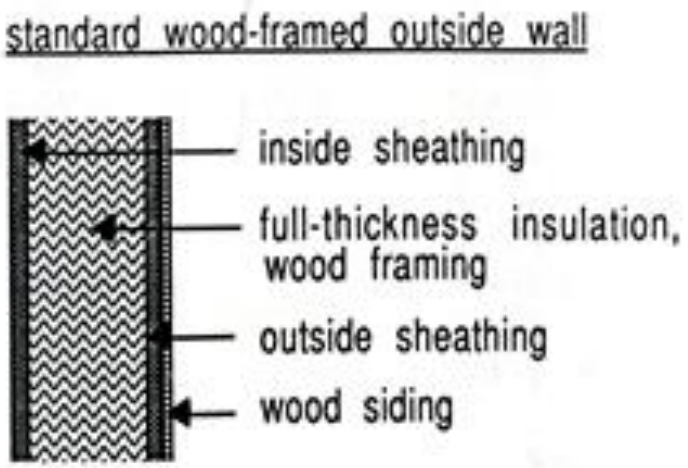
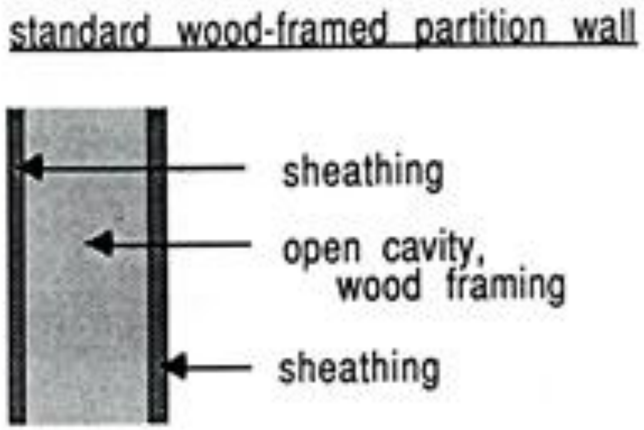
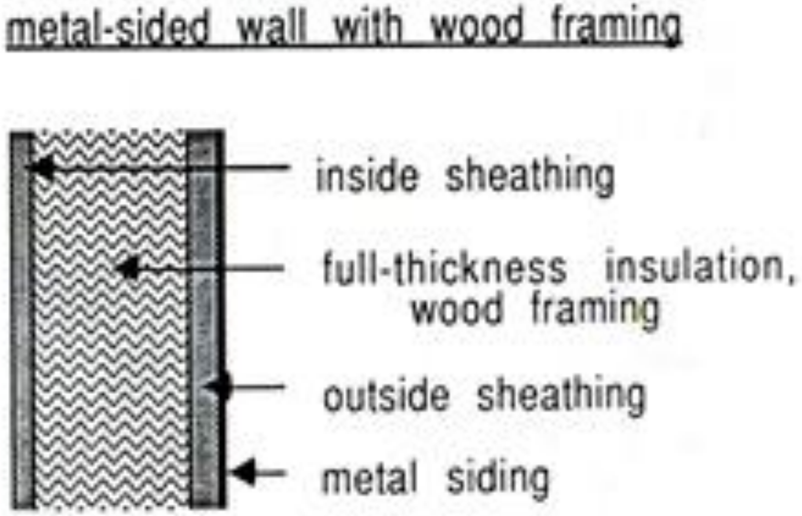
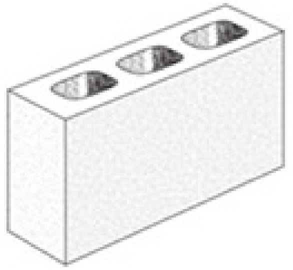




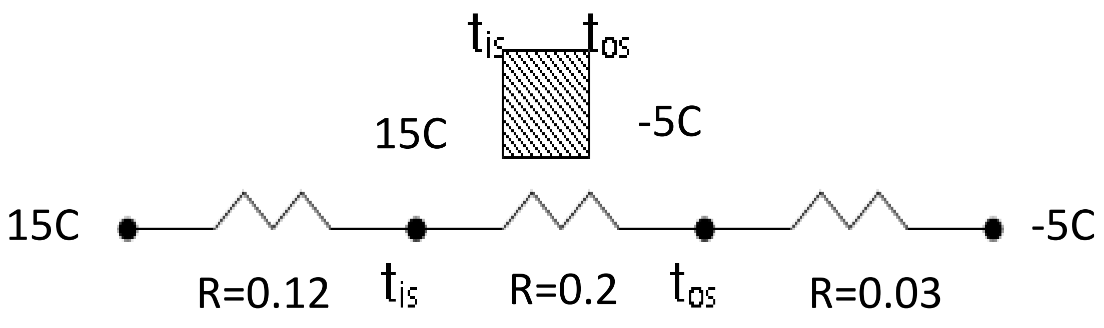




透過牆面的熱傳導

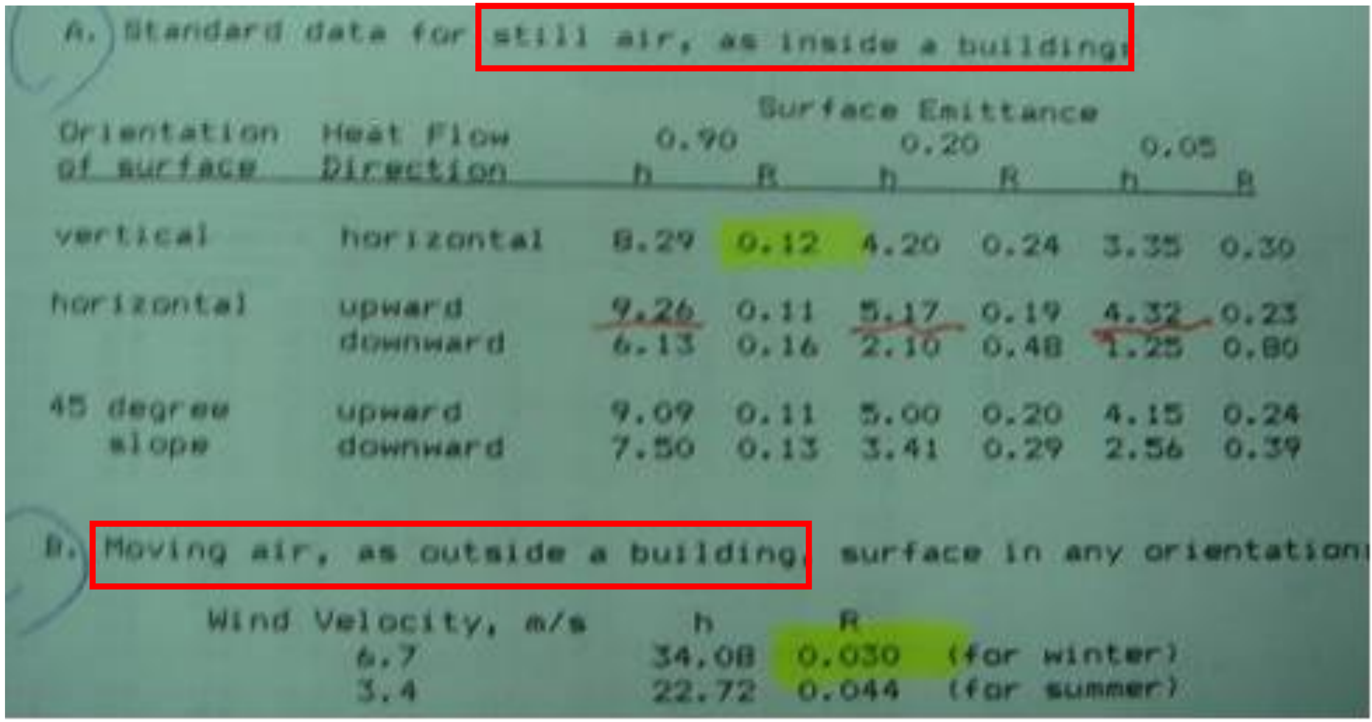


Ex. 4-1 某牛舍使用 203.2 mm 厚度的水泥磚(三橢圓孔)做牆壁，請估算R值以及內外牆的表面溫度，假設室內外溫度分別為 15 與 -5 °C。The walls of a dairy barn have constructed of (three oval core) concrete blocks 203.2 mm thick (8 in. blocks). Determine the R-value of the wall and estimate the temperatures of the inside and outside surfaces when it is 15 °C indoors and -5 °C outdoors.



t_{is} = 15- (0.12/ 0.35)(15 – (-5)) = 8.1 C

t_{os} = 15 – ((0.12 + 0.20) / 0.35)(15 – (- 5)) = - 3.3 C



A. Standard data for still air, as inside a building:

Orientation of surface	Heat Flow Direction	Surface Emittance 0.90 h	0.90 R	0.20 h	0.20 R	0.05 h	0.05 R
vertical	horizontal	8.29	0.12	4.20	0.24	3.35	0.30
horizontal	upward	9.26	0.11	5.17	0.19	4.32	0.23
	downward	6.13	0.16	2.10	0.48	1.25	0.80
45 degree slope	upward	9.09	0.11	5.00	0.20	4.15	0.24
	downward	7.50	0.13	3.41	0.29	2.56	0.39

B. Moving air, as outside a building, surface in any orientation:

Wind Velocity, m/s	h	R	
6.7	34.08	0.030	(for winter)
3.4	22.72	0.044	(for summer)

Appendix 3-2, at p388 典型農用建築材料與保溫材料的熱傳性質

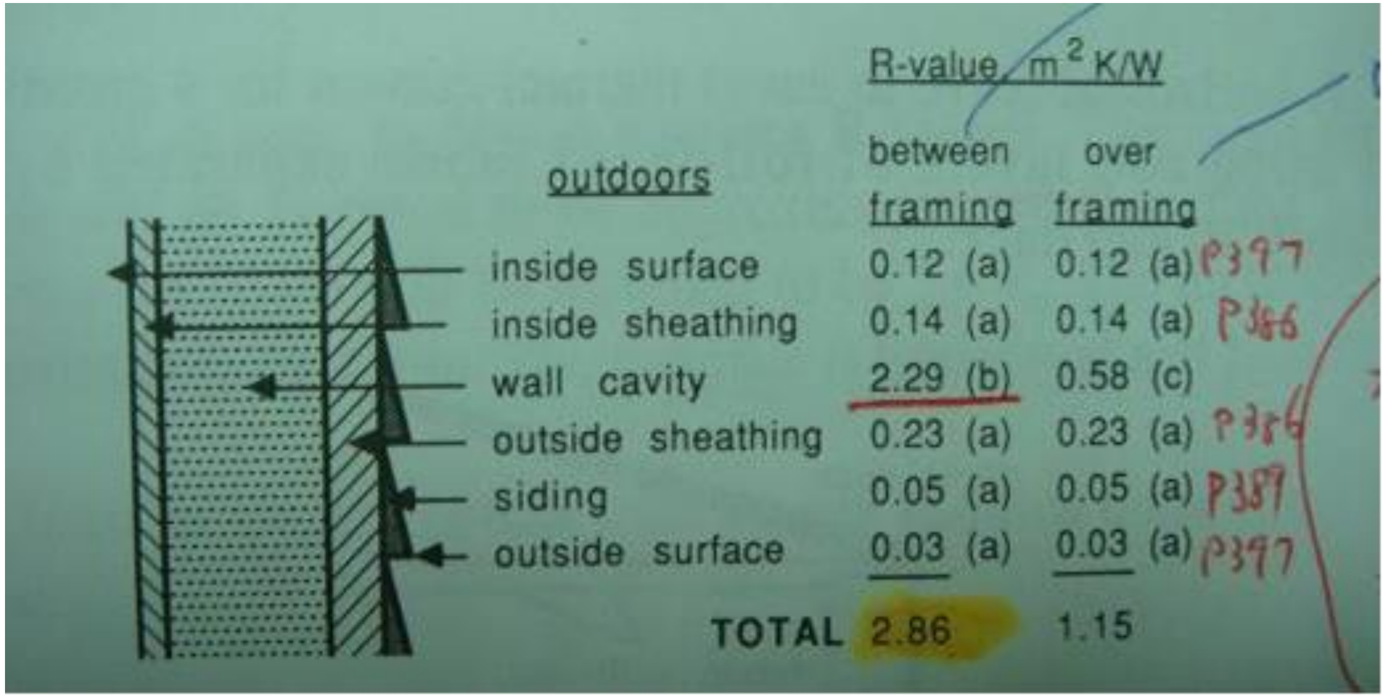
Thermal Properties of Typical Building and Insulating Materials—Design Values*

Description	Density kg/m³	Conductivity (λ) W/m·°C	Conductance (C) W/m²·°C	Resistance (R) Per meter thickness	Resistance (R) For thickness listed	Specific Heat kJ/(kg·°C)
PLASTERING MATERIALS 粉刷材料						
Sand aggregate	1680	0.806	—	*1.25*	—	0.84
Sand aggregate 12.70 mm	1680	—	63.05	—	*0.016*	
Sand aggregate 15.88 mm	1680	—	51.69	—	*0.019*	
Sand aggregate on metal lath 19.05 mm	—	—	43.74	—	*0.023*	
Vermiculite aggregate	720	0.245	—	*4.09*	—	
MASONRY MATERIALS 石材						
Concretes						
Cement mortar	1856	0.720	—	*1.39*	—	
Gypsum-fiber concrete 87.5% gypsum, 12.5% wood chips	816	0.239	—	*4.16*	—	0.88
Lightweight aggregates including expanded shale, clay or slate; expanded slags; cinders; pumice; vermiculite; also cellular concretes	1920	0.749	—	*1.32*	—	
	1600	0.518	—	*1.94*	—	
	1280	0.360	—	*2.78*	—	
	960	0.245	—	*4.09*	—	
	640	0.166	—	*5.97*	—	
	480	0.130	—	*7.70*	—	
	320	0.101		*9.92*		
Perlite, expanded	640	0.134		*7.50*		
	480	0.102		*9.79*		
	320	0.072		*13.88*		1.34
Sand and gravel or stone aggregate (oven dried)	2240	1.296	—	*0.76*		0.92
Sand and gravel or stone aggregate (not dried)	2240	1.728	—	*0.56*		
Stucco	1856	0.720	—	*1.39*		

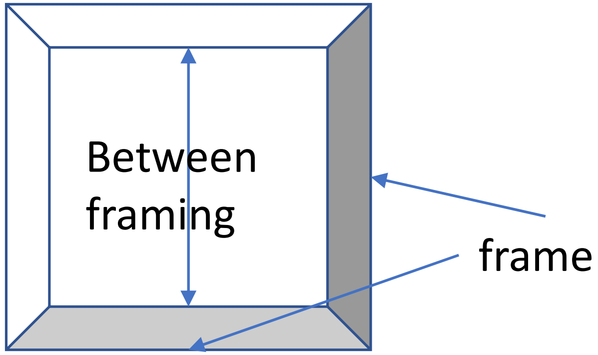
Thermal Properties of Typical Building and Insulating Materials—Design Values*

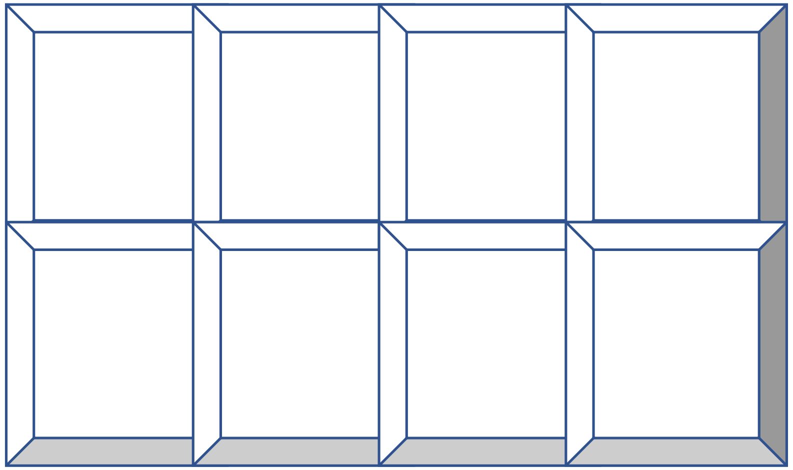
Description	Density kg/m³	Conductivity (λ) W/m·°C	Conductance (C) W/m²·°C	Resistance (R) Per meter thickness	Resistance (R) For thickness listed	Specific Heat kJ/(kg·°C)
MASONRY UNITS 石材元件						
Brick, common[f]	1920	0.720	—	*1.39*	—	0.80
Brick, face[f]	2080	1.296	—	*0.76*	—	
Clay tile, hollow:						
1 cell deep 76.2 mm	—	—	7.10	—	*0.14*	0.88
1 cell deep 101.6 mm	—	—	5.11	—	*0.20*	
2 cells deep 152.4 mm	—	—	3.75	—	*0.27*	
2 cells deep 203.2 mm	—	—	3.07	—	*0.33*	
2 cells deep 254.0 mm	—	—	2.56	—	*0.39*	
3 cells deep 304.8 mm	—	—	2.27	—	*0.44*	
Concrete blocks, three oval core:						
Sand and gravel aggregate 101.6 mm	—	—	7.95	—	*0.12*	0.92
203.2 mm	—	—	5.11	—	*0.20*	
304.8 mm	—	—	4.43	—	*0.23*	
Cinder aggregate 76.2 mm	—	—	6.59	—	*0.15*	0.88
101.6 mm	—	—	5.11	—	*0.20*	
203.2 mm	—	—	3.29	—	*0.30*	
304.8 mm	—	—	3.01	—	*0.33*	
Lightweight aggregate 76.2 mm	—	—	4.49	—	*0.22*	0.88
expanded shale, clay, slate 101.6 mm	—	—	3.81	—	*0.26*	
or slag; pumice 203.2 mm	—	—	2.84	—	*0.35*	
304.8 mm	—	—	2.50	—	*0.40*	
Concrete blocks, rectangular core.[g]						
Sand and gravel aggregate						
2 core,[h] 203.2 mm, 16.3 kg	—	—	5.45	—	*0.18*	0.92
Same with filled cores[i]	—	—	2.95	—	*0.34*	0.92
Lightweight aggregate (expanded shale, clay, slate or slag, pumice):						
3 core,[h] 152.4 mm, 8.6 kg	—	—	3.46	—	*0.29*	0.88
Same with filled cores[i]	—	—	1.87	—	*0.53*	
2 core,[h] 203.2 mm, 10.9 kg	—	—	2.61	—	*0.38*	
Same with filled cores[i]	—	—	1.14	—	*0.89*	
3 core,[h] 304.8 mm, 17.3 kg	—	—	2.27	—	*0.44*	
Same with filled cores[i]	—	—	0.97	—	*1.02*	
Stone, lime or sand	—	1.800	—	*0.56*	—	0.80
Gypsum partition tile:						
76.2 · 304.8 · 762.0 mm, solid	—	—	4.49	—	*0.22*	0.80
76.2 · 304.8 · 762.0 mm, 4-cell	—	—	4.20	—	*0.24*	
101.6 · 304.8 · 762.0 mm, 3-cell	—	—	3.41	—	*0.29*	

Ex. 4-2 如下圖所示，某木框牆內側(inside sheathing)使用15.88 mm 厚Douglas fir plywood三夾板，外側(outside sheathing)使用12.7 mm 厚一般密度的蔬菜纖維板外加11.11 mm 厚硬木板做裝飾外牆 (siding)。內外側之間的空間填以保溫的玻璃棉。假設在冬天所需要的熱阻是 2 m^2K/W，請問是否需填滿整個空間或者是只需填入較小的厚度？ 木框由 88.9 mm 厚，38.1 mm 寬 (2 x 4 牆框木條)組成 。



outdoors	R-value, m^2 K/W between framing	over framing
inside surface	0.12 (a)	0.12 (a) P397
inside sheathing	0.14 (a)	0.14 (a) P386
wall cavity	2.29 (b)	0.58 (c)
outside sheathing	0.23 (a)	0.23 (a) P386
siding	0.05 (a)	0.05 (a) P387
outside surface	0.03 (a)	0.03 (a) P397
TOTAL	2.86	1.15





1 m^2 of Insulated materials: $R_{insulated} = 2.86\ m^2K/W$

0.8 m^2 of Insulated materials and 0.2 m^2 of framing: $R_{overall} = 2.2\ m^2K/W$

$0.8/2.86 + 0.2/1.15 = 1/R_{overall}$

$R_{overall} = 2.2\ m^2K/W$

$0.8/2.86 + 0.2/1.15 = 1/R_{overall}$

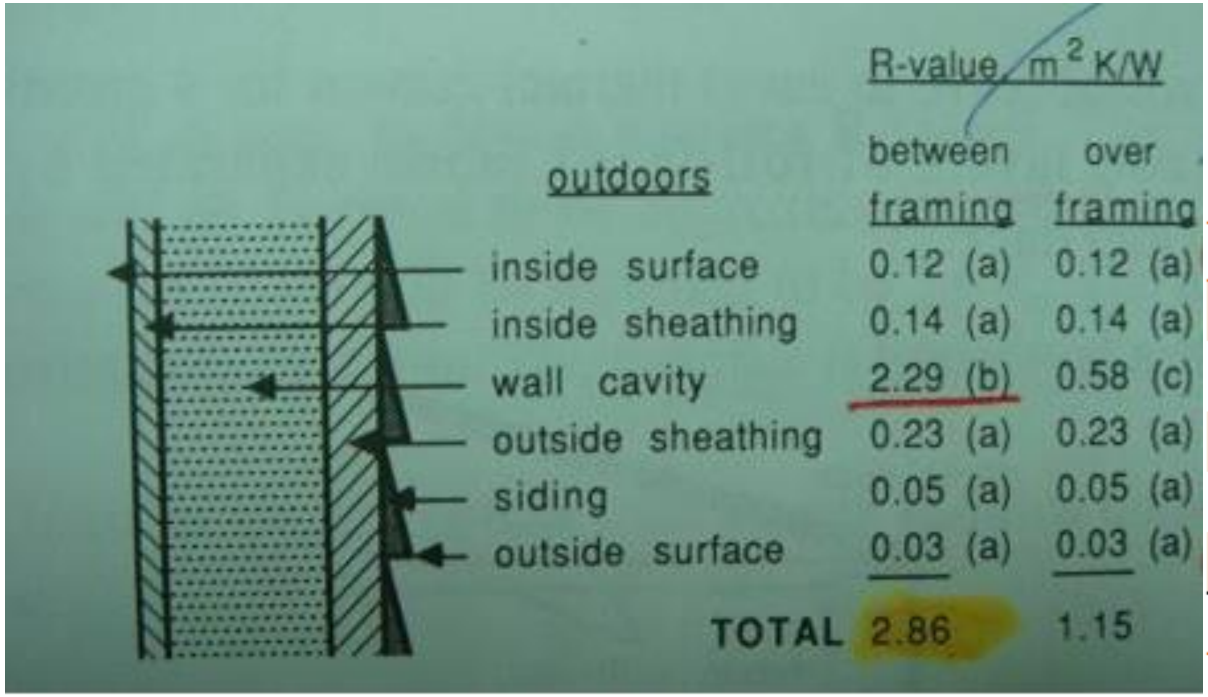
$R_{overall} = 2.2\ m^2K/W$

$0.8/X + 0.2/1.15 = 1 / 2.0$

$X = 2.45\ m^2K/W$

若$R_{overall} = 2.0\ m^2K/W$ 則$R_{insulated} = 2.45\ m^2K/W$ 即可，可減少0.41 m^2K/W。

因只有中空部份(cavity)的 R值為可調，所以由 2.29 減少0.41，得 1.88 m^2K/W。



outdoors	R-value, m^2 K/W between framing	over framing
inside surface	0.12 (a)	0.12 (a)
inside sheathing	0.14 (a)	0.14 (a)
wall cavity	2.29 (b)	0.58 (c)
outside sheathing	0.23 (a)	0.23 (a)
siding	0.05 (a)	0.05 (a)
outside surface	0.03 (a)	0.03 (a)
TOTAL	2.86	1.15

0.12
0.14
1.88
0.23
0.05
0.03
2.45

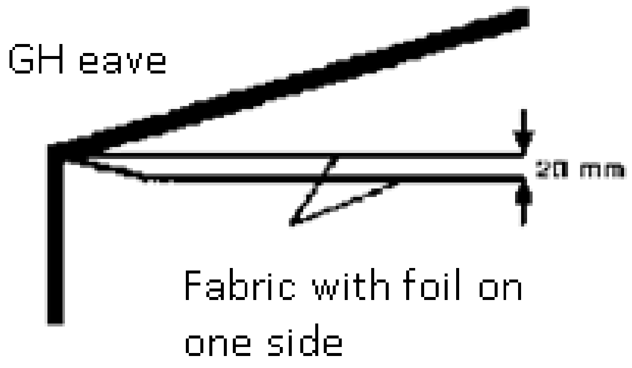
$0.8/2.45 + 0.2/1.15 = 1/R_{overall}$

$R_{overall} = 2.0$

Ex. 4-3 某溫室內安裝於屋簷高度的水平方向的保溫簾 (thermal curtain) 使用兩層單側織上鋁箔 (foil-faced fabric) 的平織(loose-weave) 膠膜間隔 20 mm。假設膠膜厚度不考慮，鋁箔面的表面輻射率為 0.2，另一側為0.6，兩層膠膜可有四種安裝方式：

1. 鋁箔都朝上
2. 鋁箔都朝下
3. 上層膠膜鋁箔朝上，下層膠膜鋁箔朝下
4. 上層膠膜鋁箔朝下，下層膠膜鋁箔朝上

哪一種有最大的R值?



Appendix 3-5, p397. Surface resistance

$$h_s = 4.02 + 5.82\varepsilon \quad \ldots[4\text{-}1]$$

top/bottom surface 的熱阻 $R = 1/h_s$

ε	h_s	R
0.2	5.18	0.19
0.6	7.51	0.13

Plain air space 的有效輻射率 (effective emittance)

ε, side one	ε, side two	effective emittance
0.20	0.20	0.11
0.60	0.60	0.43
0.20	0.60	0.18

已知 effective emittance

由Appendix 3-6, p398. 可透過內插法查到 R value of the Airspace

假設 Air space 的平均溫度10 ºC，溫差 5.6 ºC，Air space 19.1 mm 為最接近給定的20 mm

當 effective emittance (value of E) = 0.11 (in between 0.05 and 0.2)

R = 0.39 + (0.11 – 0.05)(0.30 – 0.39)/(0.20 – 0.05) = 0.35 m2K/W

當 E = 0.43 (in between 0.2 and 0.5), R = 0.30 + (0.43 – 0.20)(0.20 – 0.30)/(0.50 – 0.20) = 0.22 m2K/W

當 E = 0.18 (in between 0.05 and 0.2), R = 0.39 + (0.18 – 0.05)(0.30 – 0.39)/(0.20 – 0.05) = 0.31 m2K/W

Orientation of foil face		R-values			
top layer	bottom layer	top surface	bottom surface	air space	total
up	up	0.19	0.13	0.31	0.63
down	down	0.13	0.19	0.31	0.63
up	down	0.19	0.19	0.22	0.60
down	up	0.13	0.13	0.35	0.61

結論：
前兩種方式
(同上或同下)
都有最大的熱阻

Appendix 3-6, p398.

THERMAL RESISTANCES OF PLANE AIR SPACES

Taken from the 1985 ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA

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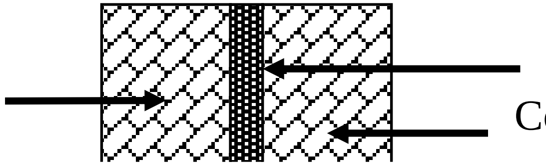
Table 2A Thermal Resistances of Plane[a] Air Spaces[b,c]
$m^2 \cdot °C/W$

Position of Air Space	Direction of Heat Flow	Air Space Mean Temp.[d] (°C)	Air Space Temp Diff.[d] (°C)	12.7-mm Air Space[c] Value of E[d,e] 0.03	0.05	0.2	0.5	0.82	19.1-mm Air Space[c] Value of E[d,e] 0.03	0.05	0.2	0.5	0.82
Horiz.	Up	32.2	5.6	0.37	0.36	0.27	0.17	0.13	0.41	0.39	0.28	0.18	0.13
		10.0	16.7	0.29	0.28	0.23	0.17	0.13	0.30	0.29	0.24	0.17	0.14
		10.0	5.6	0.37	0.36	0.28	0.20	0.15	0.40	0.39	0.30	0.20	0.15
		-17.8	11.1	0.30	0.30	0.26	0.20	0.16	0.32	0.32	0.27	0.20	0.16
		-17.8	5.6	0.37	0.36	0.30	0.22	0.18	0.39	0.38	0.31	0.23	0.18
		-45.6	11.1	0.30	0.29	0.26	0.22	0.18	0.31	0.31	0.27	0.22	0.19
		-45.6	5.6	0.36	0.35	0.31	0.25	0.20	0.38	0.37	0.32	0.26	0.21
45° Slope	Up	32.2	5.6	0.43	0.41	0.29	0.19	0.13	0.52	0.49	0.33	0.20	0.14
		10.0	16.7	0.36	0.35	0.27	0.19	0.15	0.35	0.34	0.27	0.19	0.14
		10.0	5.6	0.45	0.43	0.32	0.21	0.16	0.51	0.48	0.35	0.23	0.17
		-17.8	11.1	0.39	0.38	0.31	0.23	0.18	0.37	0.36	0.30	0.23	0.18
		-17.8	5.6	0.46	0.45	0.36	0.25	0.19	0.48	0.46	0.37	0.26	0.20
		-45.3	11.1	0.37	0.36	0.31	0.25	0.21	0.36	0.35	0.31	0.25	0.20
		-45.6	5.6	0.46	0.45	0.38	0.29	0.23	0.45	0.43	0.37	0.25	0.23
Vertical	Horiz.	32.2	5.6	0.43	0.41	0.29	0.19	0.14	0.62	0.57	0.37	0.21	0.15
		10.0	16.7	0.45	0.43	0.32	0.22	0.16	0.51	0.49	0.35	0.23	0.17
		10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.65	0.61	0.41	0.25	0.18
		-17.8	11.1	0.50	0.48	0.38	0.26	0.20	0.55	0.53	0.41	0.28	0.21
		-17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.66	0.63	0.46	0.30	0.22
		-45.6	11.1	0.51	0.50	0.41	0.31	0.24	0.51	0.50	0.42	0.31	0.24
		-45.6	5.6	0.56	0.55	0.45	0.33	0.26	0.65	0.63	0.51	0.36	0.27
45° Slope	Down	32.2	5.6	0.44	0.41	0.29	0.19	0.14	0.62	0.58	0.37	0.21	0.15
		10.0	16.7	0.46	0.44	0.33	0.22	0.16	0.60	0.57	0.39	0.24	0.17
		10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.67	0.63	0.42	0.26	0.18
		-17.8	11.1	0.51	0.49	0.39	0.27	0.20	0.66	0.63	0.46	0.30	0.22
		-17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.73	0.69	0.49	0.32	0.23
		-45.6	11.1	0.56	0.54	0.44	0.33	0.25	0.67	0.64	0.51	0.36	0.28
		-45.6	5.6	0.57	0.56	0.45	0.33	0.26	0.77	0.74	0.57	0.39	0.29
Horiz.	Down	32.2	5.6	0.44	0.41	0.29	0.19	0.14	0.62	0.58	0.37	0.21	0.15
		10.0	16.7	0.47	0.45	0.33	0.22	0.16	0.66	0.62	0.42	0.25	0.18
		10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.68	0.63	0.42	0.26	0.18
		-17.8	11.1	0.52	0.50	0.39	0.27	0.20	0.74	0.70	0.50	0.32	0.23
		-17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.75	0.71	0.51	0.32	0.23
		-45.6	11.1	0.57	0.55	0.45	0.33	0.26	0.81	0.78	0.59	0.40	0.30
		-45.6	5.6	0.58	0.56	0.46	0.33	0.26	0.83	0.79	0.60	0.40	0.30

Ex. 4-4 蘋果冷藏庫的設計目標是要達到 2.5 m^2K/W 的熱阻值，已知內外牆使用 101.1 mm 厚的水泥磚，中間需要使用多厚的PU 發泡板 (polyurethane foam boards) 為絕熱材料？
Design the wall using steady-state analysis to meet this goal.

Concrete blocks



Foam insulation

Concrete blocks

- h Inside surface resistance: 0.12
- k Concrete block resistance: 0.12 (check 右表紅框)
- k Concrete block resistance: 0.12 (check 右表紅框)
- h outside surface resistance: 0.03 sum = 0.39 m^2K/W

$0.12 + 0.12 + 0.12 + 0.03 = 0.39\ m^2K/W$

R value of 2.5 m^2K/W is desired.
The insulation must provide $2.5 – 0.39 = 2.11\ m^2K/W$

Thermal Properties of Typical Building and Insulating Materials—Design Values[a]

Description	Density kg/m³	Conductivity (λ) W/m·°C	Conductance (C) W/m²·°C	Resistance (R) Per meter thickness	Resistance (R) For thickness listed	Specific Heat kJ/(kg·°C)
MASONRY UNITS						
Brick, common[f]	1920	0.720	—	1.39	—	0.80
Brick, face[f]	2080	1.296	—	0.76	—	
Clay tile, hollow:						
1 cell deep … 76.2 mm	—	—	7.10	—	0.14	0.88
1 cell deep … 101.6 mm	—	—	5.11	—	0.20	
2 cells deep … 152.4 mm	—	—	3.75	—	0.27	
2 cells deep … 203.2 mm	—	—	3.07	—	0.33	
2 cells deep … 254.0 mm	—	—	2.56	—	0.39	
3 cells deep … 304.8 mm	—	—	2.27	—	0.44	
Concrete blocks, three oval core:						
Sand and gravel aggregate … 101.6 mm	—	—	7.95	—	0.12	0.92
… 203.2 mm	—	—	5.11	—	0.20	
… 304.8 mm	—	—	4.43	—	0.23	
Cinder aggregate … 76.2 mm	—	—	6.59	—	0.15	0.88
… 101.6 mm	—	—	5.11	—	0.20	
… 203.2 mm	—	—	3.29	—	0.30	
… 304.8 mm	—	—	3.01	—	0.33	
Lightweight aggregate … 76.2 mm	—	—	4.49	—	0.22	
expanded shale, clay, slate … 101.6 mm	—	—	3.81	—	0.26	0.88
or slag; pumice … 203.2 mm	—	—	2.84	—	0.35	
… 304.8 mm	—	—	2.50	—	0.40	
Concrete blocks, rectangular core.[g]						
Sand and gravel aggregate						
2 core,[h] … 203.2 mm, 16.3 kg	—	—	5.45	—	0.18	0.92
Same with filled cores[i] …	—	—	2.95	—	0.34	0.92
Lightweight aggregate (expanded shale, clay, slate or slag, pumice):						
3 core,[h] … 152.4 mm, 8.6 kg	—	—	3.46	—	0.29	0.88
Same with filled cores[i] …	—	—	1.87	—	0.53	
2 core,[h] … 203.2 mm, 10.9 kg	—	—	2.61	—	0.38	
Same with filled cores[i] …	—	—	1.14	—	0.89	
3 core,[h] … 304.8 mm, 17.3 kg	—	—	2.27	—	0.44	
Same with filled cores[i] …	—	—	0.97	—	1.02	
Stone, lime or sand …	—	1.800	—	0.56	—	0.80
Gypsum partition tile:						
76.2 · 304.8 · 762.0 mm, solid …	—	—	4.49	—	0.22	0.80
76.2 · 304.8 · 762.0 mm, 4-cell …	—	—	4.20	—	0.24	
101.6 · 304.8 · 762.0 mm, 3-cell …	—	—	3.41	—	0.29	

Appendix 3-2, at p387 典型農用建築材料與保溫材料的熱傳性質

INSULATING MATERIALS

Description	Density kg/m³	Conductivity (λ) W/m·°C	Conductance (C) W/m²·°C	Resistance (R) Per meter thickness	Resistance (R) For thickness listed	Specific Heat kJ/(kg·°C)
Blanket and Batt[b]						
Mineral Fiber, fibrous form processed from rock, slag, or glass						
approx.[c] 76.2–101.6 mm	4.8–32.0	—	0.52	—	*1.94*[b]	
approx.[c] 88.9 mm	4.8–32.0		0.44	—	*2.29*[b]	
approx.[c] 139.7–165.1 mm	4.8–32.0	—	0.30	—	*3.34*[b]	
approx.[c] 152.4–177.8 mm	4.8–32.0		0.26		*3.87*[b]	
approx.[c] 215.9–228.6 mm	4.8–32.0		0.19		*5.28*[b]	
approx. 304.8 mm	4.8–32.0	—	0.15		*6.69*[b]	

Description	Density kg/m³	Conductivity (λ) W/m·°C	Conductance (C) W/m²·°C	Resistance (R) Per meter thickness	Resistance (R) For thickness listed	Specific Heat kJ/(kg·°C)
Board and Slabs 板材與保溫材						
Cellular glass	136	0.050	—	*19.85*	—	0.75
Glass fiber, organic bonded	64–144	0.036	—	*27.76*	—	0.96
Expanded perlite, organic bonded	16.0	0.052	—	*19.29*	—	1.26
Expanded rubber (rigid)	72.0	0.032	—	*31.58*	—	1.68
Expanded polystyrene extruded						
Cut cell surface	28.8	0.036	—	*27.76*	—	1.22
Smooth skin surface	28.8–56.0	0.029	—	*34.70*	—	1.22
Expanded polystyrene, molded beads	16.0	0.037	—	*23.25*	—	—
	20.0	0.036	—	*27.76*	—	—
	24.0	0.035	—	*28.94*	—	—
	28.0	0.035	—	*28.94*	—	—
	32.0	0.033	—	*30.19*	—	—
Cellular polyurethane[c] (R-11 exp.)(unfaced)	24.0	0.023	—	*43.38* ←	—	1.59
Foil-faced, glass fiber-reinforced cellular Polyisocyanurate (R-11 exp.)[d]	32.0	0.020	—	*49.97*	—	0.92
Nominal 12.70 mm		—	1.58	—	*0.63*	
Nominal 25.40 mm		—	0.79	—	*1.27*	
Nominal 50.80 mm		—	0.39	—	*2.53*	
Mineral fiber with resin binder	240	0.042	—	*23.94*	—	0.71
Mineral fiberboard, wet felted						
Core or roof insulation	256–272	0.049	—	*20.40*	—	
Acoustical tile	288	0.050	—	*19.85*	—	0.80
Acoustical tile	336	0.053	—	*18.74*	—	
Mineral fiberboard, wet molded						
Acoustical tile[e]	368	0.060	—	*16.52*	—	0.59
Wood or cane fiberboard						
Acoustical tile[e] 12.70 mm	—	—	4.54	—	*0.22*	1.30
Acoustical tile[e] 19.05 mm	—	—	3.01	—	*0.33*	

1 m 厚的R = 43.38

設計的 R 為 2.11

所以只需要

2.11/43.38*100 =

4.86 cm 厚

透過天花板的熱傳導

- 與牆面的計算方式相同
- 天花板上方通常有保溫材料

Thermal Properties of Typical Building and Insulating Materials—Design Values[a]

Description	Density kg/m³	Conductivity (λ) W/m·°C	Conductance (C) W/m²·°C	Resistance (R) Per meter thickness	Resistance (R) For thickness listed	Specific Heat kJ/(kg·°C)
LOOSE FILL						
Cellulosic insulation (milled paper or wood pulp)	36.8-51.2	0.039-0.046	—	25.68-21.72	—	1.38
Sawdust or shavings	128-240	0.065	—	15.41	—	1.38
Wood fiber, softwoods	32.0-56.0	0.043	—	23.11	—	1.38
Perlite, expanded	32.0-65.6	0.039-0.045		25.68-22.90		
	65-118	0.045-0.052		22.90-19.43		
	118-176	0.052-0.060		19.43-16.66		
Mineral fiber (rock, slag or glass)						
approx. 95.3-127.0 mm	9.6-32.0	—	—		1.94	0.71
approx. 165.1-222.3 mm	9.6-32.0	—	—		3.34	
approx. 190.5-254.0 mm	9.6-32.0	—	—		3.87	
approx. 260.4-349.3 mm	9.6-32.0	—	—		5.28	
Mineral fiber (rock, slag or glass) approx. 83.8 mm (closed sidewall application)	32.0-56.0	—	—	—	2.46	1.34
Vermiculite, exfoliated	112-131	0.068	—	14.78	—	
	64.0-96.0	0.063	—	15.75	—	
FIELD APPLIED						
Polyurethane foam	24.0-40.0	0.023-0.026	—	43.38-36.50	—	
Ureaformaldehyde foam	11.2-25.6	0.032-0.040	—	24.78-31.58	—	
Spray cellulosic fiber base	32.0-96.0	0.035-0.043	—	13.11-28.94	—	
PLASTERING MATERIALS 粉刷材料						
Cement plaster, sand aggregate	1865	0.720	—	1.39	—	0.84
Sand aggregate 9.53 mm	—	—	75.54	—	0.014	0.84
Sand aggregate 19.05 mm	—	—	37.83	—	0.026	0.84
Gypsum plaster:						
Lightweight aggregate 12.70 mm	720	—	17.72	—	0.056	
Lightweight aggregate 15.88 mm	720	—	15.17	—	0.069	
Lightweight agg. on metal lath 19.05 mmin.	—	—	12.10	—	0.083	
Perlite aggregate	720	0.216	—	4.65	—	1.34
矽酸鈣板 (防火) 6 mm	800	0.15	250	6.67	0.004	
8 mm			187.5		0.0053	
9 mm			166.7		0.006	
10 mm			150		0.0067	
12 mm			125		0.008	

387

Thermal Properties of Typical Building and Insulating Materials—Design Values[a]

Description	Density kg/m³	Conductivity (λ) W/m·°C	Conductance (C) W/m²·°C	Resistance (R) Per meter thickness	Resistance (R) For thickness listed	Specific Heat kJ/(kg·°C)
PLASTERING MATERIALS 粉刷材料						
Sand aggregate	1680	0.806	—	1.25	—	0.84
Sand aggregate 12.70 mm	1680	—	63.05	—	0.016	
Sand aggregate 15.88 mm	1680	—	51.69	—	0.019	
Sand aggregate on metal lath 19.05 mm	—	—	43.74	—	0.023	
Vermiculite aggregate	720	0.245	—	4.09	—	

透過窗戶與溫室被覆材料的熱傳導

Appendix 4-2, at p400: Overall thermal resistances of glazing.

A. Windows (vertical), no indoor shades, no storm sash

Storm sash

Type	Thermal Resistance, $m^2 K/W$ Winter	Summer
Single glass, clear,		
surface emittance of 0.84	0.16	0.17
0.60	0.17	0.18
0.40	0.19	0.20
0.20	0.22	0.23
Insulating glass, double,		
5 mm air space, 3 mm glass	0.29	0.27
6 mm air space, 3 mm glass	0.30	0.29
13 mm air space, 6 mm glass	0.36	0.31
Insulating glass, triple,		
6 mm air space, 3 mm glass	0.45	0.40

B. Windows (vertical), no indoor shades, glass outdoor storm sash with 25 mm air space

Type	Thermal Resistance, m^2K/W Winter	Summer
Single glass, clear,		
surface emittance of 0.84	0.43	0.36
0.60	0.37	0.29
0.40	0.40	0.29
0.20	0.43	0.36
Insulating glass, double,		
5 mm air space, 3 mm glass	0.48	0.43
6 mm air space, 3 mm glass	0.50	0.45
13 mm air space, 6 mm glass	0.56	0.45
Insulating glass, triple,		
6 mm air space, 3 mm glass	0.67	0.56

C. Adjustment factors for windows (multiply R-values in parts A and B by these factors)

	Wood Frame (> 1)	Metal Frame (< 1)
Single glass	1.05 - 1.18	0.91 - 1.00
Double glass	1.00 - 1.11	0.77 - 0.83
Triple glass	1.00 - 1.05	0.67 - 0.77
Storm sash applied over single glass	1.00 - 1.11	0.71 - 0.83
Storm sash applied over double or triple glass	1.00 - 1.05	0.67 - 0.77

D. Greenhouse Glazings

Material (includes surface resistance)	Unit Area Thermal Resistance, m^2K/W	U $\frac{W}{m^2K}$
Glass, single	0.16	6.25
Glass, double, 6 mm air space	0.25	4
Polyethylene film, single	0.14	7.14
Polyethylene film, double, 100 mm space	0.25	4
Fiberglass reinforced panel	0.15	6.67
Double panel, acrylic or polycarbonate	0.35	2.86

Notes:

a. Winter conditions are -18 C outdoor air, 21 C indoor air, and 24 km/hr (6.67 m/s) wind speed.

b. Summer conditions are 32 C outdoor air, 24 C indoor air, solar radiation of 782 W/m^2, and 12 km/hr (3.33 m/s) wind speed.

c. Manufacturer's data should be consulted for more accurate data for specific products, especially for thermally improved windows.

d. Data obtained from the ASHRAE Handbook of Fundamentals. Consult that reference for more detail and other glazing configurations.

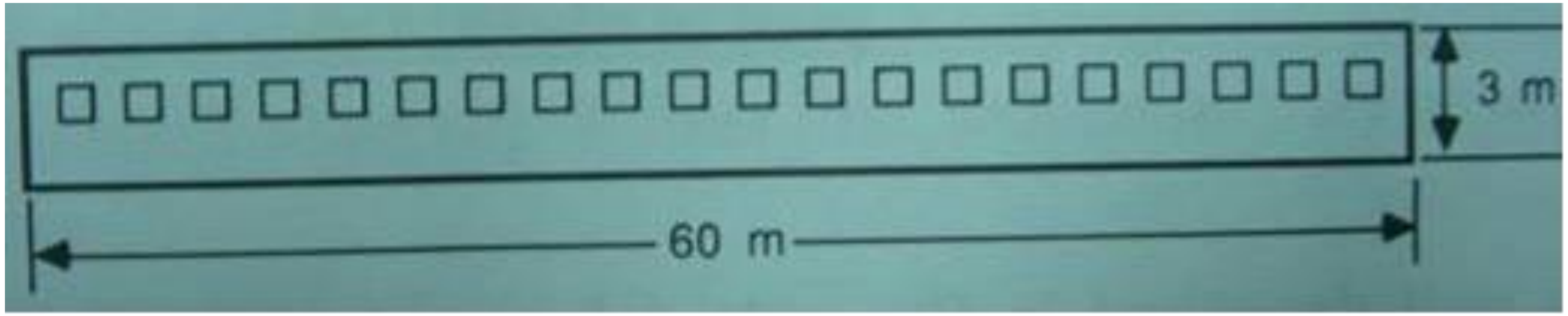
F-Clean (單層)塑膠布之光學及熱學性質

品目	厚度 (微米)	光學性能						熱性能	
		可視光 (%)		日射 (%)			紫外線透過率 (%)	日射熱取得率	熱貫流率 (U值)
		反射率	透過率	反射率	透過率	吸收率		(η值)	W / (m^2·K)
自然光流滴品	100	6.2	93.4	5.4	94.4	0.2	88.5	0.94	6.6
自然光流滴品	60	5.8	93.9	5.2	94.7	0.1	90.9	0.95	6.7
浮式玻璃	3 mm	8.2	90.2	7.8	85.8	6.3	71.1	0.88	6.0
浮式玻璃	6 mm	7.8	88.9	7.2	80.2	12.6	61.4	0.84	5.9

F-Clean (雙層)塑膠布之光學及熱學性質

品目	厚度 (微米)	光學性能						熱性能	
		可視光 (%)		日射 (%)			紫外線透過率 (%)	日射熱取得率	熱貫流率 (U值)
		反射率	透過率	反射率	透過率	吸收率		(η值)	W / (m^2·K)
自然光流滴品	100+100	11.5	87.5	10.3	89.4	0.4	79.2	0.90	3.7
自然光流滴品	100+60	11.5	88.0	10.0	89.7	0.3	81.2	0.90	3.8

Ex. 4-5 範例 4-2 所描述的木框牆壁中間的孔隙內填滿保溫材料，其平均熱阻為 2.2 m^2K/W。如下圖所示牆壁高3 m，長 60 m，牆上共有20 個窗戶，每個窗戶使用厚度 3 mm的雙層玻璃，中間以 6 mm 空氣層隔開。窗戶使用木框，窗高 0.6 m，窗寬 1 m。請問窗戶本身的熱阻值與牆壁含窗戶的平均熱阻值。註：以冬季天候進行設計。



$A_{windows} = 20(1.0 \text{ x } .6) = 12m^2$

$A_{wall} = (3 \text{ x } 60) – 12 = 168m^2$

$180 / R_{average} = 12 / 0.32 + 168 / 2.20$

$R_{average} = 180 / (37.5 + 76.3636) = 180/113.8636 = 1.58$

透過門的熱傳導

Appendix 4-3, overall thermal resistances of doors.

A. Wood doors, no storm doors

Type	Thermal Resistance, m²K/W Winter	Summer
Flush doors		
hollow core, 35 mm thick	0.37	0.39
hollow core, 44 mm thick	0.38	0.40
with single glazing	0.28	0.33
solid core, 35 mm thick	0.45 ✓	0.46
solid core, 44 mm thick	0.53	0.55
with single glazing	0.38	0.40
with double glazing	0.48	0.49
solid core, 57 mm thick	0.65	0.68
with single glazing	0.43	0.44
with double glazing	0.53	0.55
Panel doors		
11 mm panels, 35 mm thick door	0.31 ✓	0.33
11 mm panels, 44 mm thick door	0.33	0.34
with single glazing	0.26	0.28
with double glazing	0.35	0.37
29 mm panels, 44 mm thick door	0.45	0.46
with single glazing	0.29	0.30
with double glazing	0.40	0.42

B. Wood doors, with storm doors, winter conditions only

Type	Thermal Resistance, m^2K/W wood storm door	metal storm doo
Flush doors		
hollow core, 35 mm thick	0.59	0.55
hollow core, 44 mm thick	0.61	0.55
with single glazing	0.53	0.49
solid core, 35 mm thick	0.68	0.63
solid core, 44 mm thick		
with single glazing	0.61	0.55
with double glazing	0.70	0.65
solid core, 57 mm thick	0.88	0.84
with single glazing	0.65	0.61
with double glazing	0.76	0.70
Panel doors		
11 mm panels, 35 mm thick door	0.53	0.48
11 mm panels, 44 mm thick door	0.55	0.49
with single glazing	0.49	0.43
with double glazing	0.57	0.52
29 mm panels, 44 mm thick door	0.68	0.63
with single glazing	0.52	0.46
with double glazing	0.63	0.57

C. Steel doors

Type	Thermal Resistance, m²K/W Winter	Summer
Solid urethane foam core, no thermal break, 44 mm thick, no storm door	0.44	0.45
Solid urethane foam core, with thermal break, 44 mm thick, no storm door	0.93	0.98
wood storm door	1.10	
metal storm door	1.03	

Notes:

a. Data is based on nominal door size of 1.12 m by 2.03 m.
b. Winter conditions are −17.8 C outdoor air temperature, 21.[illegible] indoor air temperature, and 24 km/hr (6.67 m/s) wind speed.
c. Summer conditions are 31.7 C outdoor air temperature, 23.9 indoor air temperature, and 12 km/hr [illegible] wind speed

Ex. 4-6 範例 4-5 所述的牆壁擬再增加兩個門，第一為車庫門 (overhead door, garage door) 高、寬各為2.5 與 3 m，第二為拉門 (flush door) ，高、寬各為2.5 與 1 m。前者使用 11 mm 厚的門板與35 mm 厚的外框；後者使用 35 mm 厚實心門板。兩個門都沒有外加防爆窗。請計算牆壁的平均熱阻。

A **Flush Door** has completely **smooth surfaces** and is made by **sandwiching** plywood or blackboard over a **light timber frame**. The hollow part between these **doors** is filled with **cardboard**/hardwood. They can be **finished** with either **laminates** or veneers.

Flush Door

Overhead Door

Ex. 4-5 範例 4-2 所描述的木框牆壁中間的孔隙內填滿保溫材料，其平均熱阻為 2.2 m^2K/W。如下圖所示牆壁高 3 m，長 60 m，牆上共有20 個窗戶，每個窗戶使用厚度 3 mm的雙層玻璃，中間以 6 mm 空氣層隔開。窗戶使用木框，窗高 0.6 m，窗寬 1 m。請問窗戶本身的熱阻值與牆壁含窗戶的平均熱阻值。註：請以冬季天候狀況進行設計。

Ex. 4-6 範例 4-5 所述的牆壁擬再增加兩個門，第一為車庫門 (overhead door, garage door) 高、寬各為2.5 與 3 m，第二為拉門 (flush door)， 高、寬各為2.5 與 1 m。前者使用 11 mm 厚的門板與35 mm 厚的外框；後者使用 35 mm 厚實心門板。兩個門都沒有外加防爆窗。請計算牆壁的平均熱阻。

牆面總面積 = 3 x 60 = 180, 窗面積 = 20 x 0.6 x 1 = 12, 拉門面積 = 2.5 x 1 = 2.5, 車庫門面積 = 2.5 x 3 = 7.5
其餘面積 = 180 – 12 – 2.5 – 7.5 = 158

$$180 / R_{avg} = 12 / 0.32 + 158 / 2.20 + 2.5 / 0.45 + 7.5 / 0.31$$

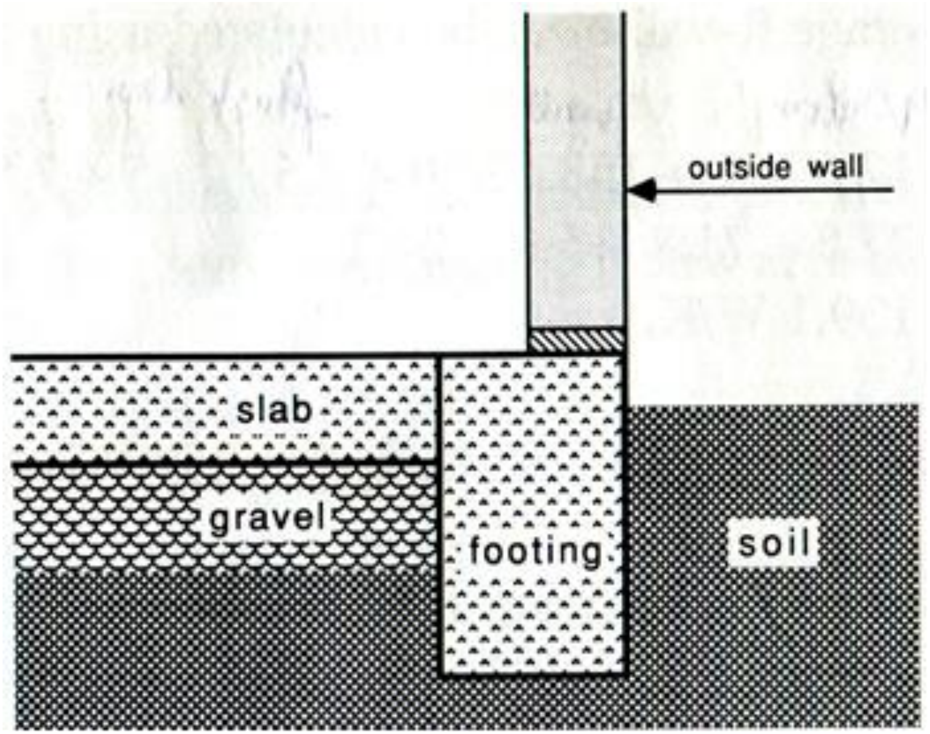
$$R_{avg} = 1.29\ m^2K/W$$

2.86 m^2K/W → 2.20 → 1.58 → 1.29
framing windows doors

透過地板的熱傳導

$$q_{floor} = F * P * (t_{inside} - t_{outdoors}) \quad \ldots[4\text{-}2]$$

其中，P 為地板周長；F為周長相關的熱損失因子 (一般需透過現場試驗來決定數值)



F 值 W/mK	**狀況**
1.4~1.6	**地下未保溫與空間未加熱**
0.8~0.9	**使用熱阻為 0.95 m^2K/W的材料做好保溫**

透過地板的熱傳導

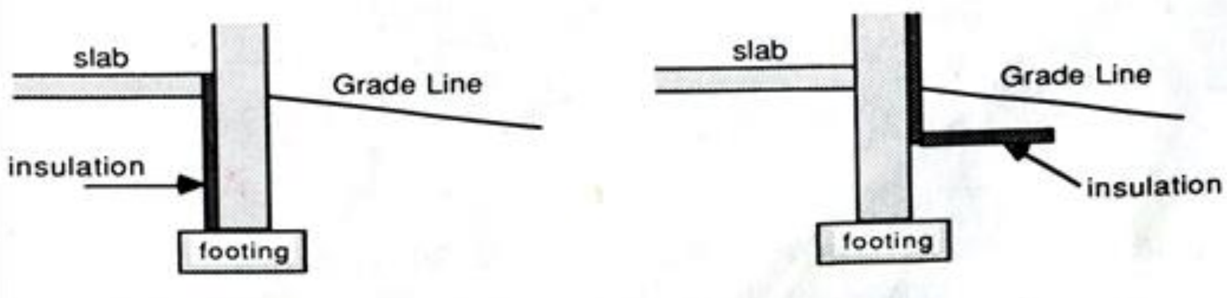


Figure 4-1. Examples of perimeter insulation placement.

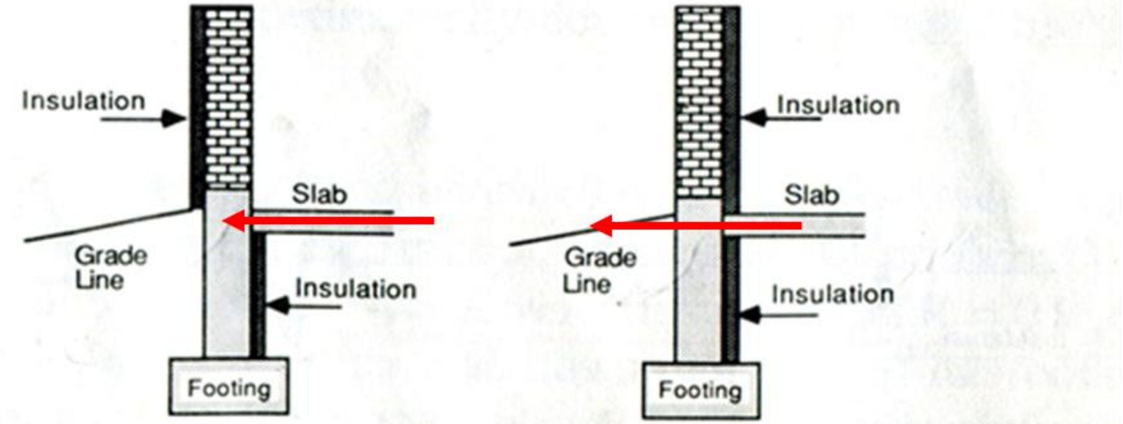
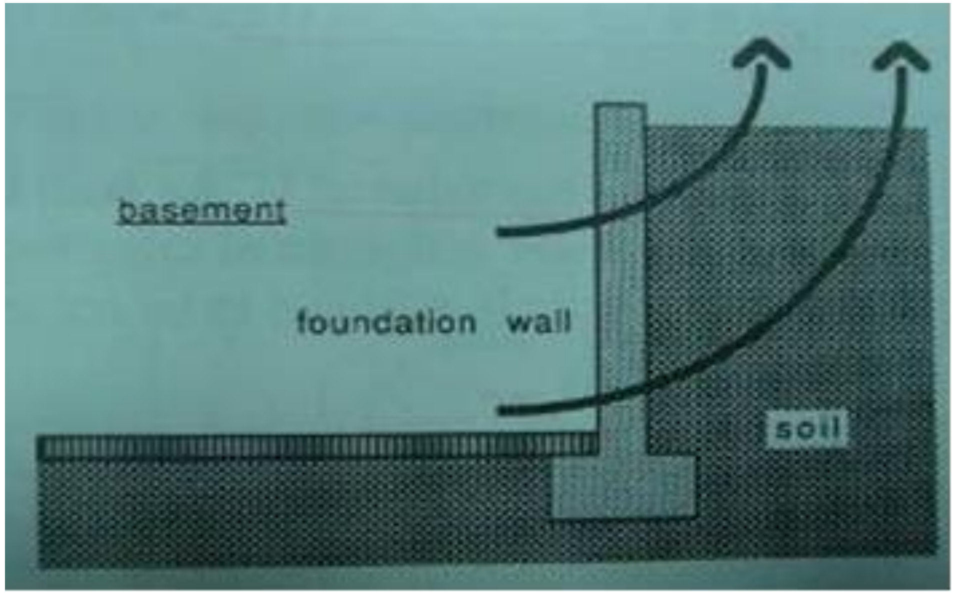


Figure 4-2. Examples of insulation added to slab floors and footings which form thermal bridges.

Thermal bridge

透過地下室牆面與地面的熱傳導



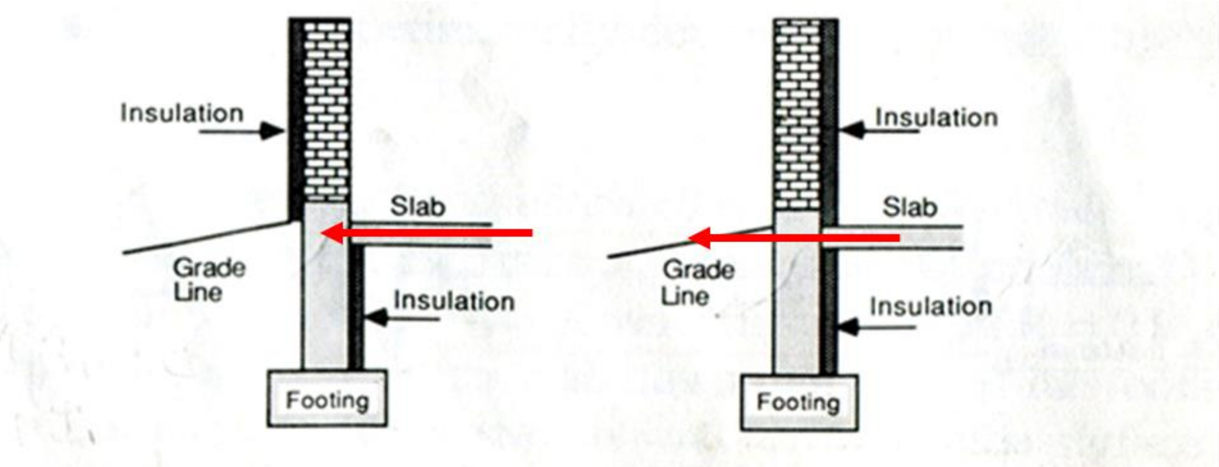


Figure 4-2. Examples of insulation added to slab floors and footings which form thermal bridges.

$$q_{ground} = U' (t_{inside} - t_{ground}) \qquad ...[4\text{-}3]$$

Ex. 4-7 位於北緯45 度，西經 120度美國華盛頓州的某水果農場打算在包裝工作室 (packing shed) 建一間地下室做儲藏空間，地下室長寬各為 8.5 x 12 m，地下室地板在地下深度 (below grade) 為 1.8 m。當地的年平均氣溫為 12 度C，地下室需維持 15 度C且四週牆壁與地板均不打算作保溫，請計算此地下室經由四壁與地板流失熱量的速率。

地下室周長 = 2 x (8.5+12) = 41

地板面積 = 8.5 x 12 = 102

$U_{average}$=(2.33+1.26+0.88+0.67+0.54+0.45)/6=1.02 W/m²k

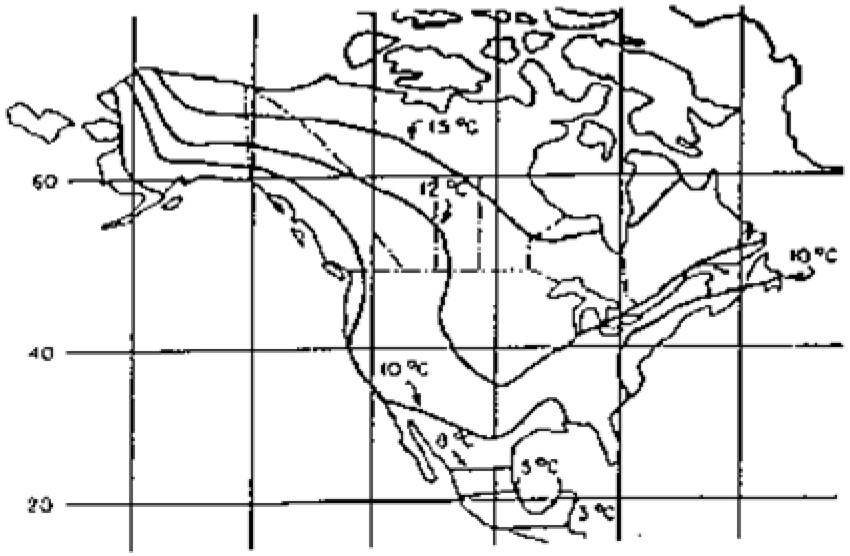
U'_{wall} = 1.02 W/m²k x 1.8 m x 41 m = 75 W/K

U'_{floor} = 0.14 W/m²k x 102 m² = 14 W/K

$U'_{basement}$ = 75 + 14 = 89 W/K

西雅圖的氣土溫差為10°C，年平均土溫 12-10=2°C

Q_{ground} = 89 * (15 – 2) = 1157 W



北美洲年平均氣溫與土壤溫度的溫差 (氣土溫差)

Table 4-1. Heat loss conductance for basements

Through walls

Depth below grade	Conductance, W/m²K, for wall insulated by: uninsulated	R – 0.73	1.47	2.20 m²K/W
0 - 0.3 m	2.33	0.86	0.53	0.38
0.3 - 0.6	1.26	0.66	0.45	0.36
0.6 - 0.9	0.88	0.53	0.38	0.30
0.9 - 1.2	0.67	0.45	0.34	0.27
1.2 - 1.5	0.54	0.39	0.30	0.25
1.5 - 1.8	0.45	0.34	0.27	0.23
1.8 - 2.1	0.39	0.30	0.25	0.21

Through the floor, conductance in W/m²K

Depth of floor below grade	Minimum width of basement, m: 6.0	7.3	8.5	9.7
1.5 m	0.18	0.16	0.15	0.13
1.8	0.17	0.15	0.14	0.12
2.1	0.16	0.15	0.13	0.12

短邊

軟體 **RVALUE程式**

- 要計算一棟建築物外殼的總熱傳導 ∑ UA，需累計所有地面上建物與地下建物的牆壁、天花板、門、窗等的熱傳導數值。本章前面各節已經介紹各自的計算方式。
- 好設計需考量多種可行性，搭配成本考量達到設計需求就是做最佳化設計，譬如絕熱材料選擇何種材質，窗戶要選擇單層還是雙層玻璃，選擇同一種或幾種保溫材料來搭配。諸如此類種種分析需要搭配軟體來計算會方便許多。

RVALUE程式 (DOS版軟體)

需要 DOSBOX 軟體

先到課程網頁下載一個壓縮的檔案，內有兩個 DOS 程式
解壓縮後將兩個 exe 程式存於d:\cea的 db 目錄內。

安裝DOSBOX之後執行程式，出現黑色背景的 DOS 視窗，
在 DOS視窗內先執行
Mount C: D:\cea\db

把 後面的目錄設定為 DOS 環境下的 C disk

C:

把 工作目錄換成 DOS 環境下的C disk

dir

可出現 db 目錄內的所有檔案，其中， .exe 為可執行的程式

DOS 版本程式：RVALUE

```
                         PROGRAM R-VALUE

This program calculates the overall R-Value of the walls, ceiling, doors,
and windows of a single air space building.  The effect of framing in the
walls and ceiling is included.

This is not a general purpose program to calculate heat loss from buildings
because of the following assumptions:

   1. Only a single type (your choice) of window is permitted.
   2. Only a single type (your choice) of door is permitted.
   3. Only a single type (your choice) of wall construction is permited.
   4. Only a single type (your choice) of ceiling construction is permitted.
   5. Framing as a fraction of the ceiling area is fixed at 12%, and is
      always 38x90 mm lumber (2x4s).
   6. Wall framing can be only 38x90 mm (2x4s) or 38x140 mm (2x6s).
   7. Wind speed at the outside surface of the wall is fixed at 6.7 m/s.


                    press any key to continue
```

PROGRAM R-VALUE DATA INPUT

When using this program, you will be asked to decide on the following:

1. the type of window and its area, and winter or summer conditions;
2. the type of door and its area, and winter or summer conditions;
3. the type of ceiling sheathing and insulation, and its area;
4. the type of material in four wall layers: the inside sheathing, insulation, outside sheathing, and siding.
5. the outside perimeter of the building and wall height.

NOTE: although the program expects four layers in the wall, your wall need not have that many. For example, if you want a concrete block wall, which is only one layer, specify layer 1 as an "other" material, enter its R-Value, and specify the other three layers as "other" with R-Values = 0.0.

press any key to continue

Doors are described in section 4-5; door R-values are listed in Appendix 4-3.

Choose the type of door
you will use

TYPE? 2

Winter (1) or Summer (2)? 1

Door area is: 20.0 m^2
Door R-Value is: 0.33 m^2K/W
Door UA value is: 60.6 W/K

Do you wish to change the
door data (Y,N)?

The following doors are available

1. 35 mm panel door, 11 mm panels
2. 44 mm panel door, 11 mm panels
3. 44 mm solid door, no storm
4. 57 mm solid door, no storm
5. 35 mm hollow core, no storm
6. 44 mm hollow core, no storm
7. 35 mm solid, metal storm
8. 57 mm solid, metal storm
9. 35 mm hollow, metal storm
10. 44 mm hollow, metal storm
11. 44 mm sol., no storm/single gl.
12. 57 mm sol., no storm/single gl.
13. 44 mm sol., mtl strm/single gl.
14. 57 mm sol., mtl strm/single gl.
15. Other

Ceiling heat loss is described in Section 4-3, with R-values in Appendix 3-2.

Here is the ceiling you designed.

The area is 500.0 m^2
The R-Value is 3.10 m^2K/W
The UA value is 161.3 W/K

The framing is fixed at 12% of the total ceiling area, and is comprised of 38x90 mm softwood.

Do you wish to change the ceiling data (Y,N)?

Windows are described in section 4-4, with R-Values in Appendix 4-2.

Choose the type of window
you will use

TYPE? 1

Winter (1) or Summer (2)? 1

Window area is: 108.0 m^2
Window R-Value is: 0.16 m^2K/W
Window UA value is: 675.0 W/K

Do you wish to change the
window data (Y,N)?

The following windows are available

1. Single glass, 0.84 emittance
2. with storm sash
3. Single glass, 0.20 emittance
4. with storm sash
5. Double glass, 6 mm air space
6. with storm sash
7. Triple glass, 6 mm air space
8. with storm sash
9. Other

NOTE: It is suggested you use the adjustment factors listed in Appendix 4-2 to calculate R-values more accurately and use "Other".

Wall heat loss is described in Section 4-2, with R-Values in Appendix 3-2.

Now enter perimeter of the outside wall, and its height.

Perimeter, m: ? 120

Height, m: ? 3

Now enter the percentage of the wall which is framed.
(normally between 12 and 20%)

Framing factor, %, is: 20

Do you wish to change the perimeter, height, or framing factor data (Y/N)?

RESULTS

Component	Area	R-Value	UA Value
Doors	20.0	0.33	60.6
Windows	108.0	0.16	675.0
Ceiling	500.0	3.10	161.3
Wall	232.0	2.52	92.2

Combined	860.0	0.87	989.1

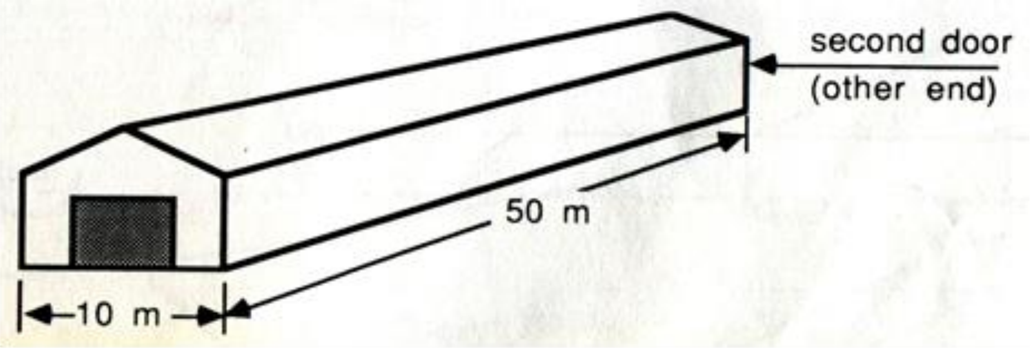
Do you wish to run this program again <y/n>?

Ex. 4-8 欲建造一棟長寬高各為 10 x 50 x 3 m 的建築物，窗戶使用單層玻璃 (single glass)，一般的輻射率 (normal emittance)。建築前後會各有一道 2.5 x 4 m,厚度 44 mm的門，選用厚度11 mm 的門板。天花板內側使用 15.88 mm 三夾板並以 150 mm 礦物纖維毯 (mineral fiber blanket) 做隔熱材料。四壁內側使用 12.7 mm 三夾板，外側使用 19.8 mm 一般密度的蔬菜纖維板，內外夾牆使用厚度 88.9 mm 的礦物纖維毯為保溫材料。牆壁的木框佔有牆壁面積的20 %。

Develop a graph to show the effect of glazing area on the overall R-value of the building. Graph the building R-value as a function of glazing area for a glazing area ranging from 0% to 30% of the gross wall area. Assume winter conditions.

Gross wall area = 3 m x 120 m = 360 m^2

Glass Area, %	Glass Area, m^2	Building R-value
0	0	2.41 m^{2}K/W
5	18	1.86
10	36	1.51
15	54	1.28
20	72	1.10
25	90	0.97
30	108	0.87



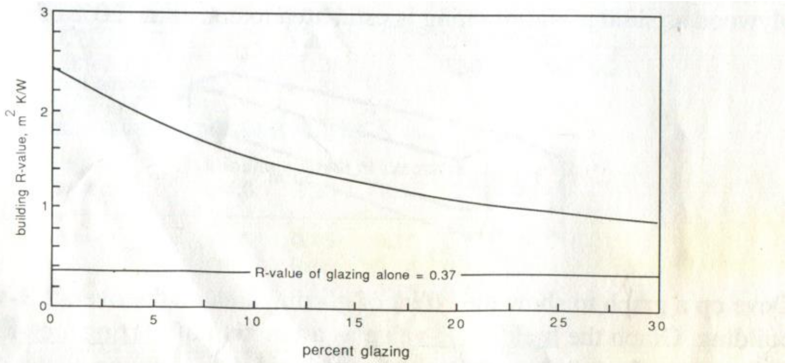


Figure 4-4. Average R-Value of the structural cover of the building described in Example 4-8 as a function of the percentage of the wall devoted to glazing.

Sol-Air 溫度 ($t_{sol\text{-}air}$)

An energy balance on the surface contains, as fluxes on the upper surface

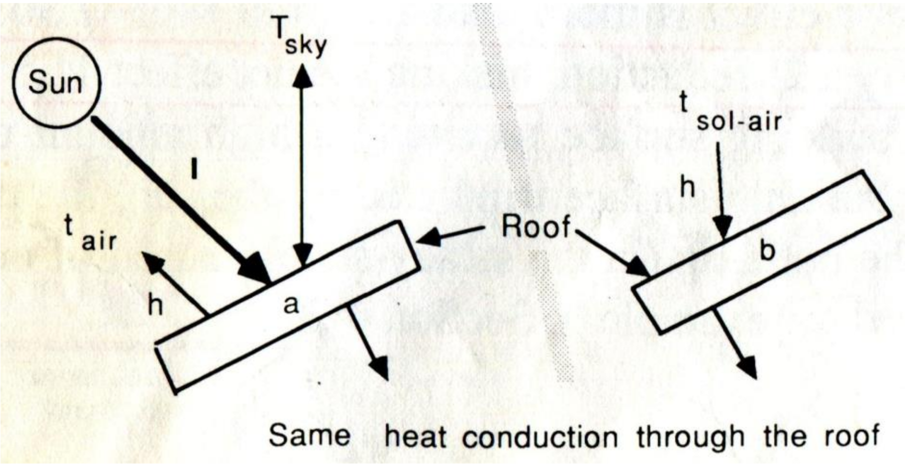
$q = h * (t_a - t_w) + \alpha * I + \varepsilon_w * \sigma * (T_{sky}^4 - T_w^4)$ …[4-4]

$q = h * (t_a - t_w) + \alpha * I - \varepsilon * \triangle R$ …[4-5]

定義 $q = h * (t_{sa} - t_w)$ …[4-6]

$t_{sa} = t_a + (\alpha * I - \varepsilon * \triangle R) / h$ …[4-7]

$\triangle R = 60$



$t_{sa} = t_a + (\alpha * I - 6 * \varepsilon * \cos\Phi * (10 - \Omega)) / h$ …[4-8]

其中，Φ is the tilt angle of the surface

Ω is the cloudiness factor, ranging from 0 for a clear day, to 10 for complete cloud cover.

Ex. 4-9 某建築物的屋頂斜率為1:3，受 500 W/m^2 的太陽輻射，空氣溫度為28 ^oC，晴天，屋頂的太陽能吸收率 (solar absorptance) 為 0.8，熱輻射率(thermal emittance)為0.95，外表面的對流熱傳係數 (surface convective coefficient) 為 30 W/m^{2}K (R_{os} = 0.03 m^{2}K/W)。請計算 solar-air 綜效溫度，並與實際空氣溫度作比較。

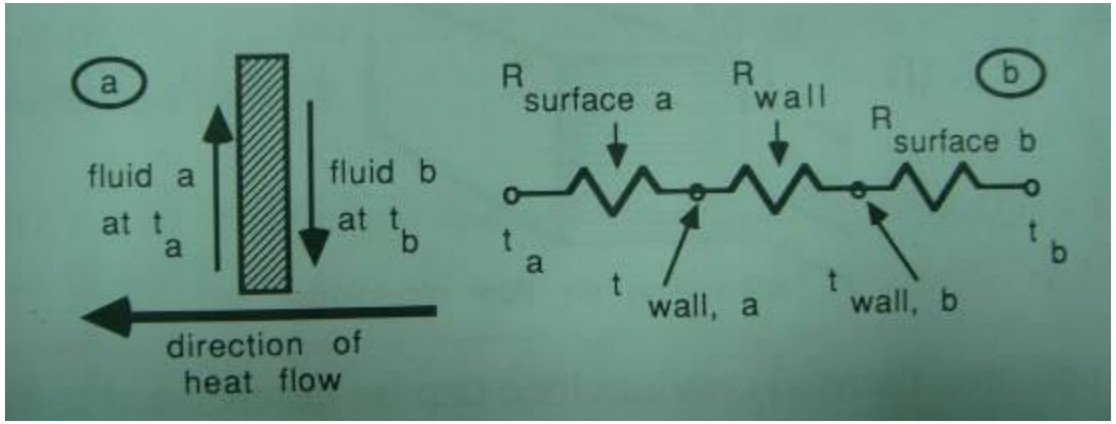
$$\Phi = \tan^{-1}(1/3)$$

$$t_{sa} = t_a + (\alpha * I - 6 * \varepsilon * \cos\Phi * (10-\Omega)) / h \qquad \ldots[4\text{-}8]$$

$$t_{sa} = 28 + [(0.80)(500 W/m^2) - (6 W/m^2)(0.95)(\cos(18.43^\circ))(10 - 0)]/30 W/m^2K$$

= 39.5，比空氣溫度高出 11.5 ^oC

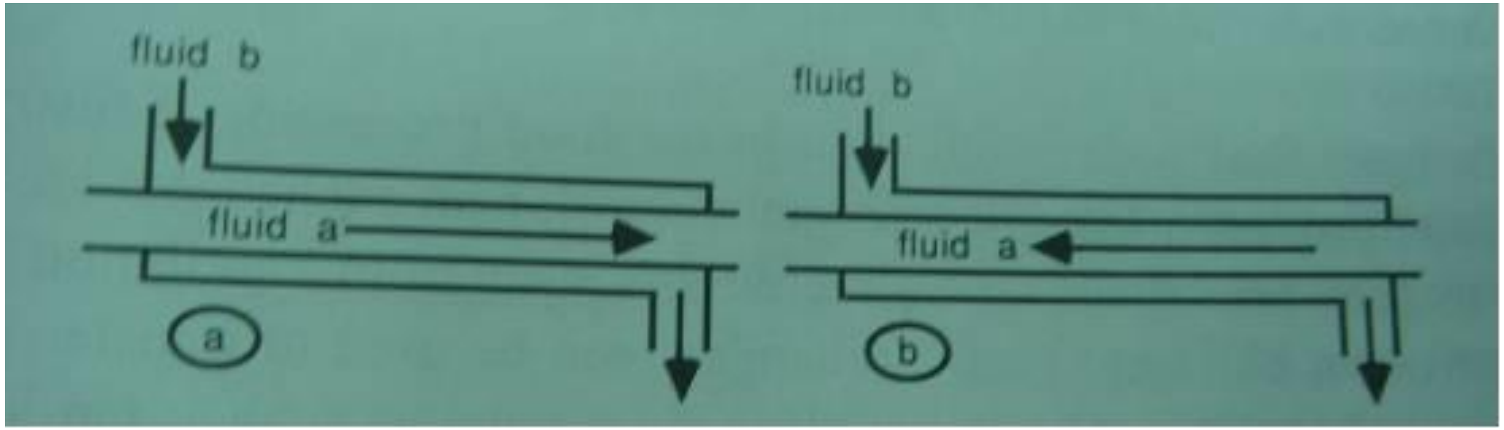
熱交換器



Overall Heat Transfer

$$q'' = \frac{t_b - t_a}{1/h_a + x/k + 1/h_b}$$ …[4-9]

$$q = U * A * \triangle tm$$ …[4-10]

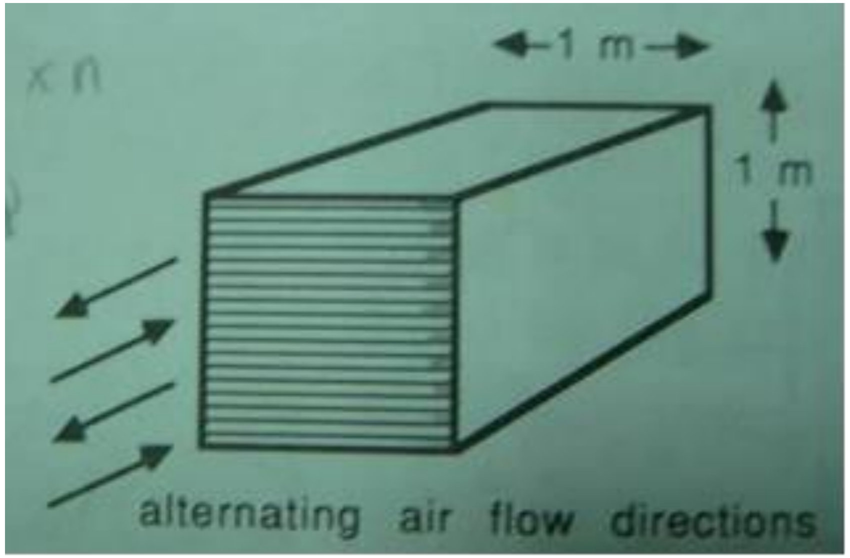


Parallel flow

counter flow

Overall Heat Transfer Coefficient

Ex. 4-10 如圖所示熱交換器用來針對進入小牛舍的空氣做預熱，此熱交換器使用0.5 mm 厚的鍍鋅金屬板平行堆疊，風量率為 0.25 m^3/s，請求出此熱交換器的 U 值。
A heat exchanger is to be designed and locally fabricated to prewarm ventilation air for a calf nursery. The exchanger will be built of parallel plates of 0.5 mm thick galvanized sheet metal. Dimensions are as shown and the airflow rate in each channel is to be approximately 0.25 m3/s. Determine the average unit area thermal conductance (U) for the exchanger.



$h = c\, G^{0.8} D^{-0.2}$ **check ch.3 forced convection**

$D = 4\,(0.125\ m^2) / (2.25\ m) = 0.222\ m$

$G = \rho\, V / A = (1.10\ kg/m^3)(0.25\ m^3/s)/(0.125\ m^2) = 2.2\ kg/m^2s$

$h = (3.10)(2.2\ kg/m^2s)^{0.8}(0.222\ m)^{-0.2} = 7.87\ W/m^2K$

$$U = \frac{1}{1/h_a + x/k + 1/h_b}$$

$U = 1/[(1 / 7.87\ W/m^2K) + (0.0005\ m / 45.3\ W/mK) + (1 / 7.78\ w/m^2K)] = 3.94\ W/m^2K$

強制對流 (forced convection)

強制通風多屬擾流，輸送管中強制吹送的風，其 h 值可用下式求出：

$$h = c\,G^{0.8}/D^{0.2}$$

其中，c is related to thermal properties of air, 查表3-3

G = ρ*Volume，mass flow of air in the duct

D= 4 *(area) / (perimeter), 水力直徑

= 直徑 for 圓管 $= 4\pi r^2 / 2\pi r = 2r$

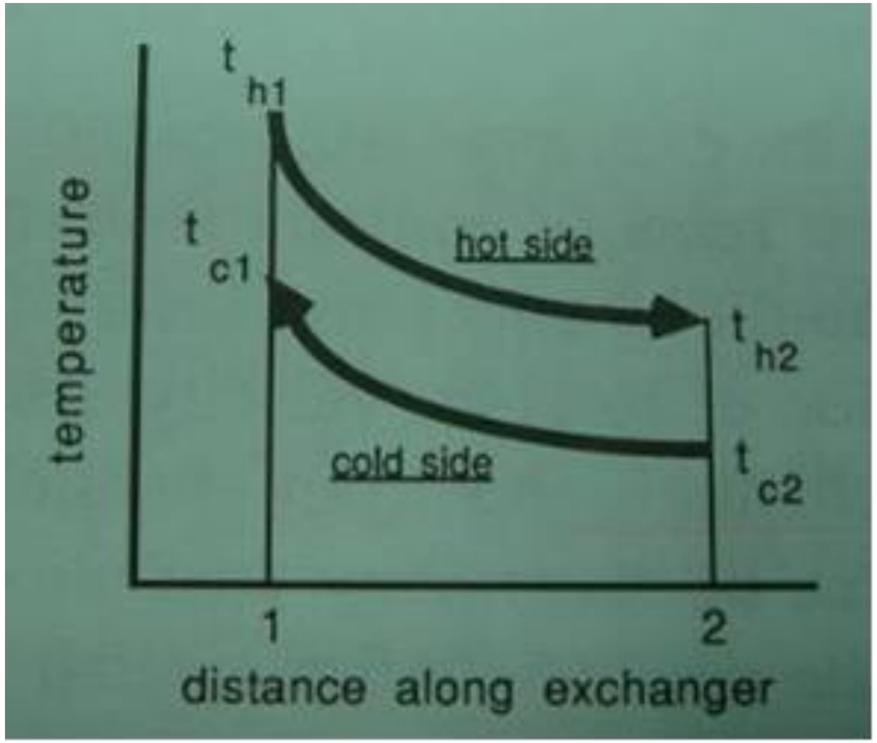
Table 3-3. Coefficient c in Equation 3-44 (SI units).

Temperature C	c
-18	3.09
4	3.18
27	3.21
49	3.26
71	3.32
93	3.37

Adapted from the *ASHRAE Handbook of Fundamentals* : for h in W/m^2K; G in kg/m^2s; D in m. An approximation of the data is the equation c = 3.14783 + 0.00240267t.

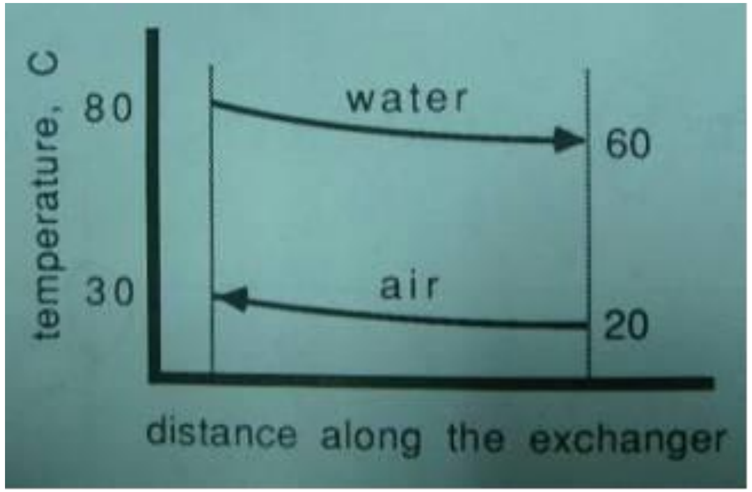
Logarithmic Mean Temperature Difference (LMTD)

$$\Delta t_m = \frac{(t_{h2} - t_{c2}) - (t_{h1} - t_{c1})}{\ln\left[(t_{h2} - t_{c2})/(t_{h1} - t_{c1})\right]} \quad \ldots[4\text{-}11]$$



Ex. 4-11 某熱水對空氣的熱交換器用來給溫室加溫，熱水進出溫度分別為 80 與60 度C，流量為 0.05 kg/s，空氣流量為 0.4165 kg/s，進出溫度為 20 與 30 度C，該熱交換器單位面積的熱傳遞係數為 25 W/m^{2}K，請問需要的熱交換面積有多少？

A heat exchanger is used to transfer heat from hot water to recirculated air within a greenhouse. Hot water arrives at the exchanger at 80 C, and leaves at 60 C, and flows at a rate of 0.05 kg/s. Air flows through the exchanger at a rate of 0.4165 kg/s, and is heated from 20 C to 30 C. The measured unit area thermal conductance of the heat exchanger is 25 W/m^{2}K (this high rate is achieved using fins on the air side of the exchange surface).
What area of heat exchange is needed to achieve these conditions?



$$q = mc_p \Delta t = 0.05 * 4180 * (80-60) = 4180 \text{ or}$$
$$= 0.4165 * 1006 * (30-20) = 4190$$

$$LMTD = \frac{(80-30)-(60-20)}{\ln(\frac{80-30}{60-20})} = 44.81K$$

$$q = UA(LMTD)$$

$$A = q / [U(LMTD)] = (4{,}190 \text{ J/s})/(25 \text{ W/m}^2\text{K})(44.81 \text{ k}) = 3.74 \text{ m}^2$$

Heat Exchanger Effectiveness and the NTU Method

The effectiveness (ε) of a heat exchanger is defined as

$\varepsilon = q_{actual} \ / \ q_{max}$ …[4-12]

其中，q_{actual} ： actual rate of heat transfer

q_{max} : maximum possible rate of heat transfer

$q_{actual} = m_h c_h \triangle t_h$ or $m_c c_c \triangle t_c$ …[4-13]

$q_{max} = (mc)_{min} (t_{h,\ inlet} - t_{c,\ inlet})$ …[4-14]

Eq 4-15,… 4-18 , given C and NTU, derive ε

其中，NTU: number of transfer units = $UA/(mc)_{min}$, can be used to indicate the relative size of the heat exchanger.

$C = (mc)_{min} ,/(mc)_{max}$

Eq 4-21,… 4-24 , given C and ε, derive NTU

parallel flow: $\varepsilon = \dfrac{1 - \exp[-NTU(1 + C)]}{1 + C}$

counter flow: $\varepsilon = \dfrac{1 - \exp[-NTU(1 - C)]}{1 - C\exp[-NTU(1 - C)]}$

counter flow, C = 1: $\varepsilon = \dfrac{NTU}{1 + NTU}$

all exchangers for C = 0: $\varepsilon = 1 - \exp(-NTU)$

parallel flow: $NTU = \dfrac{-\ln[1 - (1 + C)\varepsilon]}{1 + C}$

counter flow: $NTU = (C - 1)^{-1} \ln\left(\dfrac{\varepsilon - 1}{\varepsilon C - 1}\right)$

counter flow, C = 1: $NTU = \varepsilon/(1 - \varepsilon)$

all exchangers, C = 0: $NTU = -\ln(1 - \varepsilon)$

Ex. 4-12 某溫室使用鄰近的火力發電廠的冷卻水來提供熱能，30度C熱水流經反向流熱交換器，流量率為2.5 kg/s的空氣通過熱交換器溫度由18度提高至27度C。熱交換器的面積為100 m^2，熱傳遞係數為 50 W/m^2K。請問熱水的流量率必須達到多少才能提供上述所需之熱能？

Warm water from the cooling condenser of a power generating station is to provide heat for a large greenhouse range. The warm water flows through counter flow heat exchangers (many exchangers operating in parallel) and greenhouse air is heated by being circulated through the exchangers. Warm water is available at 30 C and greenhouse air is to be heated from 18 C to 27 C. Air flows through the exchanger at a mass flow rate 2.5 kg/s. The heat exchanger surface area is 100 m2 and the average unit area thermal conductance (U) is 50 W/m^2K.

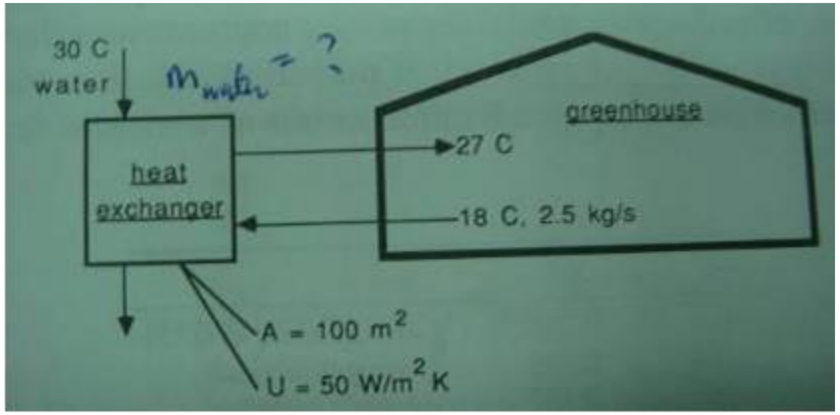
At what rate must water be pumped through the exchanger to provide this amount of air heating?

$(mc)_{min}$ = (2.5 kg/s) (1006 J/kg K) = 2515 J/sK

q_{air} = (2515 J/sK)(27 C – 18 C) = 22,635 W

NTU = UA / $(mc)_{min}$ = (100 m^2) (50 W/m^2K)/(2515 J/sK) = 1.99

$$\varepsilon = \frac{\text{actual temperature change}}{\text{maximum possible temperature change}} = \frac{27\,C - 18\,C}{30\,C - 18\,C} = 0.75$$



C	ε	
0.5	0.773	(already close to 0.75)
0.4	0.793	(wrong direction)
0.6	0.753	(looking better)
0.65	0.742	(too far)
0.62	0.748	(still too far)
0.61	0.750	(good enough for me)

$(mc)_{max} = (mc)_{min}$ / C = 2515 J/sK / 0.61 = 4123 J/sK

m_{water} = (4123 J/sK)/(4180J/kg K) = 0.986 kg/s

Δt_{water} = (22,635 J/s)/[(0.986 kg/s)(4180 J/kg K)]

Water exits the exchanger at 30 C – 5.5 K = 24.5 C

Ex. 4-13 重複上題，假設熱水溫度為 35 度C而非 30度C時。

Reconsider Example 4-12 and determine the required water pumping rate when water enters the heat exchanger at a temperature of 35 C instead of 30 C.

ε=(27 C - 18 C)/(35 C – 18 C) = 0.53

C	ε	(as before)
0.5	0.773	
0.7	0.731	
0.9	0.688	
0.99	0.668	(not even close)

由於 mc_{air} = 2515 並非限制因子，所以 $mc_{water} < 2515$，如右表，由 2000 起算

$C = mc_{water}$ /2515 J/sK

NTU = (50 W/m^2K) (100m^2)/mc_{water}

Δt_{water} = (22,635 J/s) / mc_{water}

$\varepsilon = \Delta t_{water} / 17$

ε= f(NTU, C)… qe. 4-16

mc_{water}	C	NTU = UA/C_{min}	Δt_{water} 22635/(mc)water	$\varepsilon = \Delta t_{water}/17$	ε by Eq. 4-16
2000	0.795	2.500	11.32 K	0.666	0.766
1500	0.596	3.333	15.09	0.888	0.876
1600	0.636	3.125	14.15	0.832	0.853
1550	0.616	3.226	14.60	0.859	0.865
1530	0.608	3.268	14.79	0.870	0.869
1533	0.610	3.262	14.77	0.869	0.868
1534	0.610	3.259	14.76	0.868	0.868

以上兩個 ε 應該相同，傳統做法可透過疊代運算如上表所示。請自我練習本例題，使用 excel 的目標求解功能，假設兩個ε為ε1, ε2。令兩者之差為0時，求 mc_{water} 之值。

求解得出 mc_{water} = 1534 J/sK 之後，除以 c_{water} 可得

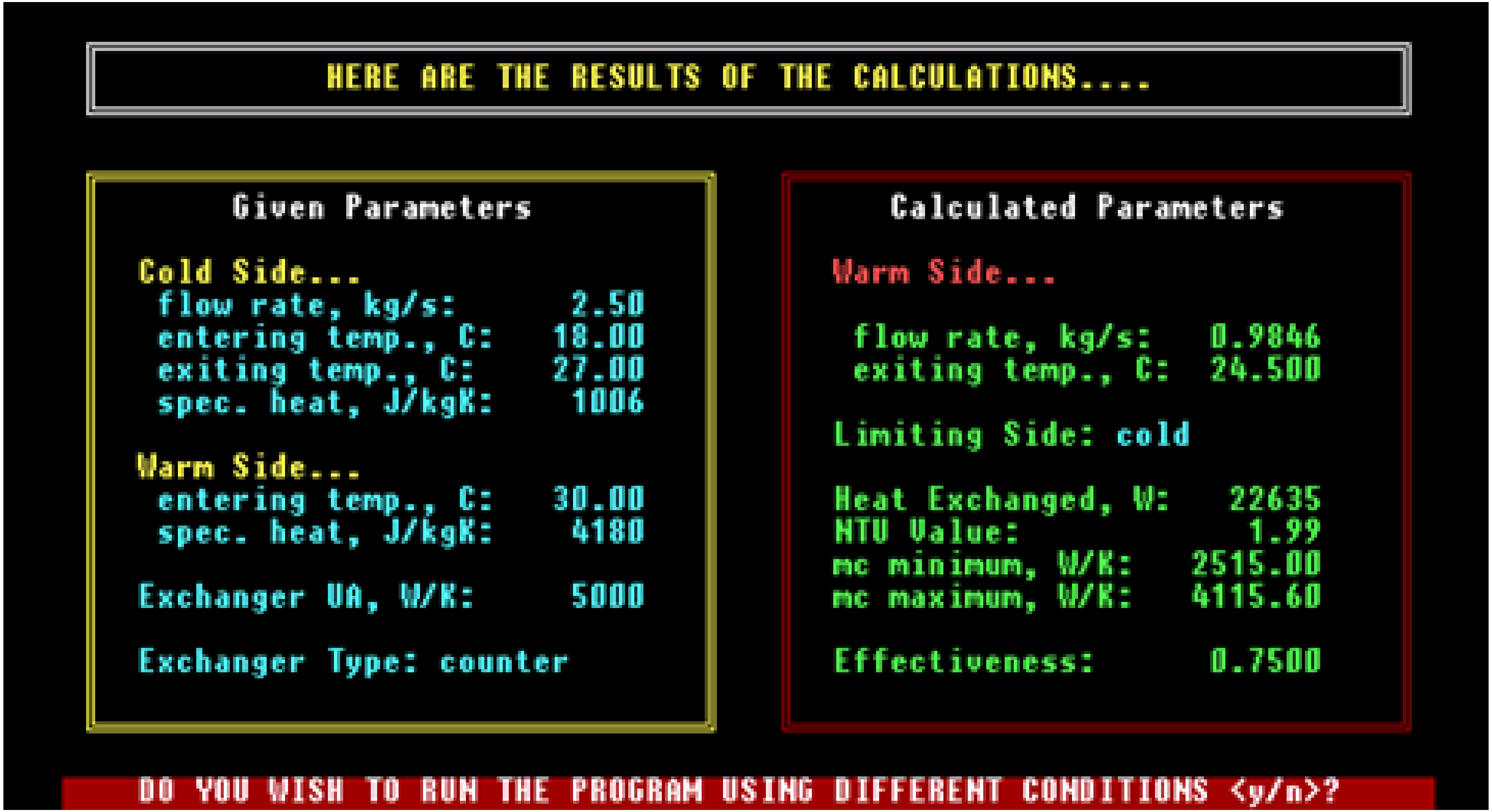
m_{water} = (1534 J/sK)/(4180 J/kg K) = 0.367 kg/s

比較

	Ex. 4_12	Ex.4_13
入口水溫	30	35
出口水溫	24.5	20.24
溫差	5.5	14.76 溫差大
流量，kg/s	0.986	0.367 馬達小
ε	0.75	0.868 效率高

DOS 版本程式：XCHANGER

Ex. 4-14 使用XCHANGER程式，重新計算 範例4-12，輸入條件與計算結果如下圖所示：



重複範例 4-13，熱交換面積由 20 m^2 間隔20 m^2 增加到 200 m^2，試探討不同的熱交換器面積對於系統設計的影響。

Area, m^2	Limiting	UA, W/K	m_{water}	t^{water}_{exit}	NTU	ε
20	solution does not converge					
40	cold side	2000	3.4837	33.446	0.80	0.5294
60	warm side	3000	0.5474	25.107	1.31	0.5819
80	warm side	4000	0.4110	21.826	2.33	0.7749
100	warm side	5000	0.3669	20.243	3.26	0.8681
120	warm side	6000	0.3468	19.386	4.14	0.9185
140	warm side	7000	0.3361	18.887	4.98	0.9479
160	warm side	8000	0.3298	18.581	5.80	0.9658
180	warm side	9000	0.3260	18.387	6.61	0.9772
200	warm side	10000	0.3235	18.262	7.39	0.9846

重複範例4-13，如果是平行流 (parallel flow) 的熱交換器，重複上題，面積由 60 m^2，增加到 200 m^2，試探討反向流與平行流熱交換器的差異？

Area, m^2	Limiting	UA	m_{water}	Water t_{exit}	NTU	ε
60	Cold	3000	0.979	29.482	1.19	0.5294
100	Cold	5000	0.7144	27.48	1.99	0.5294
140	Cold	7000	0.6831	27.092	2.78	0.5294
200	Cold	10000	0.6761	27.01	3.98	0.5294

第四章 作業

1. Exercise 1 on p139 of Textbook.
2. Exercise 8 on p140 of Textbook
3. 算完後請分別使用RVALUE 與 XCHANGER 兩程式進行驗證，並將最後結果直接由螢幕上HARD COPY。

加分題：

1. 建立MATLAB 版本的RVALUE程式。
2. 建立 MATLAB 版本的XCHANGER程式。