The f-Chart Method for Solar Collectors

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Mechanical Engineering 496ALT

Alternative Energy

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California State University Northridge

Outline

- Review heat exchangers
- Solar collector performance equations
- Derivation of f-chart method
- Demonstration of f-chart results
- Main reference: Duffie and Beckman, *Solar Engineering of Thermal Processes*, Wiley, 2006
- See http://www.fchart.com/ for f-chart software information

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Heat Exchangers

- Used to transfer energy from one fluid to another
  - U = overall heat transfer coefficient, $W/m^2 \cdot K$
- One fluid, the hot fluid, is cooled while the other, the cold fluid, is heated
- May have phase change: temperature of one or both fluids is constant
- Simplest is double pipe heat exchanger
  - Parallel flow and counter flow
- More complex designs may be used

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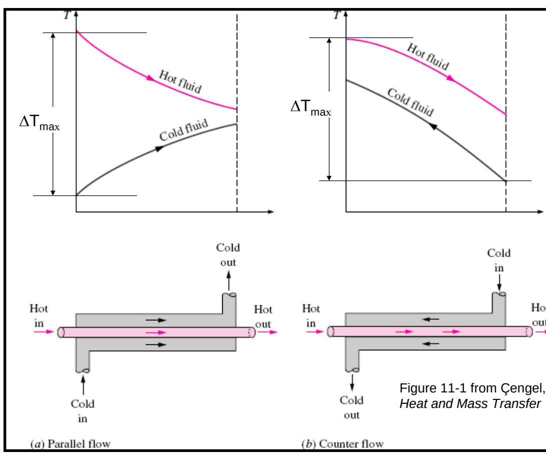
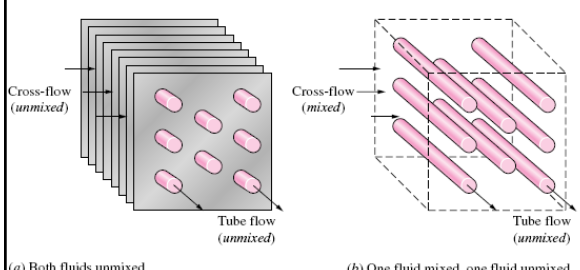


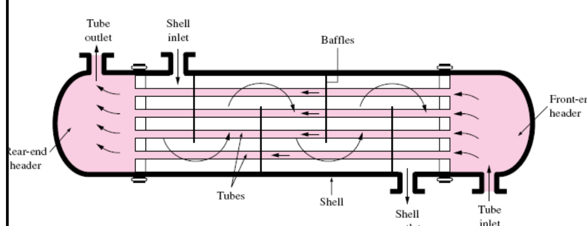
Figure 11-1 from Çengel, *Heat and Mass Transfer*

Compact Heat Exchangers III



California State University Northridge Figure 11-3 from Çengel, *Heat and Mass Transfer* 5

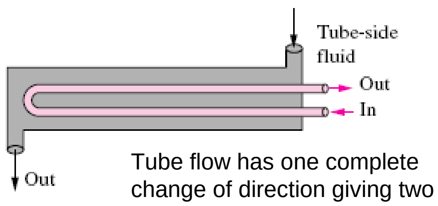
Shell-and-Tube Exchanger



- Counter flow exchanger with larger surface area; baffles promote mixing

California State University Northridge Figure 11-4 from Çengel, *Heat and Mass Transfer* 6

Shell and Tube Passes II



Tube flow has one complete change of direction giving two tube passes

(a) One-shell pass and two-tube passes

Figure 11-5(a) from Çengel, *Heat and Mass Transfer*

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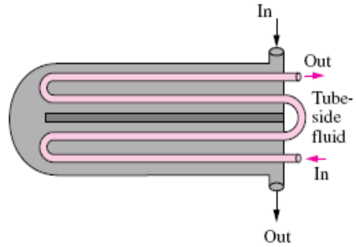
Shell and Tube Passes III



Tube flow has three complete changes of direction giving four tube passes

Shell flow changes direction to give two shell passes

(b) Two-shell passes and four-tube passes

Figure 11-5(b) from Çengel, *Heat and Mass Transfer*

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Effectiveness-NTU Method

- Analysis approach for heat exchangers when not all temperatures are known
  - Based on ratio of actual heat transfer to maximum possible heat transfer
  - Maximum possible temperature difference for one fluid, ΔT_{max} is $T_{h,in} - T_{c,in}$
  - Subscripts **c** and **h** for **c**old and **h**ot
  - Only one fluid, the one with the smaller value of $\dot{m}c_p$, can have ΔT_{max}
  - Define $C_c = (\dot{m}c_p)_c$ and $C_h = (\dot{m}c_p)_h$

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Effectiveness, ε

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{\dot{Q}}{C_{min}\left(T_{h,in} - T_{c,in}\right)} \qquad C_{min} = \min\left(C_h, C_c\right) \qquad NTU = UA/C_{min}$$

- In effectiveness-NTU method we find ε, then find $\dot{Q} = \varepsilon\dot{Q}_{max}$
  - Use $C_{min}\Delta T_{max}$ to find $\dot{Q}_{max}$
  - $C_1\Delta T_1 = C_2\Delta T_2$ or $\Delta T_2 = C_1\Delta T_1/C_2$
  - If $\Delta T_1 = \Delta T_{max}$ and $C_1/C_2 > 1$, $\Delta T_2 > \Delta T_{max}$
  - $C_{min}\Delta T_{max}$ is maximum heat transfer without impossible $T < T_{c,in}$ or $T > T_{h,in}$

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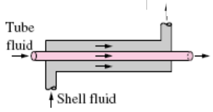
Effectiveness Equations

- Double pipe parallel flow

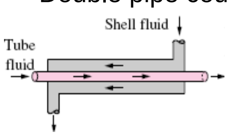
$$NTU = \frac{UA}{C_{min}}$$



$$\varepsilon = \frac{1 - e^{-NTU(1+c)}}{1 + c}$$

- Double pipe counter flow

$$c = \frac{C_{min}}{C_{max}}$$

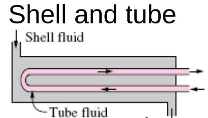


$$\varepsilon = \frac{1 - e^{-NTU(1-c)}}{1 - ce^{-NTU(1-c)}}$$

California State University Northridge Figures from Figure 11-26 from Çengel, *Heat and Mass Transfer* 11

More Effectiveness Equations

- Shell and tube



One shell pass and 2, 4, 6, … tube passes

$$c = \frac{C_{min}}{C_{max}}$$

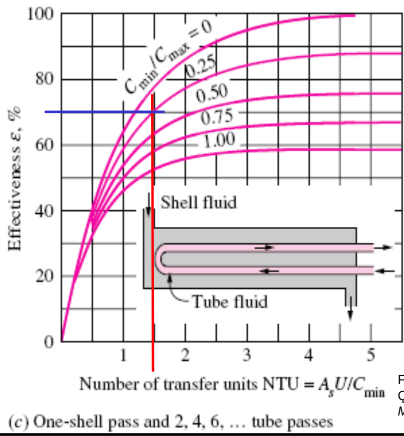
$$\varepsilon = 2\left\{1 + c + \sqrt{1+c^2}\,\frac{1 + e^{-NTU\sqrt{1+c^2}}}{1 - e^{-NTU\sqrt{1+c^2}}}\right\}^{-1}$$

- Any geometry with c = 0

$$\varepsilon = 1 - e^{-NTU} \qquad NTU = \frac{UA}{C_{min}}$$

California State University Northridge Figure from Figure 11-26 from Çengel, *Heat and Mass Transfer* 12

Find ε



Example chart for finding effectiveness from NTU = UA/C_{min} and C_{min}/C_{max} ratio

For NTU = 1.5 and C_{min}/C_{max} = 0.25, ε = .7

Figure 11-26 from Çengel, *Heat and Mass Transfer*

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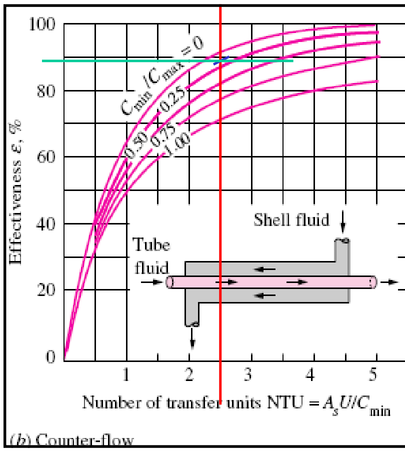
Chart ε



From chart for counter flow:

NTU = 2.5

C_{min}/C_{max} = 0.16

ε = 0.89

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Basic Collector Performance

- Energy balance on collector
- Useful energy gain = solar energy input adsorbed by collector – losses by heat transfer to ambient
- Look at variation throughout year to get overall performance
  - Detailed hour-by-hour computer analysis for large installations
  - Simplified f-chart method for residences

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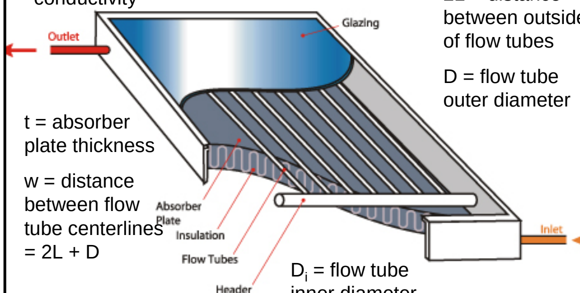
Flat Plate Collector

k = absorber thermal conductivity

2L = distance between outside of flow tubes

D = flow tube outer diameter



t = absorber plate thickness

w = distance between flow tube centerlines = 2L + D

D_i = flow tube inner diameter

Useful Energy Gain

- Q_u = rate of useful heat into collector
- A_c = collector area
- H_a = solar energy absorbed = $H_i\tau\alpha$
- U_c = collector overall heat-loss coefficient
- $T_{f,in}$ = inlet collector fluid temperature
- T_a = ambient temperature
- F_R = collector heat removal factor

$$Q_u = A_c F_R \left[H_a - U_c\left(T_{f,in} - T_a\right)\right]$$

Hottel-Willier-Bliss equation

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Heat Removal Factor, F_R

- A_c and U_c defined on previous chart
- $(\dot{m}c_p)_c$ = product of mass flow rate and heat capacity of collector fluid
- F' = collector efficiency factor
- $T_{f,out}$ = outlet collector fluid temperature

$$F_R = \frac{(\dot{m}c_p)_c}{A_c U_c}\left[1 - e^{-\frac{F' A_c U_c}{(\dot{m}c_p)_c}}\right]$$

- Energy balance on collector fluid

$$Q_u = (\dot{m}c_p)_c\left(T_{f,out} - T_{f,in}\right)$$

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Collector Efficiency Factor

$$F' = \frac{\text{Thermal resistance between absorber plate and ambient}}{\text{Thermal resistance between collector fluid and ambient}}$$

$$F' = \frac{1/U_c}{w\left[\frac{1}{U_c(2LF+D)}+\frac{1}{C_B}+\frac{1}{h_{c,i}\pi D_i}\right]}$$

- F = tanh(mL)/mL $m^2 = U_c/tk$, t, k = absorber plate thickness, thermal conductivity
- C_B = bond conductance = $k_B w_B / k_B$
- $h_{c,i}$ = flow tube internal heat transfer coefficient

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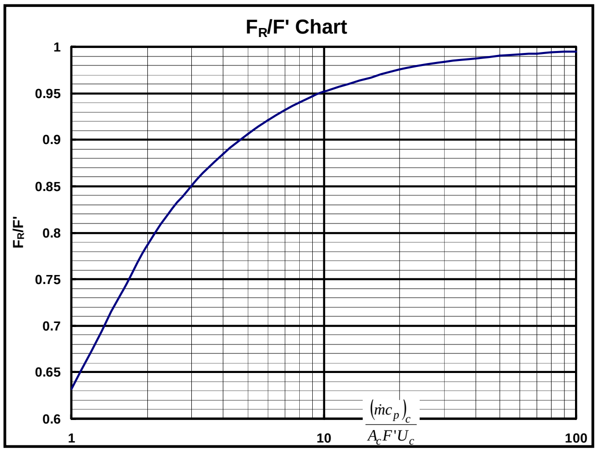

F-chart Water Heating Only

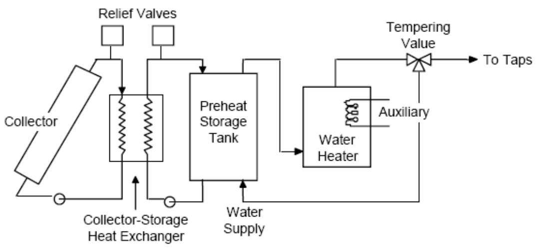

Figure 4.1: Two-Tank Domestic Water Heating System

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System with Solar Air Heating

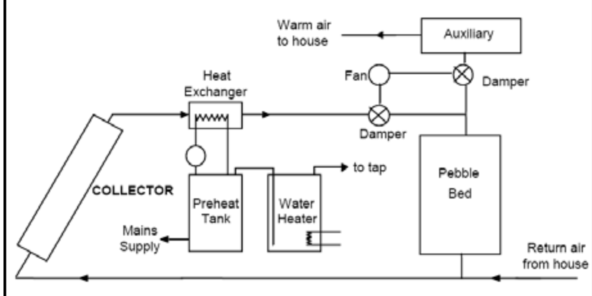

Figure 4.2: Pebble Bed Storage Space and Water Heating System

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F-Chart Water and Space Heating

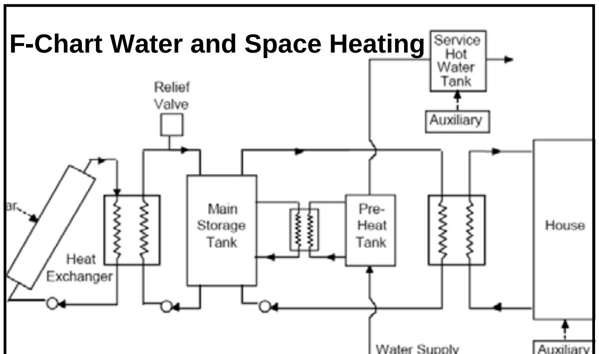

Figure 4.3: Water Storage Space and Water Heating System

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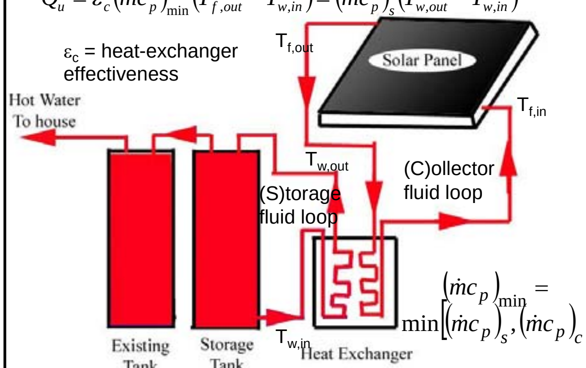
$$Q_u = \varepsilon_c(\dot{m}c_p)_{min}(T_{f,out} - T_{w,in}) = (\dot{m}c_p)_s(T_{w,out} - T_{w,in})$$

ε_c = heat-exchanger effectiveness



http://starfiresolar.com/db2/00144/starfiresolar.com/_uimages/solardiagramallred.jpg

Combine Equations

$$Q_u = A_c F_R\left[H_a - U_c\left(T_{f,in} - T_a\right)\right]$$

$$Q_u = \left(\dot m c_p\right)_c\left(T_{f,out} - T_{f,in}\right) \;\Rightarrow\; T_{f,in} = T_{f,out} - \frac{Q_u}{\left(\dot m c_p\right)_c}$$

- Eliminate $T_{f,in}$ in favor of $T_{f,out}$

$$Q_u = A_c F_R H_a - A_c F_R U_c\left[T_{f,out} - \frac{Q_u}{\left(\dot m c_p\right)_c} - T_a\right]$$

$$Q_u\left[1 - \frac{A_c F_R U_c}{\left(\dot m c_p\right)_c}\right] = A_c F_R H_a - A_c F_R U_c\left(T_{f,out} - T_a\right)$$

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Heat Exchanger

$$Q_u = \varepsilon_c\left(\dot m c_p\right)_{min}\left(T_{f,out} - T_{w,in}\right) \;\Rightarrow\; T_{f,out} = T_{w,in} + Q_u/\varepsilon_c\left(\dot m c_p\right)_{min}$$

- Substitute into previous Q_u equation, rearrange, and define F'_R

$$Q_u\left[1 - \frac{A_c F_R U_c}{\left(\dot m c_p\right)_c}\right] = A_c F_R H_a - A_c F_R U_c\left(T_{f,out} - T_a\right)$$
$$= A_c F_R H_a - A_c F_R U_c\left(T_{w,in} + Q_u/\varepsilon_c\left(\dot m c_p\right)_{min} - T_a\right)$$

$$Q_u\left[1 - \frac{A_c F_R U_c}{\left(\dot m c_p\right)_c} + \frac{A_c F_R U_c}{\varepsilon_c\left(\dot m c_p\right)_{min}}\right] = A_c F_R H_a - A_c F_R U_c\left(T_{w,in} - T_a\right)$$

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$$Q_u = A_c F'_R\left[H_a - U_c\left(T_{w,in} - T_a\right)\right]$$

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Heat Exchanger II

$$F'_R = F_R\left[1 - \frac{A_c F_R U_c}{\left(\dot m c_p\right)_c} + \frac{A_c F_R U_c}{\varepsilon_c\left(\dot m c_p\right)_{min}}\right]^{-1} = F_R\left[1 + \frac{A_c F_R U_c}{\left(\dot m c_p\right)_c}\left(\frac{\left(\dot m c_p\right)_c}{\varepsilon_c\left(\dot m c_p\right)_{min}} - 1\right)\right]^{-1}$$

- F'_R/F_R about 0.97 (Hodge – for water)
- If $T_{w,out} > T_{max}$ = 100ºC, water is vented
- Define Q_d as solar heat delivered

$$Q_d = \begin{cases} \max\left[\left(\dot m c_p\right)_s\left(T_{w,out} - T_{w,in}\right), 0\right] & T_{w,out} \le T_{max} \\ \left(\dot m c_p\right)_s\left(T_{max} - T_{w,in}\right) & T_{w,out} > T_{max} \end{cases}$$

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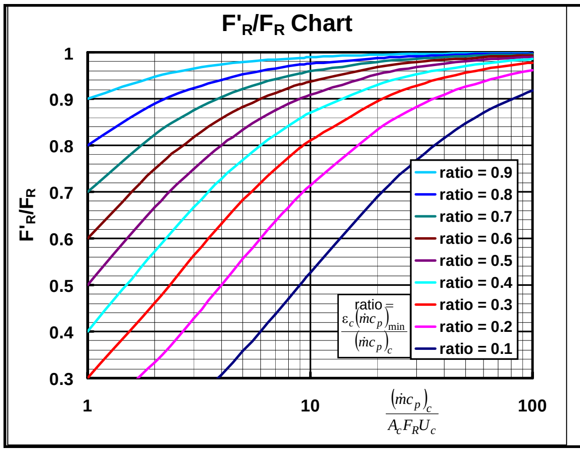

Storage Tank Energy Change

$$Mc_p\frac{dT_s}{dt} = Q_d - Q_{L,s} - Q_{w,s} - Q_{TL}$$

- Mc_p = mass * c_p for storage tank liquid
- $Q_{L,s}$ = space heating supplied by solar
- $Q_{w,s}$ = water heating supplied by solar
- Q_{TL} = storage tank heat loss
- t = time
- f-chart method integrates this equation over some time period (1 month)

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f-chart Method Development

$$\int_{\Delta t} Mc_p\frac{dT_s}{dt}dt = \int_{\Delta t} Q_d\,dt - \int_{\Delta t} Q_{L,s}\,dt - \int_{\Delta t} Q_{w,s}\,dt - \int_{\Delta t} Q_{TL}\,dt$$

0 = $-Q_S$

- For a long time period, the initial transient term is negligible
- The tank loss warms the house and contributes to the home heating load
- The last three integrals are the total energy supplied by solar, Q_s

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f-chart Method Development II

$$0=\int_{\Delta t} Q_d\,dt - Q_s \quad\Rightarrow\quad Q_s=\int_{\Delta t} Q_d\,dt \quad\Rightarrow\quad f=\frac{Q_s}{D}=\frac{1}{D}\int_{\Delta t} Q_d\,dt$$

- D = total energy demand
- f = fraction of total supplied by solar
- Use the definition of Q_s, total energy supplied by solar from previous slide

$$f=\frac{Q_s}{D}=\frac{1}{D}\int_{\Delta t}Q_d\,dt=\frac{1}{D}\int_{\Delta t}A_cF_R'\left[H_a-U_c\left(T_{w,in}-T_a\right)\right]dt$$

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f-chart Method Development III

- The absorbed solar radiation, H_a, is the incident radiation, H_i, times the factor $\tau\alpha$
  - τ is the fraction transmitted through the glass cover(s)
  - α is the fraction absorbed
- Set $H_a = H_i\tau\alpha$ and multiply the last term, top and bottom, by $T_{ref} - T_a$

$$f=\frac{Q_s}{D}=\frac{A_cF_R'}{D}\int_{\Delta t}\left[H_i\tau\alpha-U_c\left(T_{ref}-T_a\right)\frac{T_{w,in}-T_a}{T_{ref}-T_a}\right]dt$$

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f-chart Method Development IV

- Cannot evaluate integral because of the dependence of T_s on other variables
  - Use engineering judgment to identify important variables and form empirical parameters based on f equation

$$f=\frac{A_cF_R'}{D}\int_{\Delta t}H_i\tau\alpha\,dt-\frac{A_cF_R'}{D}\int_{\Delta t}U_c\left(T_{ref}-T_a\right)\frac{T_{w,in}-T_a}{T_{ref}-T_a}dt$$

$$Y=\frac{A_cF_R'}{D}\int_{\Delta t}H_i\tau\alpha\,dt \qquad X=\frac{A_cF_R'}{D}\int_{\Delta t}U_c\left(T_{ref}-T_a\right)dt$$

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What are X and Y?

$$X=\frac{A_cF_R'}{D}\int_{\Delta t}U_c\left(T_{ref}-T_a\right)dt$$

$$Y=\frac{A_cF_R'}{D}\int_{\Delta t}H_i\tau\alpha\,dt$$

- X is ratio of reference collector loss to total heating load
- Y is ratio of absorbed solar energy to total heating load

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f-chart Method Development V

- Integrate X and Y to get averages

$$Y=\frac{A_cF_R'}{D}\int_{\Delta t}H_i\tau\alpha\,dt=\frac{A_cF_R'\overline{\tau\alpha}}{D}\int_{\Delta t}H_i\,dt=\frac{A_cF_R'\overline{\tau\alpha}}{D}H_{i,total}$$

$$X=\frac{A_cF_R'}{D}\int_{\Delta t}U_c\left(T_{ref}-T_a\right)dt=\frac{A_cF_R'U_c}{D}\left(T_{ref}-\overline{T_a}\right)$$

- Rearrange equations to introduce factors F_RU_c and $F_R(\tau\alpha)_n$ available from standard collector test results

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f-chart Method Development VI

$$Y=\frac{F_R(\tau\alpha)_n}{F_R(\tau\alpha)_n}\frac{A_cF_R'\overline{\tau\alpha}}{D}H_{i,total} \quad\Rightarrow\quad \frac{Y}{A_c}=F_R(\tau\alpha)_n\frac{F_R'}{F_R}\frac{\overline{\tau\alpha}}{(\tau\alpha)_n}\frac{H_{i,total}}{D}$$

$$X=\frac{F_R}{F_R}\frac{A_cF_R'U_c}{D}\left(T_{ref}-\overline{T_a}\right)\Delta t \quad\Rightarrow\quad \frac{X}{A_c}=F_RU_c\frac{F_R'}{F_R}\frac{\Delta t}{D}\left(T_{ref}-\overline{T_a}\right)$$

- $(\tau\alpha)_n$ = value of the $\tau\alpha$ product for normal radiation measured in tests
- $H_{i,total}$ is available from NREL data for Δt = 1 month

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Collector Efficiency Equations

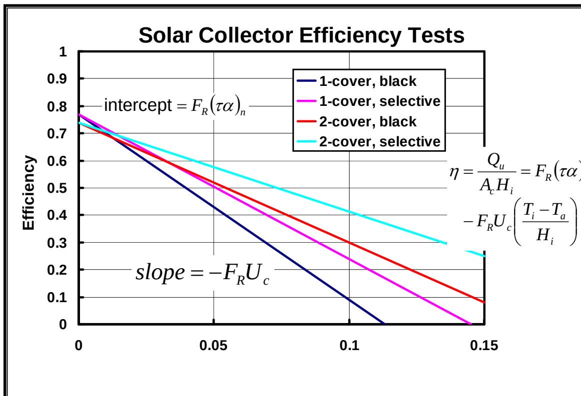
- From March 22-24 lecture

$$Q_u = \left(\dot{m}c_p\right)_c\left(T_{f,out} - T_{f,in}\right)$$

$$Q_u = A_c F_R\left[H_i(\tau\alpha)_n - F_R U_c\left(T_{f,in} - T_a\right)\right]$$

$$\eta = \frac{Q_u}{A_c H_i} = F_R(\tau\alpha)_n - F_R U_c\left(\frac{T_{f,in} - T_a}{H_i}\right)$$

- Plot of η *versus* $(T_{f,in} - T_a)/H_i$ is straight line with slope = $-F_R U_c$ and intercept $F_R(\tau\alpha)_n$



Sample Rating Sheet

SOLAR COLLECTOR CERTIFICATION AND RATING

SRCC OG-100

CERTIFIED SOLAR COLLECTOR

SUPPLIER: **Heliodyne, Inc.**
4910 Seaport Avenue
Richmond, CA 94804

MODEL: Heliodyne Gobi 408
COLLECTOR TYPE: Glazed Flat-Plate
CERTIFICATION #: 100-1981-085A

COLLECTOR THERMAL PERFORMANCE RATING

Megajoules Per Panel Per Day				Thousands of Btu Per Panel Per Day			
CATEGORY (Ti-Ta)	CLEAR DAY 23 MJ/m²·d	MILDLY CLOUDY 17 MJ/m²·d	CLOUDY DAY 11 MJ/m²·d	CATEGORY (Ti-Ta)	CLEAR DAY 2000 Btu/ft²·d	MILDLY CLOUDY 1500 Btu/ft²·d	CLOUDY DAY 1000 Btu/ft²·d
A (-5°C)	49	37	25	A (-9°F)	46	35	24
B (5°C)	45	33	21	B (9°F)	43	32	20
C (20°C)	39	27	15	C (36°F)	37	25	14
D (50°C)	24	14	4	D (90°F)	23	13	4
E (80°C)	10	2		E (144°F)	10	2	

A-Pool Heating (Warm Climate) B-Pool Heating (Cool Climate) C-Water Heating (Warm Climate) D-Water Heating (Cool Climate) E-Air Conditioning

Original Certification Date: August 1, 1983

http://www.builditsolar.com/References/Ratings/SRCCRating.htm

Sample Rating Sheet II

COLLECTOR SPECIFICATIONS

Gross Area:	2.996	m²	32.25	ft²
Dry Weight:	60.382	kg	133	lb
Test Pressure:	1034	kPa	150	psig
Net Aperture Area:	2.771	m²	29.83	ft²
Fluid Capacity:	3.0	l	0.8	gal

COLLECTOR MATERIALS

Frame:	Aluminum Extrusion
Cover (Outer):	Low Iron Tempered Glass
Cover (Inner):	None
Absorber Material:	Tube - Copper / Plate - Copper
Absorber Coating:	Black Chrome
Insulation (Side):	Isocyanurate Foam
Insulation (Back):	Isocyanurate Foam & Fiberglass

PRESSURE DROP

Flow		ΔP	
ml/s	gpm	Pa	in H_2O

slope = $-F_R U_c$
intercept = $F_R(\tau\alpha)_n$

TECHNICAL INFORMATION

Efficiency Equation [NOTE: Based on gross area and (P) = Ti-Ta]

						Y Intercept	Slope	
S I Units:	η = 0.725	-3.2000	(P)/I	-0.0220	(P)²/I	0.737	-4.57	W/m²·°C
I P Units:	η = 0.725	-0.5639	(P)/I	-0.0022	(P)²/I	0.737	-0.805	Btu/hr·ft²·°F

Incident Angle Modifier [(S) = 1/cos θ - 1, 0°≤ θ ≤60°]

$K_{\alpha\tau}$ = 1.0 -0.0900 (S) 0.0000 (S)²
$K_{\alpha\tau}$ = 1.0 -0.09 (S) (Linear Fit)

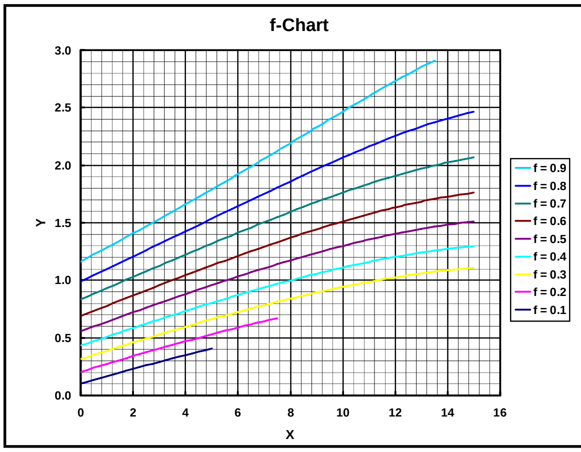
Model Tested: Gobi 408
Test Fluid: Water
Test Flow Rate: 56 ml/s 0.89 gpm

REMARKS:

November, 2006

Back to f Equation

- Had equation for f depending on factors like X and Y
- Form empirical relationship between f, X, and Y
- This is basis for f-chart method
- For water heating: $f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3$
- Klein, Beckman and Duffie developed method and software



Computing X (dimensionless)

$$X = A_c\left[F_R U_c \frac{F_R'}{F_R}\frac{\Delta t}{D}\left(T_{ref} - \overline{T}_a\right)\right]$$

- A_c = collector area (m^2)
- $F_R U_c$ ($W/m^2 \cdot K$) from slope of collector test data
- F'_R/F_R computed or assumed = 0.97
- Usual averaging period, Δt = 1 month, converted to seconds
- D = heating demand for averaging period (J)
- Tref = 100ºC; $\overline{T}_a$ from NREL data

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Computing Y (dimensionless)

$$Y = A_c\left[F_R(\tau\alpha)_n \frac{F_R'}{F_R}\frac{\overline{\tau\alpha}}{(\tau\alpha)_n}\frac{H_{i,total}}{D}\right]$$

- A_c = collector area (m^2)
- $F_R(\tau\alpha)_n$ from intercept of collector test
- F'_R/F_R computed or assumed = 0.97
- Ratio $\overline{\tau\alpha}/(\tau\alpha)_n$ = 0.94 (October – March), = 0.90 (April – September) or computed
- $H_{i,total}$ is available from NREL data for Δt = 1 month (convert to J/m^2)
- D is heating demand J

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NREL Data

- National Renewable Energy Laboratory
- Collector data for 1961-1990 for 360 individual months and monthly averages
  - Available for variety of collectors
    - Flat plate collector data for several angles
- TMY3 data: Typical Meteorological Year
  - Hourly data on radiation components
  - Compute resultant for given collector geometry

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NREL Solar Data

- 1961-1990 measured data for 239 sites
  - 56 sites measured; other had some modeled data
- 1991-2005 update for 1,454 locations
  - 99% of sites contain modeled data
  - Van Nuys Airport is in this update, but LAX is only LA site in original data set
  - Data format different from 1961-1990 data
- TMY3 data: Typical Meteorological Year
  - Hourly data on radiation components
  - Compute resultant for given collector geometry
- http://www.nrel.gov/rredc/solar_data.html

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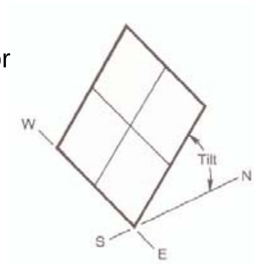
NREL Collector Types '61-'90

- Data available at different tilt levels for flat-plate collectors facing south
  - Horizontal (0º)
  - Latitude – 15º
  - Latitude
  - Latitude + 15º
  - Vertical (90º)



Flat-plate collector facing south at fixed tilt

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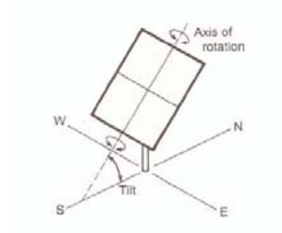
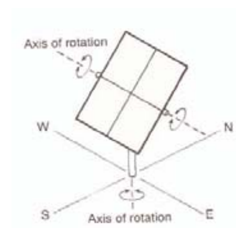
NREL Collector Types '61-'90 II



One-axis tracking flat-plate collector with axis oriented north-south



Two-axis tracking flat-plate collector

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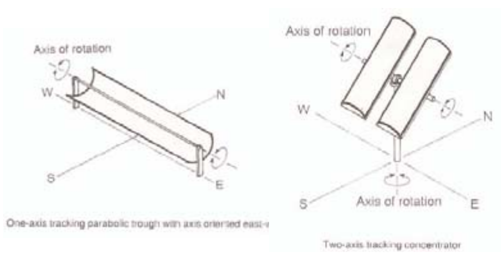
NREL Collector Types '61-'90 III



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NREL 1961-1990 LAX Average

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day) Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	2.8	3.6	4.8	6.1	6.4	6.6	7.1	6.5	5.3	4.2	3.2	2.6	4.9
	Minimum	2.3	3.0	4.0	5.5	5.7	5.6	6.4	6.1	4.4	3.8	2.7	2.1	4.7
	Maximum	3.3	4.4	5.6	6.8	7.2	7.7	8.0	7.0	5.8	4.5	3.6	3.0	5.1
Lat - 15	Average	3.8	4.5	5.5	6.4	6.4	6.4	7.1	6.8	5.9	5.0	4.2	3.6	5.5
	Minimum	2.9	3.6	4.5	5.8	5.7	5.4	6.3	6.3	4.7	4.4	3.4	2.7	5.2
	Maximum	4.6	5.7	6.4	7.3	7.3	7.3	7.9	7.2	6.6	5.6	4.9	4.3	5.7
Lat	Average	4.4	5.0	5.7	6.3	6.1	6.0	6.6	6.6	6.0	5.4	4.7	4.2	5.6
	Minimum	3.3	3.8	4.7	5.6	5.4	5.0	5.9	6.1	4.8	4.7	3.7	3.0	5.3
	Maximum	5.4	6.4	6.7	7.2	6.8	6.7	7.3	7.0	6.7	6.0	5.6	5.0	5.9
Lat + 15	Average	4.7	5.1	5.6	5.9	5.4	5.2	5.8	6.0	5.7	5.5	5.0	4.5	5.4
	Minimum	3.4	3.8	4.5	5.2	4.8	4.4	5.2	5.5	4.5	4.7	3.9	3.1	5.1
	Maximum	5.9	6.6	6.6	6.7	6.1	5.8	6.3	6.4	6.5	6.1	6.0	5.4	5.7
90	Average	4.1	4.1	3.8	3.3	2.5	2.2	2.4	3.0	3.6	4.2	4.3	4.1	3.5
	Minimum	2.9	3.0	3.1	2.9	2.3	2.1	2.3	2.8	2.9	3.5	3.2	2.7	3.3
	Maximum	5.2	5.4	4.5	3.6	2.7	2.3	2.5	3.2	4.1	4.7	5.2	5.0	3.7

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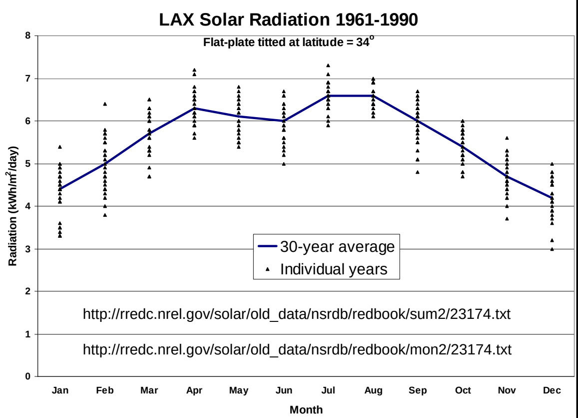

Flat-Plate Collector

Number of collector panels	26	
Collector panel area	20.80	ft^2
FR*UL (Test slope)	0.740	Btu/hr-ft^2-F
FR*TAU*ALPHA (Test intercept)	0.700	
Collector slope	45	degrees
Collector azimuth (South=0)	0	degrees
Incidence angle modifier calculatic	Glazings	
Number of glass covers	2	
Inc angle modifier constant	0.050	
Inc angle modifier value(s)	Ang Dep	
Collector flowrate/area	11.000	lb/hr-ft^2
Collector fluid specific heat	0.24	Btu/lb-F
Modify test values	No	
Test collector flowrate/area	11.000	lb/hr-ft^2
Test fluid specific heat	1.00	Btu/lb-F

Fchart Input data screen

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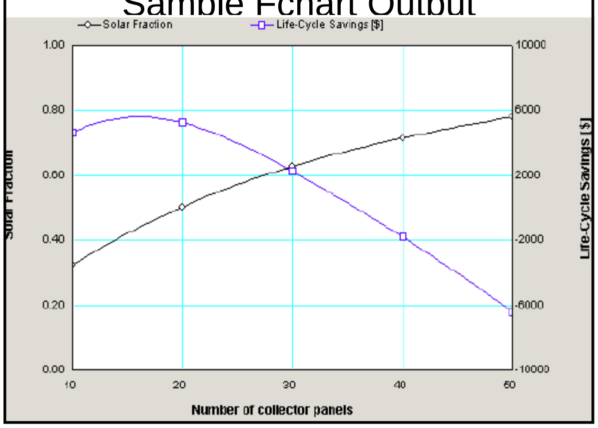
Thermal Output

	Solar [10^6 Btu]	Heat [10^6 Btu]	Dhw [10^6 Btu]	Aux [10^6 Btu]	f [ ]
Jan	17.98	18.69	2.384	13.64	0.353
Feb	20.06	15.24	2.148	8.77	0.495
Mar	23.99	12.36	2.368	4.95	0.664
Apr	24.94	7.11	2.277	0.72	0.924
May	27.89	3.27	2.341	0.00	1.000
Jun	28.46	0.83	2.255	0.00	1.000
Jul	29.52	0.37	2.326	0.00	1.000
Aug	28.06	0.68	2.330	0.00	1.000
Sep	24.07	2.43	2.263	0.00	1.000
Oct	21.02	6.28	2.351	1.34	0.844
Nov	14.38	10.95	2.287	7.82	0.409
Dec	14.05	16.53	2.378	13.66	0.277
Year	274.41	94.73	27.709	50.90	0.584

Sample Fchart Output



Adjustments

- Adjust X for storage capacity, M, in L/m^2
  $X' = X(75/M)^{1/4}$
- Adjust Y for load heat exchanger factor, Z: $Y' = Y(0.39 + 0.65e^{-0.139/Z})$
  - ε_L = heat exchanger effectiveness
  - mass flow times heat capacity and UA factors defined previously

$$Z = \varepsilon_L \left(\dot{m}c_p\right)_{\min} / (UA)_L$$

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Another Adjustment

- For systems with only water heating
  - T_w = water temperature to household
  - T_m = cold water supply temperature
  - T_a = monthly average ambient temperature
- Multiply X by correction factor, CF, below

$$CF = \frac{11.6 + 1.18T_w + 3.86T_m - 2.32\overline{T}_a}{100 - \overline{T}_a}$$

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