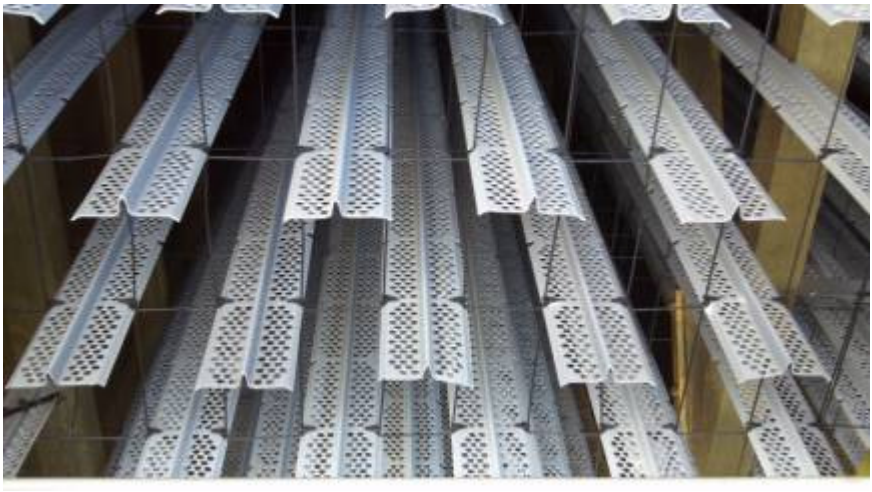
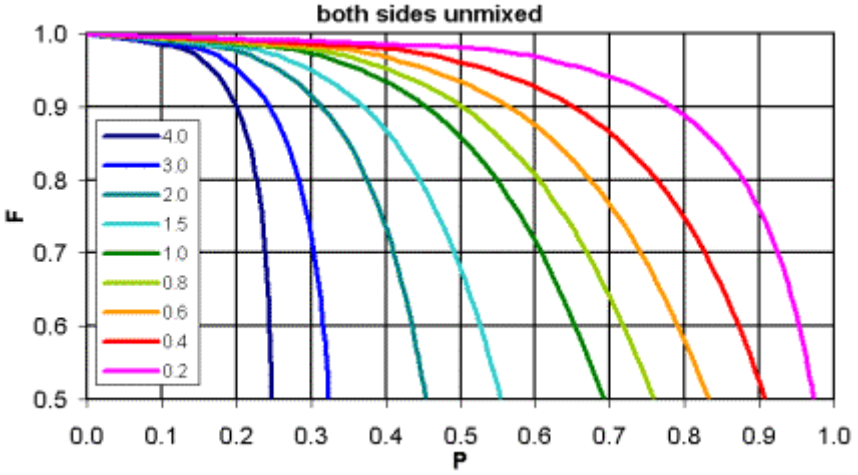
Heat Transfer:
Heat Exchangers,
Steam Generators
Cooling Towers
...just the figures for those who got the B&W version...

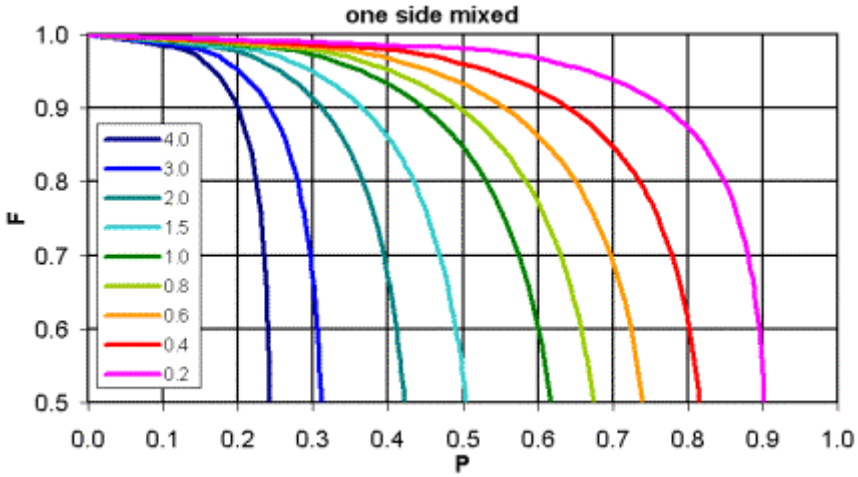
by D. James Benton

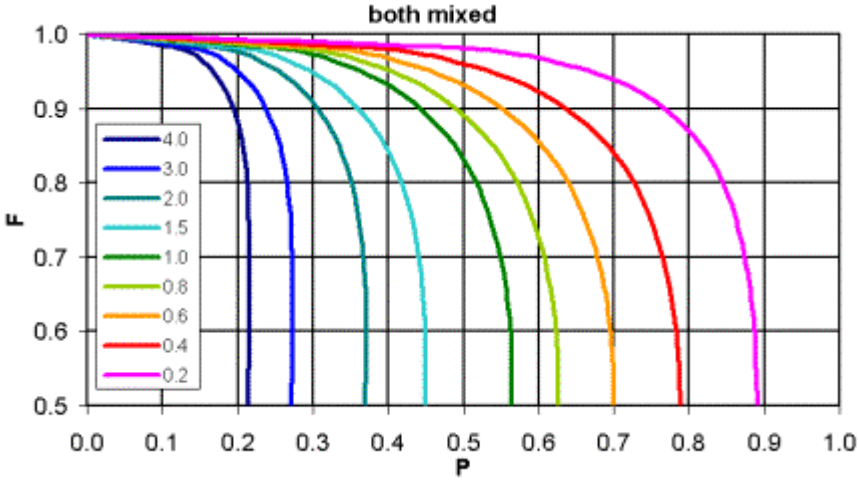
Typical Tube Bundle and Tube Sheet

Typical Spray and Splash Bars




both sides unmixed
1.0
0.9
0.8
0.7
0.6
0.5
F
4.0
3.0
2.0
1.5
1.0
0.8
0.6
0.4
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
P


one side mixed
F
P
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
4.0
3.0
2.0
1.5
1.0
0.8
0.6
0.4
0.2

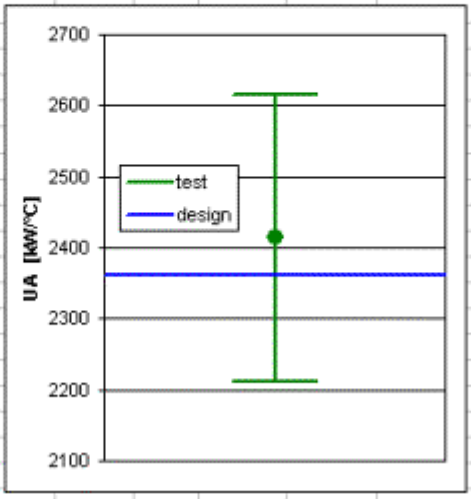

both mixed
F
P
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
4.0
3.0
2.0
1.5
1.0
0.8
0.6
0.4
0.2

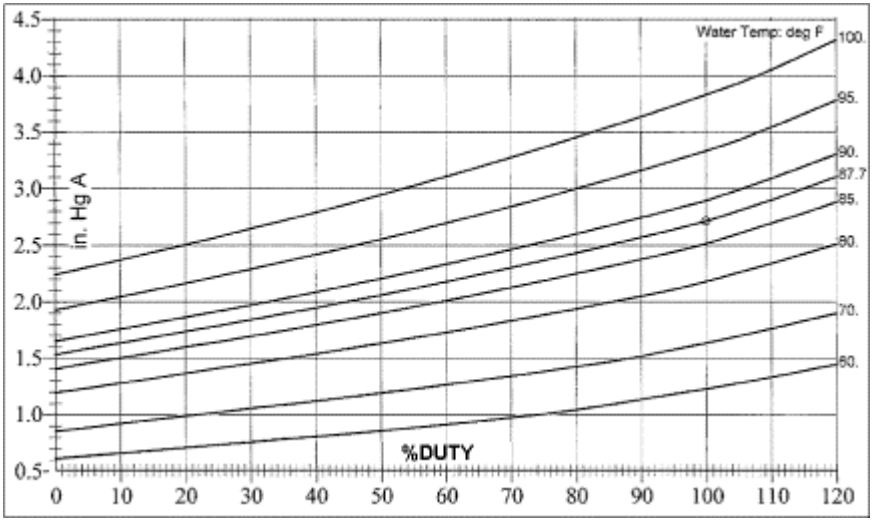
	A	B	C	D	E
1	**crossflow example**				
2	symbol	units	hot	cold	
3	U	W/m²/°C	**150**		
4	Cp	kJ/kg/°C	**4.0**	**1.0**	
5	m	kg/s	**100**	**500**	
6	Tin	°C	**50**	**15**	
7	Tout	°C	**20**	**39.0**	
8	q	kW	**12,000**		
9	LMTD	°C	**7.61**		
10	P	-	**0.686**		
11	R	-	**0.800**		
12	symbol	units	unmix	1 mix	mixed
13	F	-	**0.667**	**0.352**	**0.183**
14	UA	kW/°C	**2362**	**4481**	**8622**
15	A	m²	**15.7**	**29.9**	**57.5**
16	**user inputs in blue**				
17	**calculations in orange**				

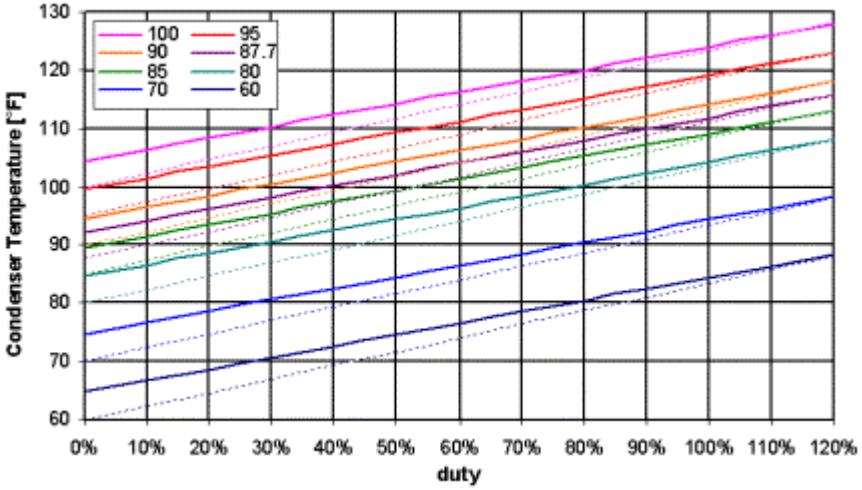
Crossflow Heat Exchanger Test with Uncertainty

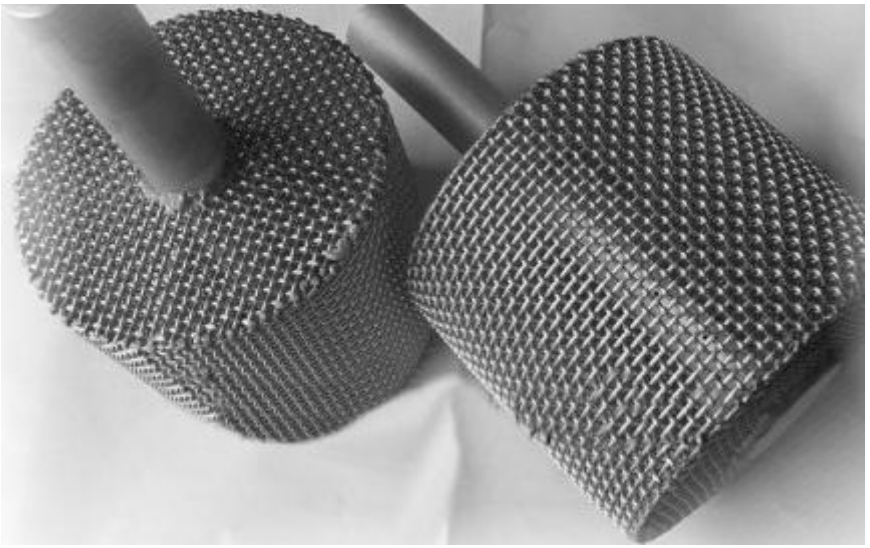
measurement	units	average	points	std.dev.	bias	total unc.	sensitivity	units	contrib
Thot,in	°C	51.25	30	0.82	0.14	0.34	-148.7	kW/°C²	-50
Thot,out	°C	20.85	30	0.79	0.14	0.33	-330.6	kW/°C²	-108
Tcold,in	°C	15.95	30	0.65	0.14	0.28	197.8	kW/°C²	56
Tcold,out	°C	40.35	30	0.63	0.14	0.28	281.6	kW/°C²	78
m,hot	kg/s	98.84	30	1.93%	2.0%	2.1%	55.41	kWs/kg/°C	116
m,cold	kg/s	497.55	30	1.62%	2.0%	2.1%	-6.156	kWs/kg/°C	-64
calculation	units	value							203
LMTD	°C	7.50							8.4%
q,hot	kW	12,019							
q,cold	kW	12,140							
q,avg	kW	12,080							
mCp,hot	kW/°C	395.358							
mCp,cold	kW/°C	497.549							
R	-	0.795							
P,hot	-	0.684							
P,cold	-	0.691							
F,hot	-	0.674							
F,cold	-	0.660							
UA,hot	kW/°C	2377							
UA,cold	kW/°C	2451							
UA,avg	kW/°C	2414							
UA,design	kW/°C	2362							
ΔUA	-	2.2%							

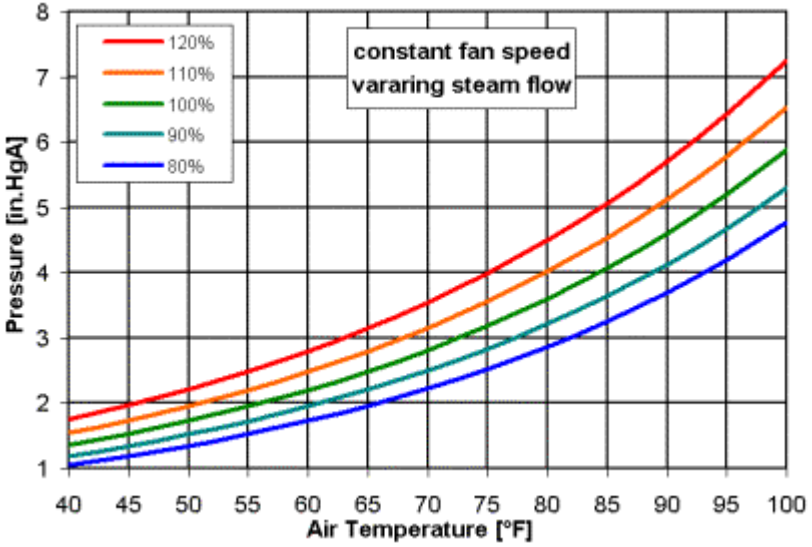
calculate sensitivities

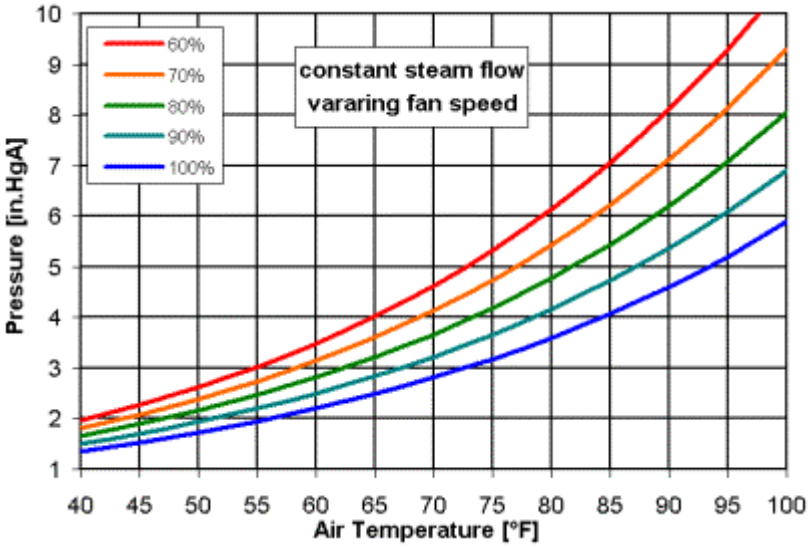


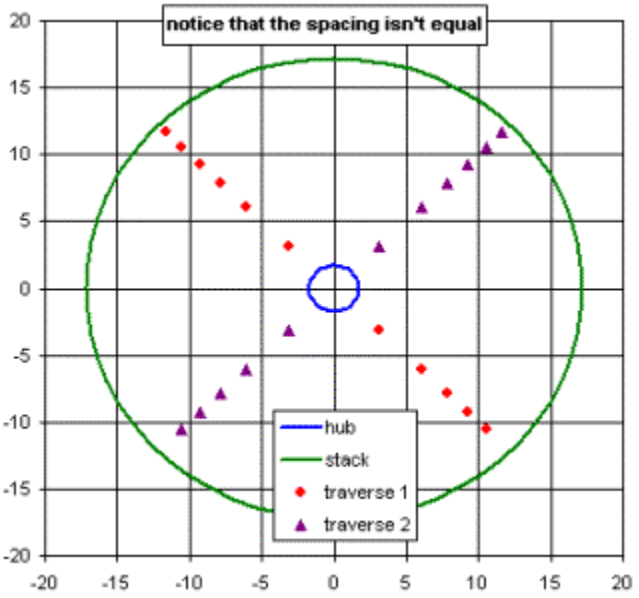

Water Temp: deg F
100.
95.
90.
87.7
85.
80.
70.
60.
in. Hg A
%DUTY
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
10
20
30
40
50
60
70
80
90
100
110
120

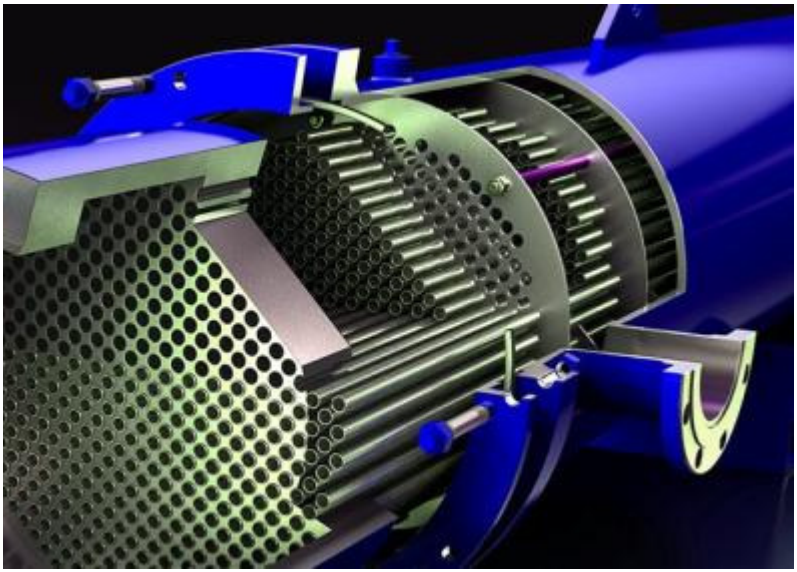

Condenser Temperature [°F]
130
120
110
100
90
80
70
60
100
95
90
87.7
85
80
70
60
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
110%
120%
duty

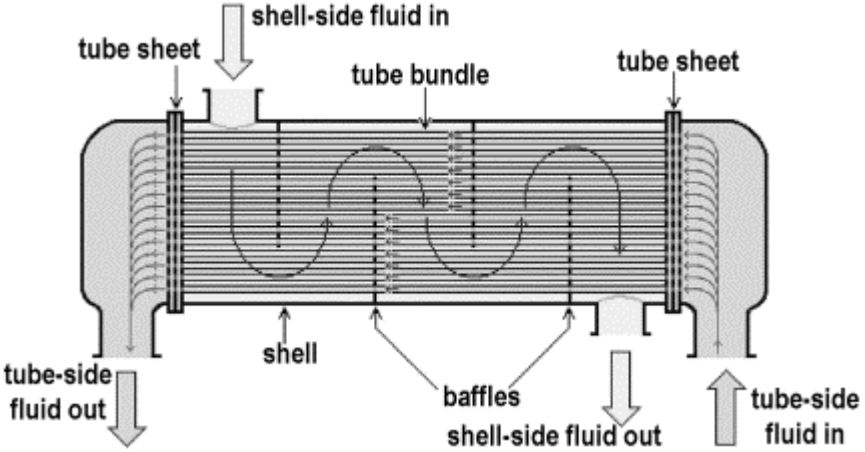



120%
110%
100%
90%
80%
constant fan speed
vararing steam flow
Pressure [in.HgA]
Air Temperature [°F]
1
2
3
4
5
6
7
8
40
45
50
55
60
65
70
75
80
85
90
95
100

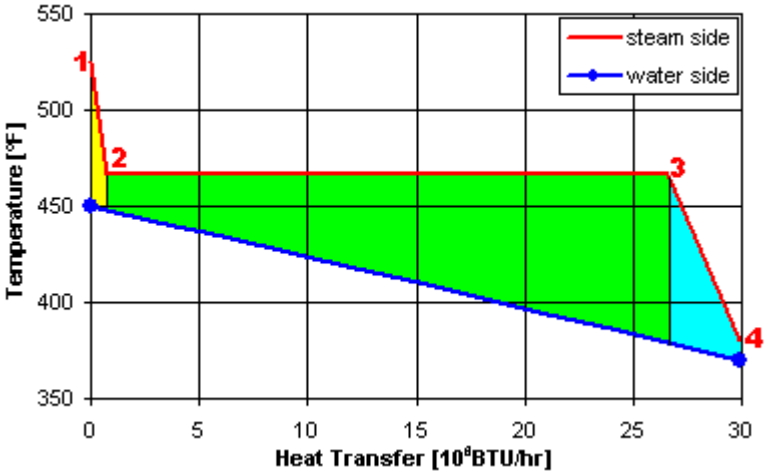

60%
70%
80%
90%
100%
constant steam flow
vararing fan speed
Pressure [in.HgA]
Air Temperature [°F]
1
2
3
4
5
6
7
8
9
10
40
45
50
55
60
65
70
75
80
85
90
95
100


notice that the spacing isn't equal
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0
5
10
15
20
hub
stack
traverse 1
traverse 2

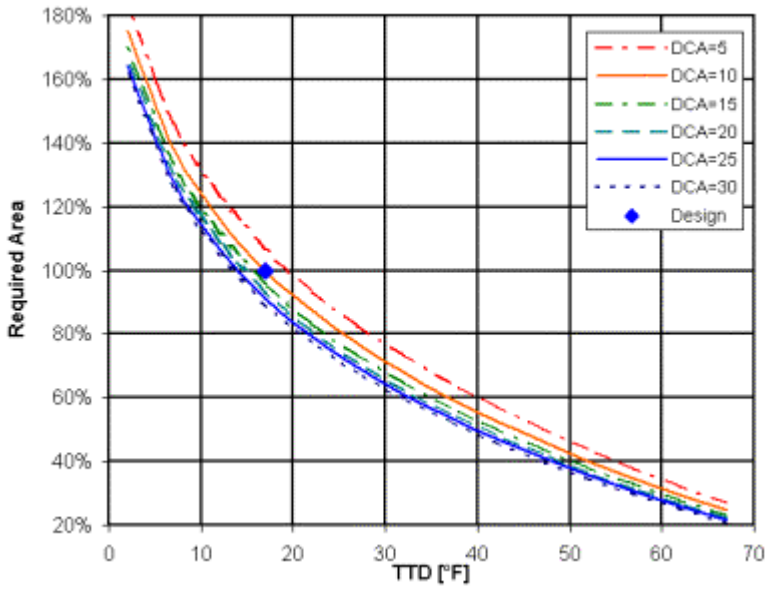




Performance Prediction

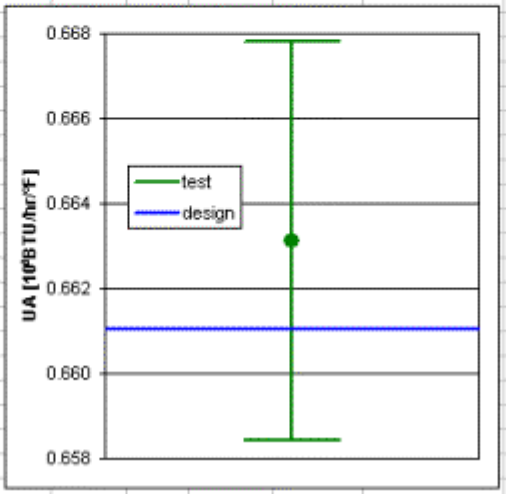


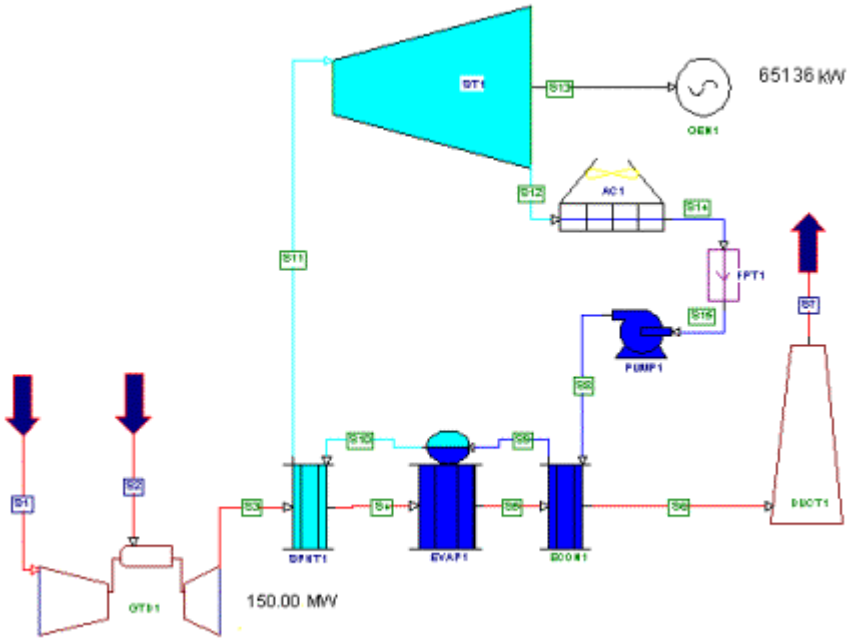
	A	B	C	D	E	F	G	H	I
1	**Feed Water Heater Example**								
2	INPUTS	units		CALCULATIONS	units				
3	feed water inlet			feed water inlet					
4	flow	lbm/hr	350,000	enthalpy	BTU/lbm	345.9			
5	pressure	psia	2250	feed water outlet					
6	temperature	°F	370	enthalpy	BTU/lbm	431.4			
7	feed water outlet			extraction					
8	pressure	psia	2200	saturation	°F	467.0			
9	temperature	°F	450	TTD	°F	17.0			
10	extraction			superheat	°F	58.0			
11	pressure	psia	500	enthalpy	BTU/lbm	1249.7			
12	temperature	°F	525	flow	lbm/hr	33,382			
13	drain			drain					
14	temperature	°F	380	DCA	°F	10.0			
15				enthalpy	BTU/lbm	354.0	U	A	area
16	heat trans. zone	Qx10^6	UA	zone color	units	ΔT	BTU/hr/ft²/°F	ft²	frac
17	de-superhtng	1.5	0.035	yellow	°F	42.4	100	354	23%
18	condensing	25.2	0.537	green	°F	46.9	600	895	58%
19	subcooling	3.2	0.089	cyan	°F	36.0	300	295	19%
20	process line		0.661	calculations		T		1544	
21	point 1	0	525	sat. vapor	BTU/lbm	1204.7			
22	point 2	1.5	467	sat. liquid	BTU/lbm	449.5			
23	point 3	26.7	467	desup. exit temp	°F	446.0			
24	point 4	29.9	380	cond. exit temp.	°F	378.5			

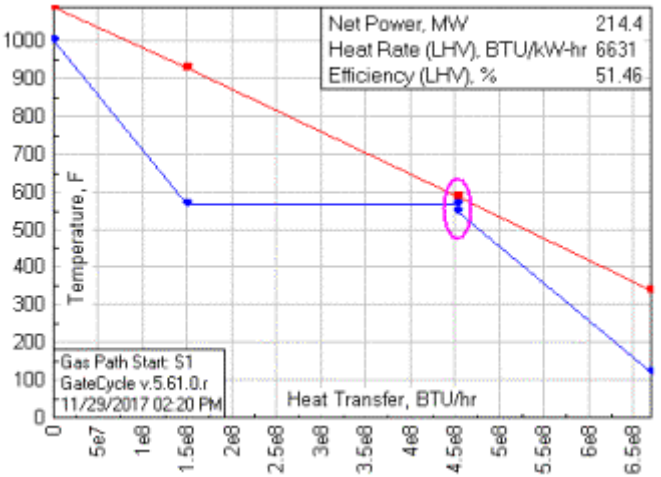


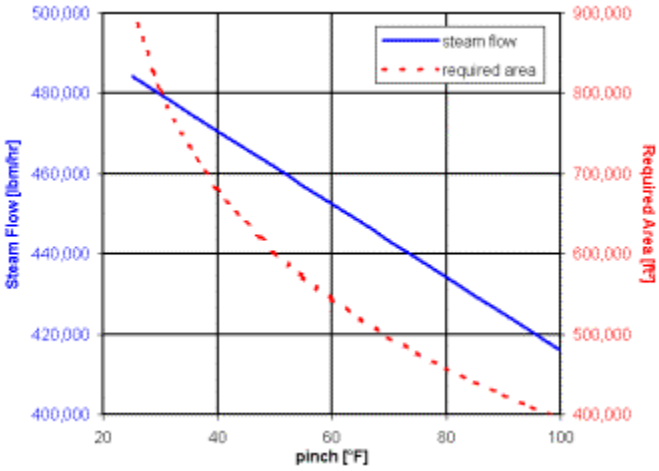
Feed Water Heater Test with Uncertainty									
measurement	units	average	points	std.dev.	bias	total unc.	sensitivity	units	contrib
Tfw,in	°F	371.5	30	0.63	0.14	0.28	-213.021	BTU/hr/°F/°F	-58.74
Tfw,out	°F	451.3	30	0.47	0.14	0.23	19948.34	BTU/hr/°F/°F	4530
Textract	°F	524.8	30	0.58	0.14	0.26	-964.167	BTU/hr/°F/°F	-250.7
Tdrain	°F	380.3	30	0.71	0.14	0.30	-3949.15	BTU/hr/°F/°F	-1191
Pfw,in	psia	2248	30	0.93%	0.75%	0.01	-11.601	BTU/hr/°F/psia	-0.096
Pfw,out	psia	2201	30	0.86%	0.75%	0.01	5.699826	BTU/hr/°F/psia	0.046
Pextract	psia	499	30	0.74%	0.75%	0.8%	-2985.15	BTU/hr/°F/psia	-23.86
flow,fw	lbm/hr	337,213	30	0.98%	2.0%	2.0%	1.966478	BTU/hr/°F/lbm/hr	0.04
calculation	units	value							4691
hfw,in	BTU/lbm	347.5							5.2%
hfw,out	BTU/lbm	432.8							
hextract	BTU/lbm	1249.6							
hg	BTU/lbm	1204.7							
hf	BTU/lbm	449.3							
hdrain	BTU/lbm	354.3							
flow,extract	lbm/hr	32,123							
Qdesuper	BTU/hr	1.4E+06							
Qconds	BTU/hr	2.4E+07							
Qsubcool	BTU/hr	3.1E+06							
Tsat	°F	466.8							
TTD	°F	15.5							
DCA	°F	8.8							
Tfw,desup	°F	447.3							
Tfw,subco	°F	380.0							
LMTD,desup	°F	40.7							
LMTD,cond	°F	45.1							
LMTD,subc	°F	34.1							
UA,desup	BTU/hr/°F	3.5E+04							
UA,conds	BTU/hr/°F	5.4E+05							
UA,subco	BTU/hr/°F	9.0E+04							
UA,total	BTU/hr/°F	6.6E+05							

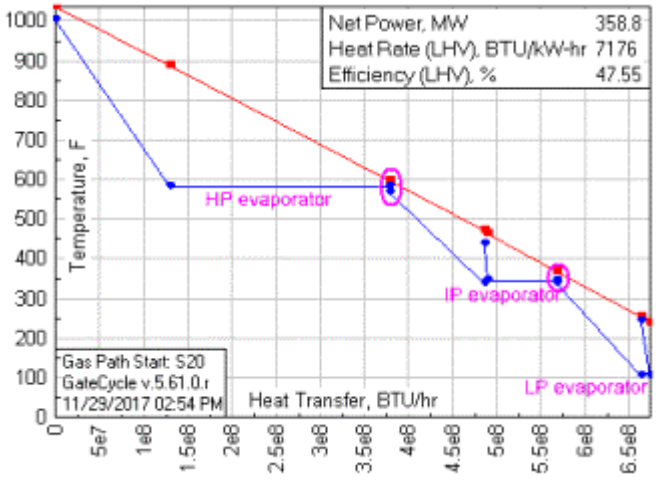
calculate sensitivities

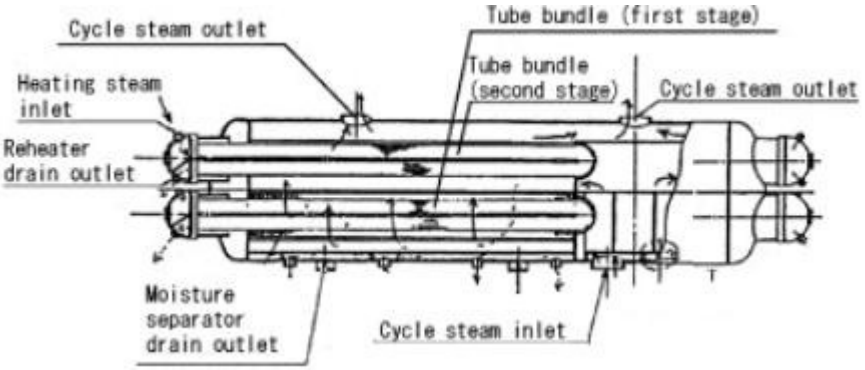



65136 kW
150.00 MW


Net Power, MW 214.4
Heat Rate (LHV), BTU/kW-hr 6631
Efficiency (LHV), % 51.46
Temperature, F
Heat Transfer, BTU/hr
Gas Path Start: S1
GateCycle v.5.61.0.r
11/29/2017 02:20 PM

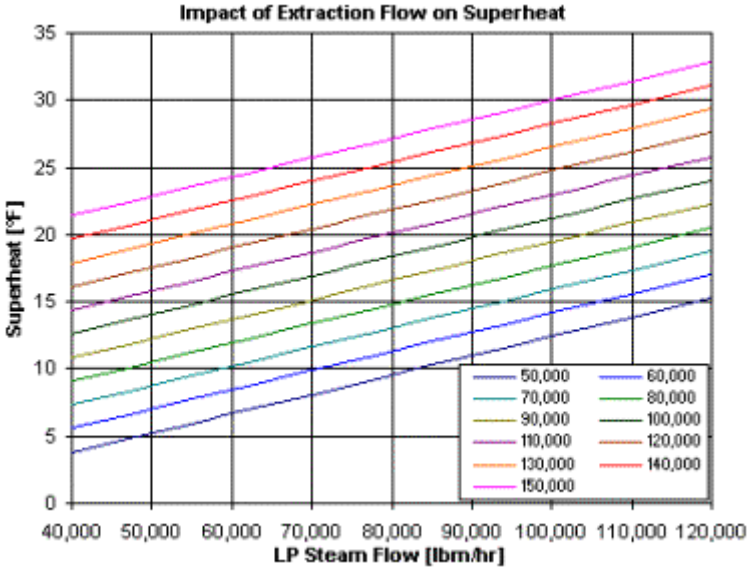

steam flow
required area
Steam Flow [lbm/hr]
Required Area [ft²]
pinch [°F]
500,000
480,000
460,000
440,000
420,000
400,000
900,000
800,000
700,000
600,000
500,000
400,000
20
40
60
80
100

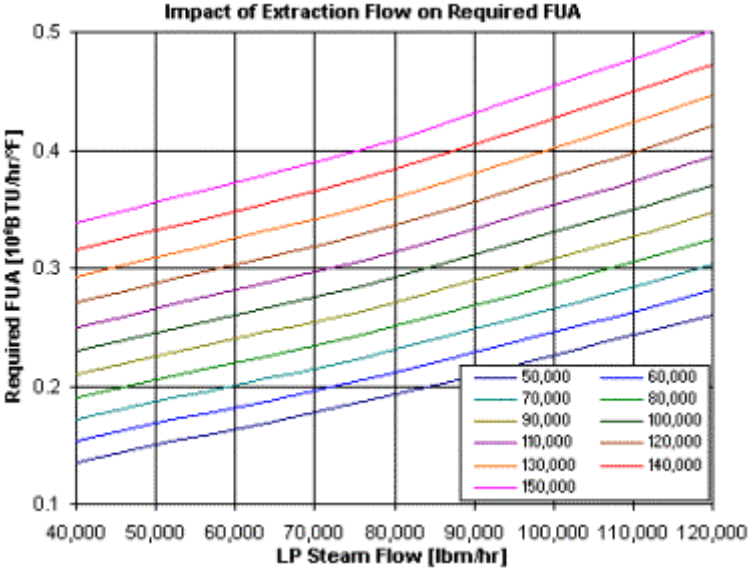

Net Power, MW 358.8
Heat Rate (LHV), BTU/kW-hr 7176
Efficiency (LHV), % 47.55
Temperature, F
HP evaporator
IP evaporator
LP evaporator
Gas Path Start: S20
GateCycle v.5.61.0.r
11/29/2017 02:54 PM
Heat Transfer, BTU/hr
1000
900
800
700
600
500
400
300
200
100
0
5e7
1e8
1.5e8
2e8
2.5e8
3e8
3.5e8
4e8
4.5e8
5e8
5.5e8
6e8
6.5e8


Cycle steam outlet
Tube bundle (first stage)
Tube bundle
(second stage)
Cycle steam outlet
Heating steam
inlet
Reheater
drain outlet
Moisture
separator
drain outlet
Cycle steam inlet

Performance Prediction

	A	B	C	D	E	F
1	**Moisture Separator Reheater Example**					
2	INPUTS	units	value	CALCS.	units	value
3	HP Tubes			LP Tubes		
4	Flow	lbm/hr	**100,000**	Tinlet	°F	**443.6**
5	Pinlet	psia	**834.5**	Toutlet	°F	**438.7**
6	Hinlet	BTU/lbm	**1295.6**	Houtlet	BTU/lbm	**1054.9**
7	Poutlet	psia	**824.2**	Shell Side		
8	Xoutlet	%	**97%**	Tinlet	°F	**370.8**
9	LP Tubes			Xinlet	%	**88.7%**
10	Flow	lbm/hr	**75,000**	Tchevr	°F	**369.2**
11	Pinlet	psia	**396.1**	Xchevr	%	**98.3%**
12	Hinlet	BTU/lbm	**1150.1**	Hchevr	BTU/lbm	**1181.7**
13	Poutlet	psia	**376.4**	Hmidl	BTU/lbm	**1196.0**
14	Xoutlet	%	**81%**	Tmidl	°F	**368.7**
15	Shell Side			Houtlet	BTU/lbm	**1219.4**
16	Flow	lbm/hr	**500,000**	Toutlet	°F	**385.8**
17	Pinlet	psia	**175.0**	superheat	°F	**17.6**
18	Hinlet	BTU/lbm	**1100.0**	LP Tubes		
19	chevrons	%	**85%**	Q	BTU/hr	**7.14E+06**
20	Pchevr	psia	**171.7**	LMTD	°F	**72.2**
21	Poutlet	psia	**169.4**	FUA	BTU/hr/°F	**9.90E+04**
22	CALCS.	units	value	HP Tubes		
23	HP Tubes			Q	BTU/hr	**1.17E+07**
24	Tinlet	°F	**596.0**	LMTD	°F	**63.7**
25	Toutlet	°F	**521.7**	FUA	BTU/hr/°F	**1.84E+05**
26	Houtlet	BTU/lbm	**1178.2**			

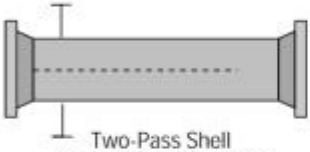

Impact of Extraction Flow on Superheat
Superheat [°F]
35
30
25
20
15
10
5
0
40,000 50,000 60,000 70,000 80,000 90,000 100,000 110,000 120,000
LP Steam Flow [lbm/hr]
50,000
60,000
70,000
80,000
90,000
100,000
110,000
120,000
130,000
140,000
150,000


Impact of Extraction Flow on Required FUA
Required FUA [10^6 BTU/hr/°F]
0.5
0.4
0.3
0.2
0.1
40,000 50,000 60,000 70,000 80,000 90,000 100,000 110,000 120,000
LP Steam Flow [lbm/hr]
50,000
60,000
70,000
80,000
90,000
100,000
110,000
120,000
130,000
140,000
150,000

E

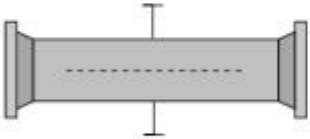
One-Pass Shell

F



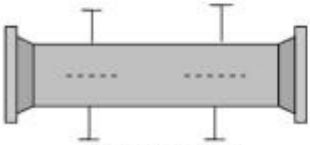
Two-Pass Shell
with Longitudinal Baffle

G



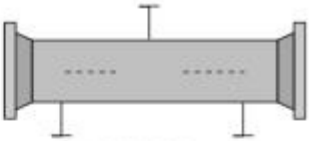
Split Flow

H



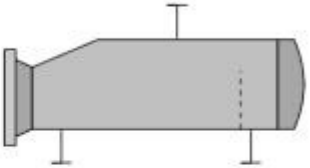
Double Split Flow

J



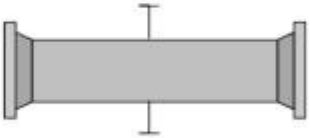
Divided Flow

K

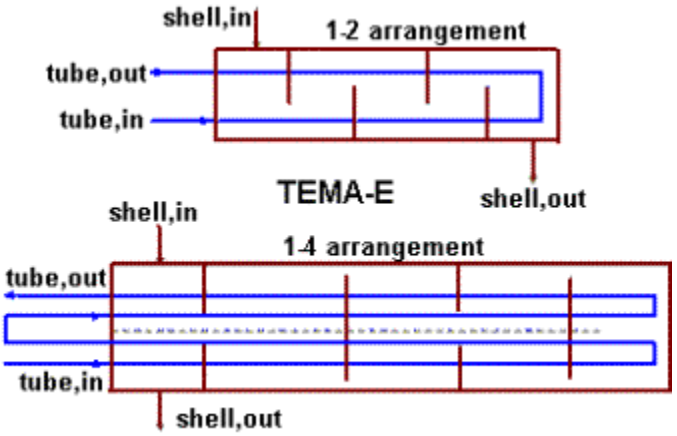


Kettle-Type Reboiler

X



Cross Flow

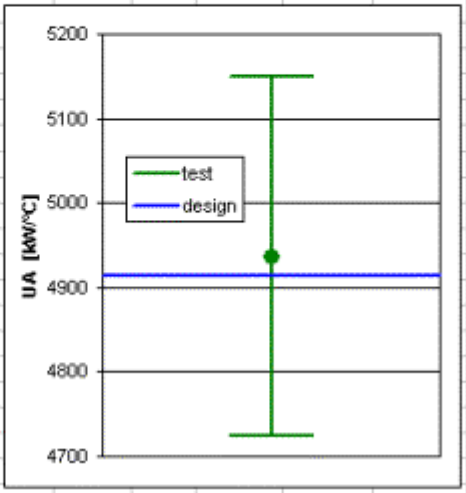


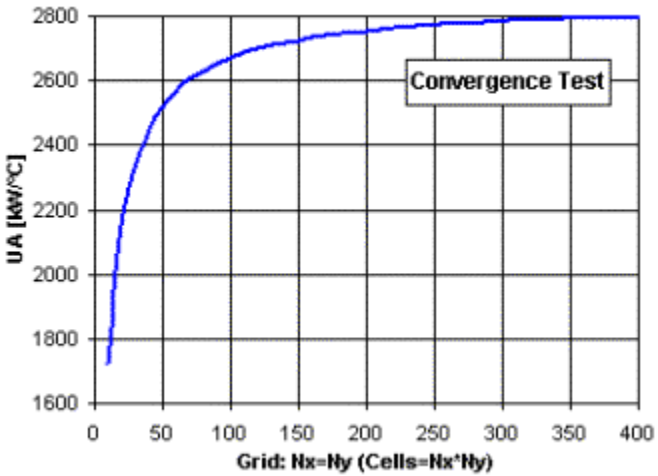
	A	B	C	D
1	**TEMA E-Shell Example**			
2	symbol	units	tube	shell
3	U	W/m²/°C	65	
4	Cp	kJ/kg/°C	2.5	1.0
5	m	kg/s	1000	8000
6	Tin	°C	250	50
7	Tout	°C	100	96.9
8	q	kW	375,000	
9	mCp	kW/°C	2,500	8,000
10	R	-	0.313	
11	ε	-	0.750	
12	NTU	-	1.965	
13	UA	-	4913	
14	A	m²	75.6	
15	user inputs in blue			
16	calculations in orange			

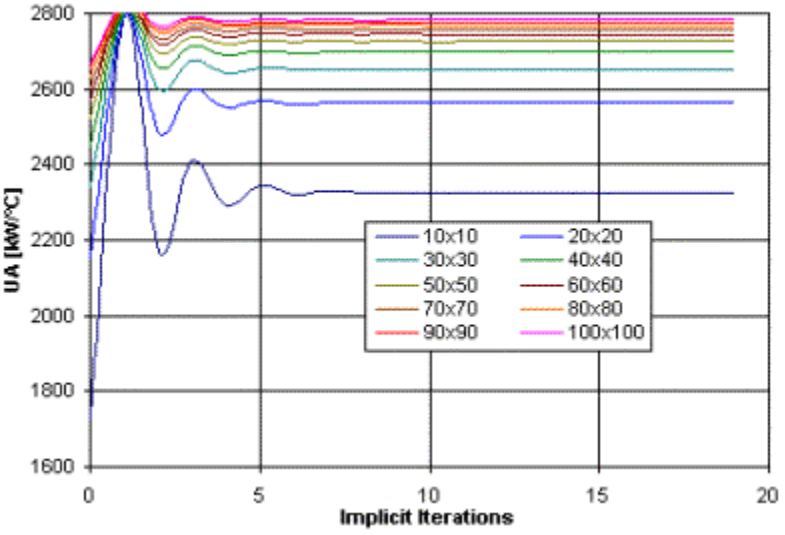
TEMA E-Shell Heat Exchanger Test with Uncertainty

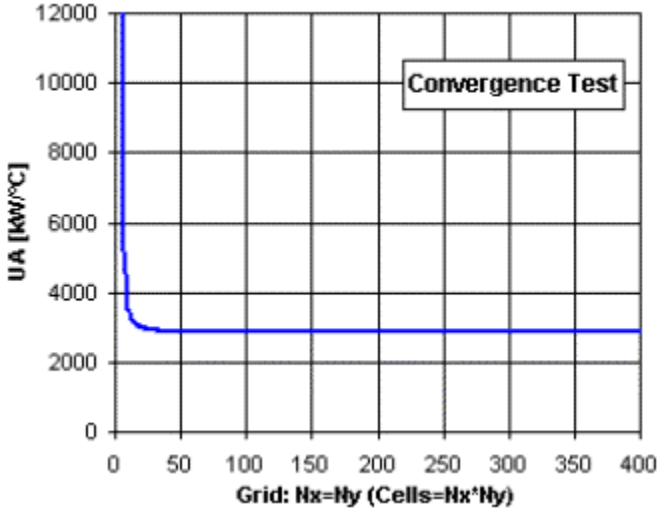
measurement	units	average	points	std.dev.	bias	total unc.	sensitivity	units	contrib
Thot,in	°C	247.61	30	2.11	0.14	0.80	-34.2	kW/°C²	-27
Thot,out	°C	101.24	30	1.79	0.14	0.68	-59.4	kW/°C²	-41
Tcold,in	°C	51.53	30	1.65	0.14	0.63	-115.0	kW/°C²	-73
Tcold,out	°C	97.81	30	1.44	0.14	0.56	208.5	kW/°C²	116
m,hot	kg/s	1000	30	1.93%	2.0%	2.1%	-2.17	kWs/kg/°C	-46
m,cold	kg/s	8000	30	1.62%	2.0%	2.1%	0.889	kWs/kg/°C	149
calculation	units	value							213
mCp,hot	kW/°C	2500							4.3%
mCp,cold	kW/°C	8000							
R	-	0.313							
q,hot	kW	365,925							
q,cold	kW	370,240							
q,avg	kW	368,083							
ε,hot	-	0.746							
ε,cold	-	0.755							
NTU,hot	-	1.932							
NTU,cold	-	2.018							
UA,hot	kW/°C	4829							
UA,cold	kW/°C	5044							
UA,avg	kW/°C	4937							
UA,design	kW/°C	4913							
ΔUA	-	0.5%							

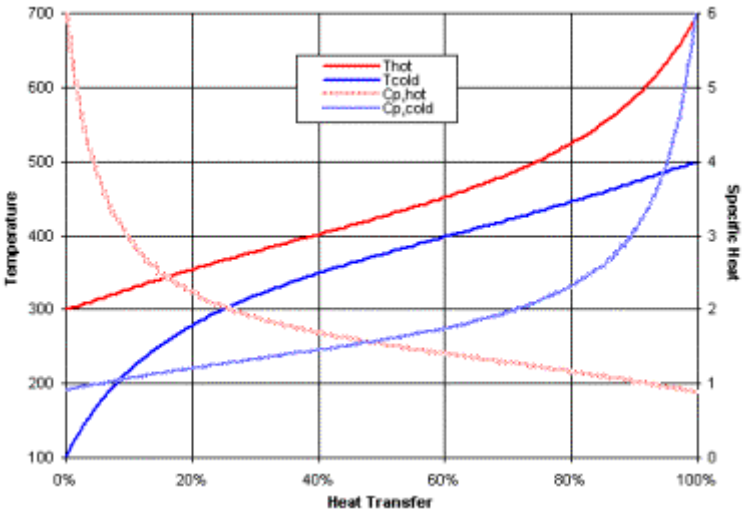
calculate sensitivities

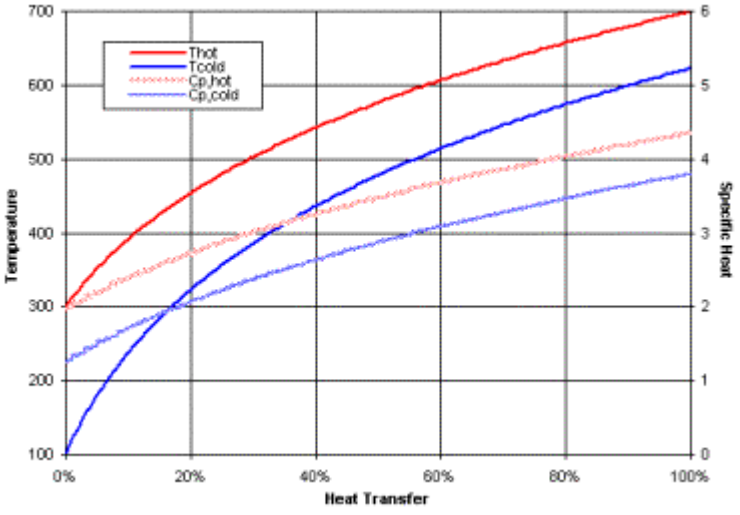


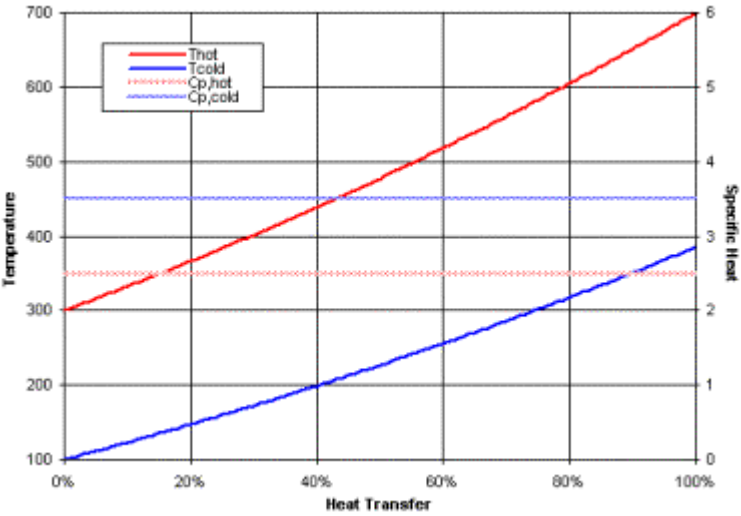


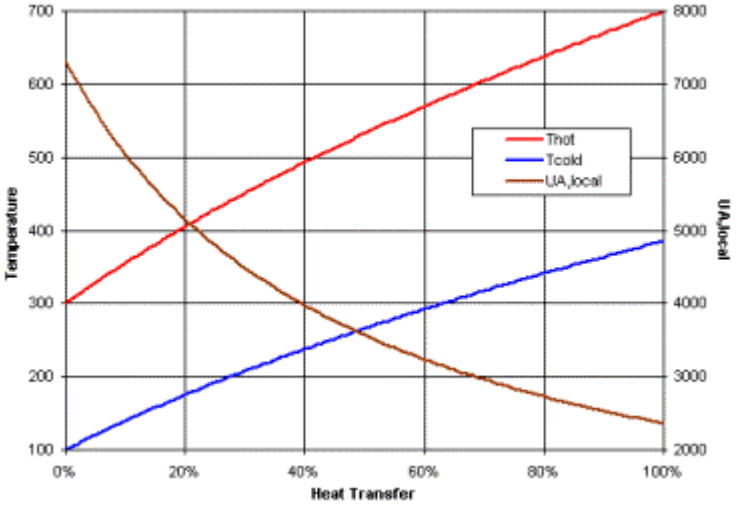

2800
2600
2400
2200
2000
1800
1600
UA [kW/°C]
0
5
10
15
20
Implicit Iterations
10x10
20x20
30x30
40x40
50x50
60x60
70x70
80x80
90x90
100x100

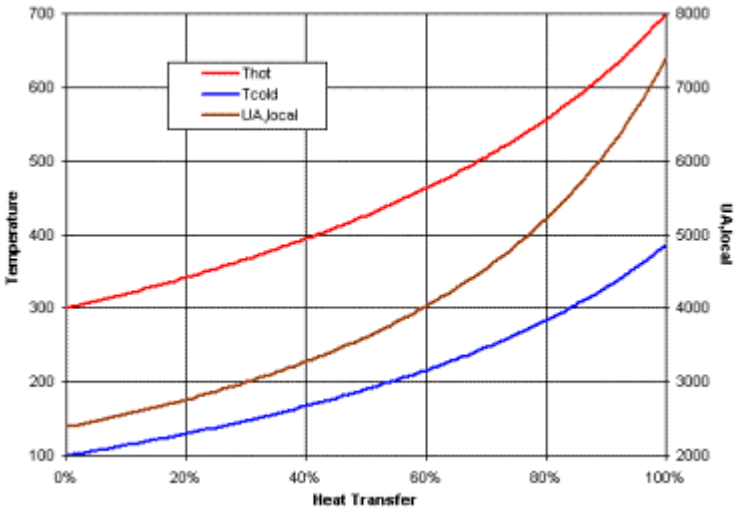

12000
10000
8000
6000
4000
2000
0
UA [kW/°C]
0
50
100
150
200
250
300
350
400
Grid: Nx=Ny (Cells=Nx*Ny)
Convergence Test

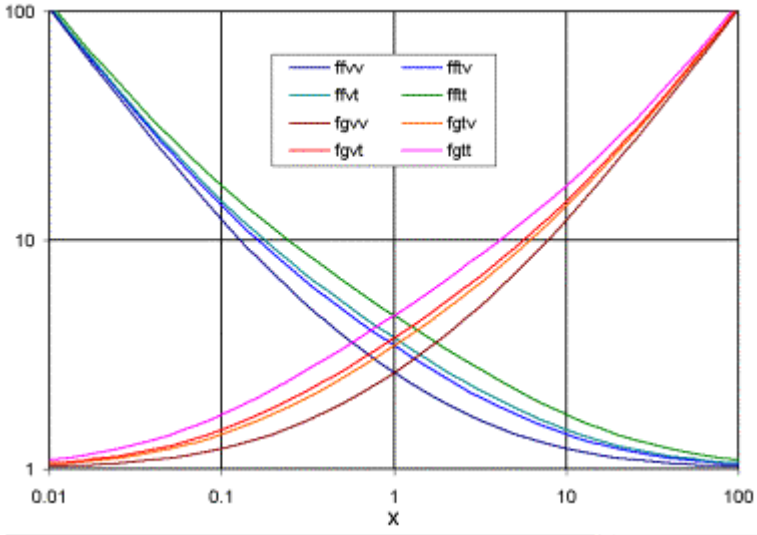

Thot
Tcold
Cp,hot
Cp,cold
Temperature
Specific Heat
Heat Transfer
700
600
500
400
300
200
100
6
5
4
3
2
1
0
0%
20%
40%
60%
80%
100%

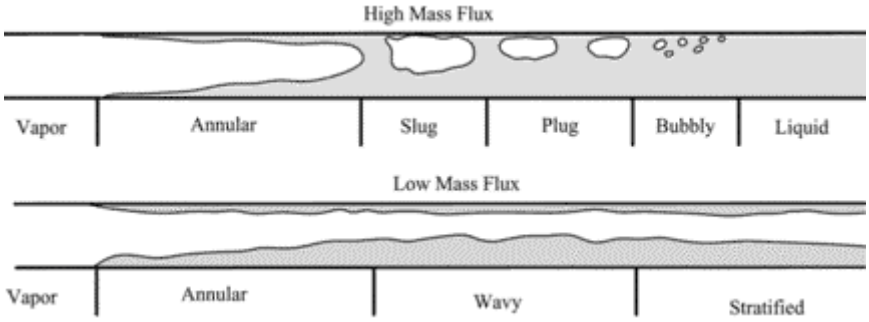

Thot
Tcold
Cp,hot
Cp,cold
Temperature
Specific Heat
Heat Transfer
700
600
500
400
300
200
100
6
5
4
3
2
1
0
0%
20%
40%
60%
80%
100%

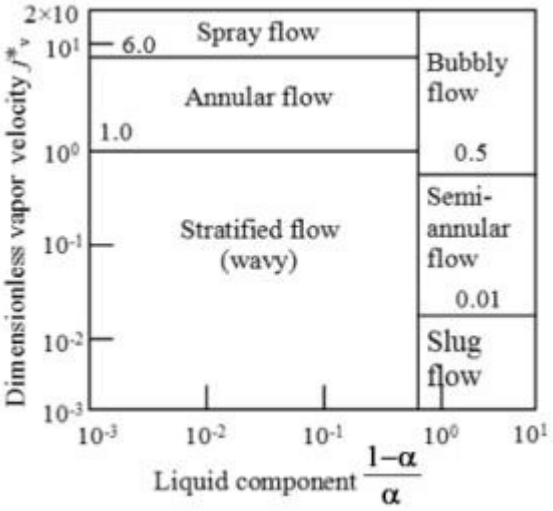

Thot
Tcold
Cp,hot
Cp,cold
Temperature
Specific Heat
Heat Transfer
700
600
500
400
300
200
100
6
5
4
3
2
1
0
0%
20%
40%
60%
80%
100%

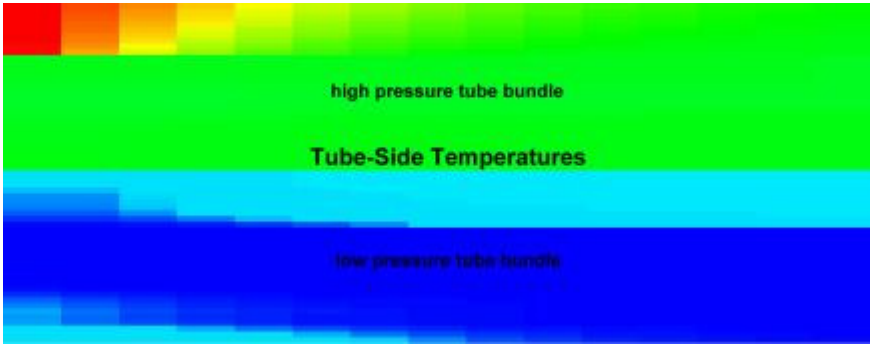

Thot
Tcold
UA,local
Temperature
UA,local
Heat Transfer
700
600
500
400
300
200
100
8000
7000
6000
5000
4000
3000
2000
0%
20%
40%
60%
80%
100%

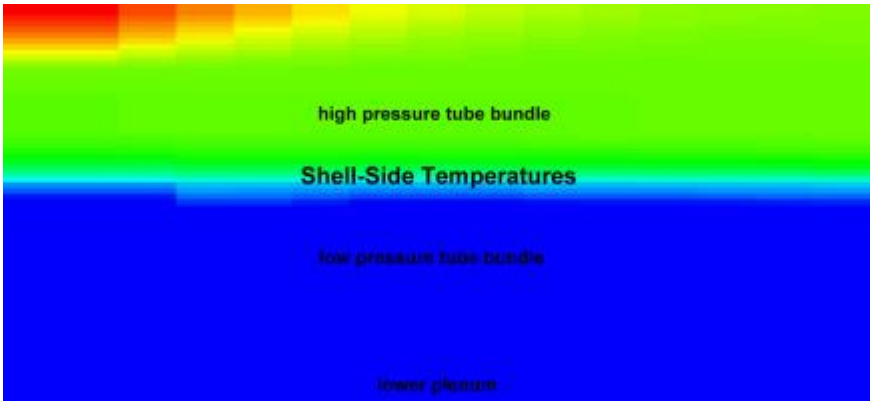

Thot
Tcold
UAJocal
Temperature
UAJocal
Heat Transfer
700
600
500
400
300
200
100
8000
7000
6000
5000
4000
3000
2000
0%
20%
40%
60%
80%
100%


ffvv
fftv
ffvt
fftt
fgvv
fgtv
fgvt
fgtt
100
10
1
0.01
0.1
1
10
100
X


High Mass Flux
Vapor
Annular
Slug
Plug
Bubbly
Liquid
Low Mass Flux
Vapor
Annular
Wavy
Stratified


Dimensionless vapor velocity j^*_v
2×10
10^1
6.0
Spray flow
Annular flow
1.0
10^0
10^{-1}
10^{-2}
10^{-3}
Stratified flow
(wavy)
Bubbly
flow
0.5
Semi-
annular
flow
0.01
Slug
flow
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
Liquid component $\frac{1-\alpha}{\alpha}$

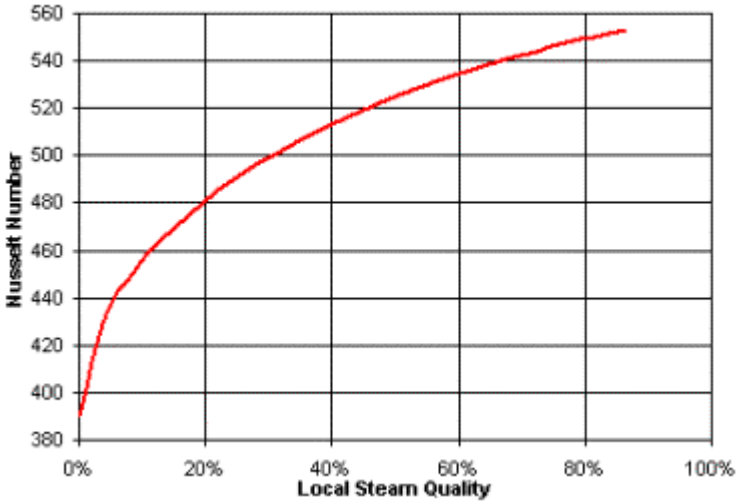

high pressure tube bundle
Tube-Side Temperatures
low pressure tube bundle

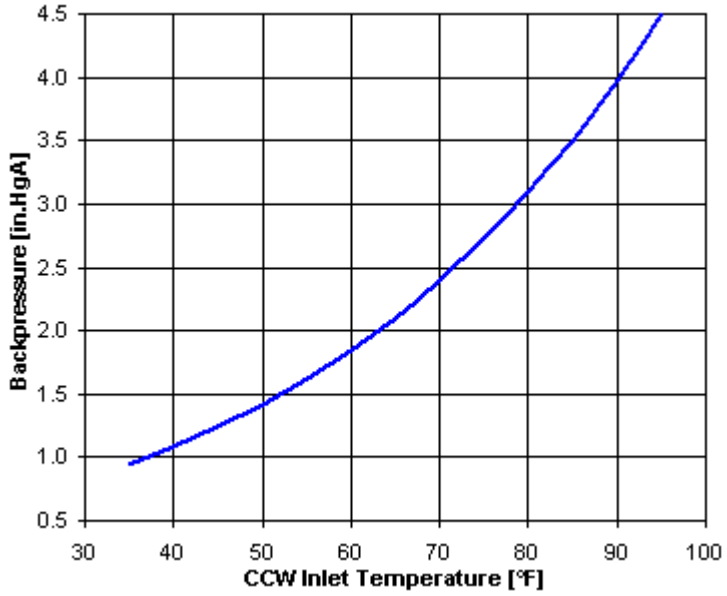


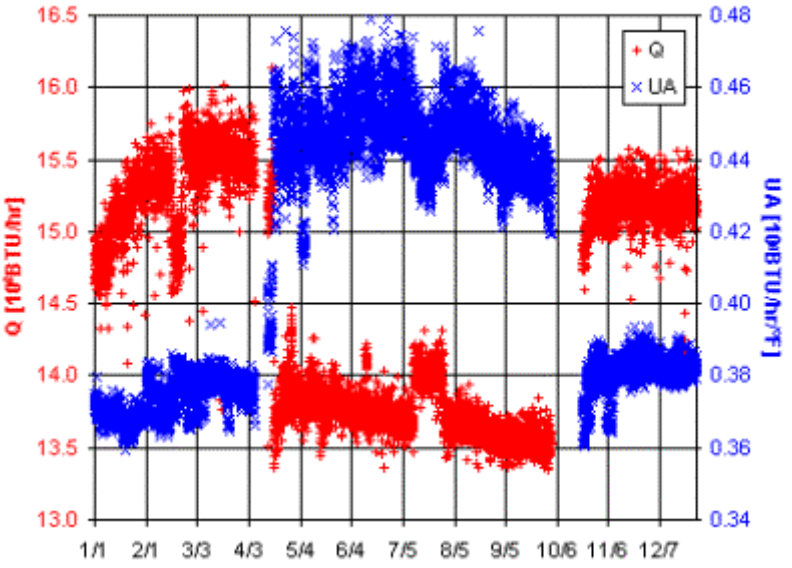
	A	B	C	D
1	**Condensation on Horizontal Tubes in Crossflow**			
2	INPUTS	symbol	units	value
3	Steam Turbine Exhaust			
4	turbine annulus area	Aan	ft²	**72**
5	number of ends	Nan	-	**4**
6	Condenser Geometry			
7	tube length	L	ft	**40.0**
8	number of tubes	N	-	**12,000**
9	tube outside dia.	do	in	**1.125**
10	tube gauge	ga	-	**22**
11	tube wall conduct.	kw	BTU/hr/ft/°F	**9.32**
12	tube pitch	pitch	in	**1.125**
13	Steam			
14	steam flow	stm	lbm/hr	**2,500,000**
15	steam quality	x	-	**91%**
16	Cooling Water			
17	flow	Qccw	gpm	**240,000**
18	inlet temperature	Tccw,in	°F	**60**
19	SOLUTION			
20	backpressure	Psat	in.HgA	**1.84**

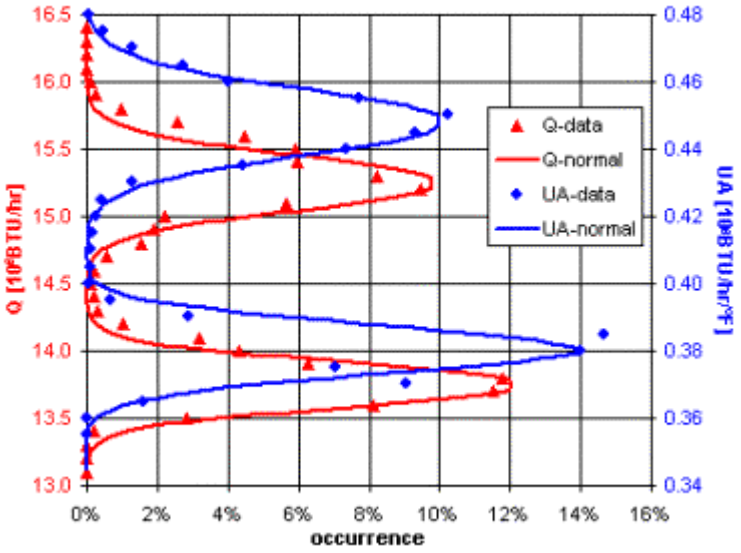
21	PROPERTIES	symbol	units	value
22	Cooling Water			
23	density	ρ	lbm/ft³	62.37
24	specific heat	Cp	BTU/lbm/°F	1.0004
25	viscosity	μ	lbm/ft/hr	2.712
26	thermal cond.	k	BTU/hr/ft/°F	0.3423
27	Prandtl Number	Pr	-	7.93
28	Steam			
29	liquid density	ρf	lbm/ft³	62.01
30	vapor density	ρg	lbm/ft³	0.0027
31	latent heat	hfg	BTU/lbm	1037.6
32	liquid viscosity	μf	lbm/ft/hr	1.678
33	liquid thermal cond.	kf	BTU/hr/ft/°F	0.3611
34	CALCULATIONS	symbol	units	value
35	Condenser Geometry			
36	tube wall thick.	wt	in	0.028
37	tube inside dia.	di	in	1.069
38	water flow area	Af	ft²	74.79
39	surface area	As	ft²	141,372
40	steam flow area	Ap	ft²	410.79

41	Cooling Water			
42	duty	duty	BTU/hr	2.358E+09
43	mass flow rate	mccw	lbm/hr	1.201E+08
44	outlet temperature	Tccw,out	°F	79.63
45	velocity inside tubes	ut	ft/sec	7.15
46	tube side Reynolds	Re,t	-	52,729
47	tube side Nusselt	Nu,t	-	315
48	tube side ht. tr. coef.	ht	BTU/hr/ft/°F	1212
49	tube wall ht. tr. coef.	hw	BTU/hr/ft/°F	3894
50	Steam			
51	operating pressure	Psat	psia	0.9046
52	saturation temp.	Tsat	°F	98.38
53	exit specific volume	1/ρan	ft³/lbm	332.5
54	annulus velocity	Van	ft/sec	802
55	log mean temp. diff.	LMTD	°F	27.4
56	required conductance	U	BTU/hr/°F	608.9
57	film Reynolds number	Re	-	2.874E+05

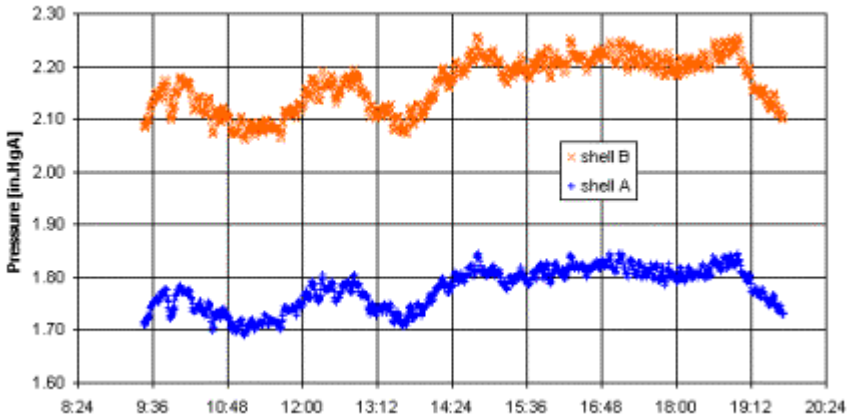

560
540
520
500
480
460
440
420
400
380
Nusselt Number
0%
20%
40%
60%
80%
100%
Local Steam Quality

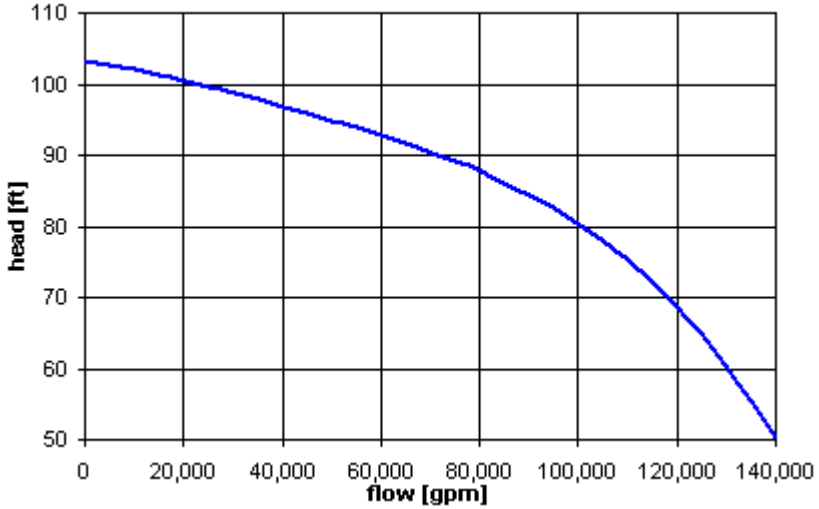

4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Backpressure [in.HgA]
30
40
50
60
70
80
90
100
CCW Inlet Temperature [°F]

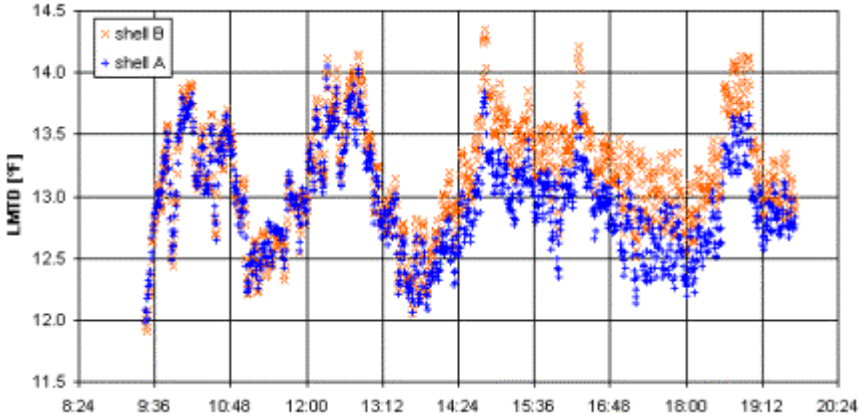

Q
UA
Q [10^6 BTU/hr]
UA [10^6 BTU/hr/°F]
16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
0.48
0.46
0.44
0.42
0.40
0.38
0.36
0.34
1/1
2/1
3/3
4/3
5/4
6/4
7/5
8/5
9/5
10/6
11/6
12/7

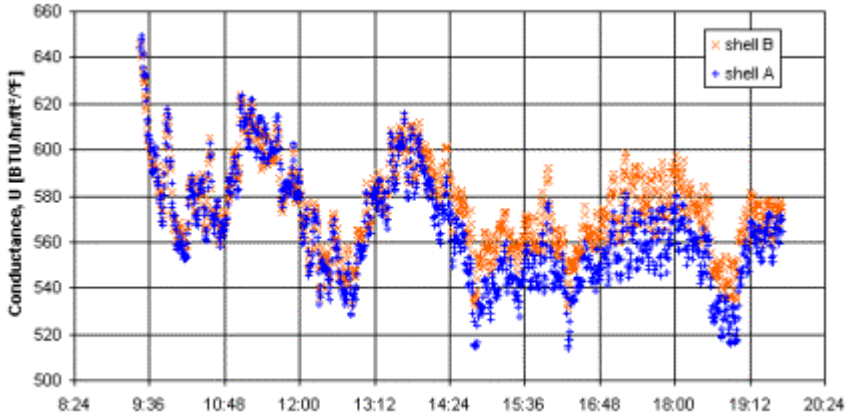

Q-data
Q-normal
UA-data
UA-normal
Q [10^6 BTU/hr]
UA [10^6 BTU/hr/°F]
16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
0.48
0.46
0.44
0.42
0.40
0.38
0.36
0.34
0%
2%
4%
6%
8%
10%
12%
14%
16%
occurrence

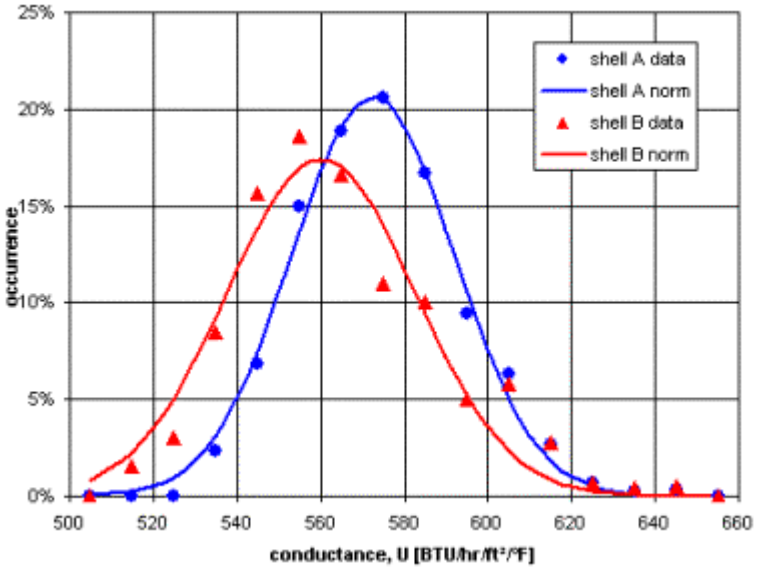
K	L	M	N	O	P	Q	R	S	T	U	V	W	X
CALCULATIONS													
CCW flow	duty	cond. density	cond. flow	LPTA exh. pres.	LPTB exh. pres.	LPTA exh. temp.	LPTB exh. temp.	LPTA exhaust quality	LPTB exhaust quality	shell A LMTD	shell B LMTD	shell A U	shell B U
gpm	BTU/hr	lbm/ft³	lbm/hr	in.HgA	in.HgA	Deg F	Deg F	-	-	Deg F	Deg F	BTU/hr/ft²/°F	
457,219	3.018E+09	61.980	3,372,124	1.710	2.091	95.88	102.54	0.8612	0.8644	11.98	12.02	645.9	644.0
457,129	3.017E+09	61.980	3,374,446	1.715	2.087	95.96	102.48	0.8604	0.8635	12.08	11.95	640.3	647.1
457,268	3.018E+09	61.980	3,370,850	1.711	2.086	95.90	102.46	0.8615	0.8646	12.01	11.94	644.2	648.1
457,140	3.016E+09	61.980	3,374,185	1.712	2.082	95.93	102.41	0.8603	0.8634	12.06	11.91	641.5	649.6
457,148	3.016E+09	61.980	3,373,994	1.717	2.090	96.04	102.53	0.8604	0.8635	12.18	12.04	635.1	642.1
457,635	3.019E+09	61.981	3,361,398	1.718	2.091	96.05	102.55	0.8645	0.8676	12.21	12.08	633.9	640.6
458,209	3.023E+09	61.980	3,346,434	1.722	2.098	96.11	102.66	0.8694	0.8725	12.28	12.20	631.3	635.4
458,291	3.023E+09	61.980	3,344,267	1.725	2.101	96.17	102.71	0.8700	0.8732	12.32	12.24	629.0	633.1
457,369	3.017E+09	61.979	3,368,202	1.722	2.099	96.11	102.68	0.8620	0.8651	12.28	12.23	629.7	632.4
456,025	3.007E+09	61.979	3,402,518	1.725	2.098	96.19	102.66	0.8508	0.8538	12.37	12.21	623.6	631.6
456,364	3.010E+09	61.979	3,393,416	1.728	2.098	96.22	102.66	0.8536	0.8567	12.40	12.21	622.3	632.1
457,793	3.019E+09	61.979	3,357,203	1.733	2.107	96.32	102.80	0.8655	0.8686	12.50	12.36	619.2	626.3
458,271	3.021E+09	61.978	3,344,665	1.734	2.113	96.36	102.90	0.8696	0.8727	12.55	12.48	617.3	620.9

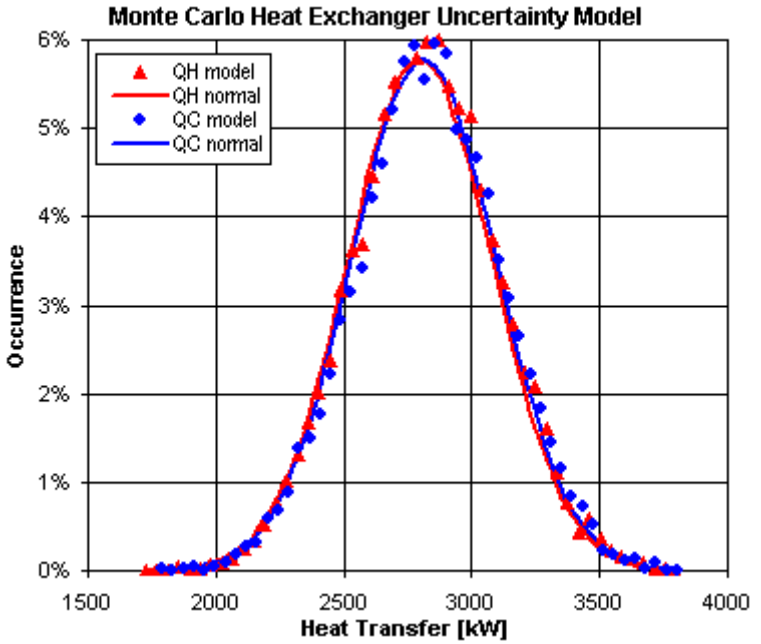


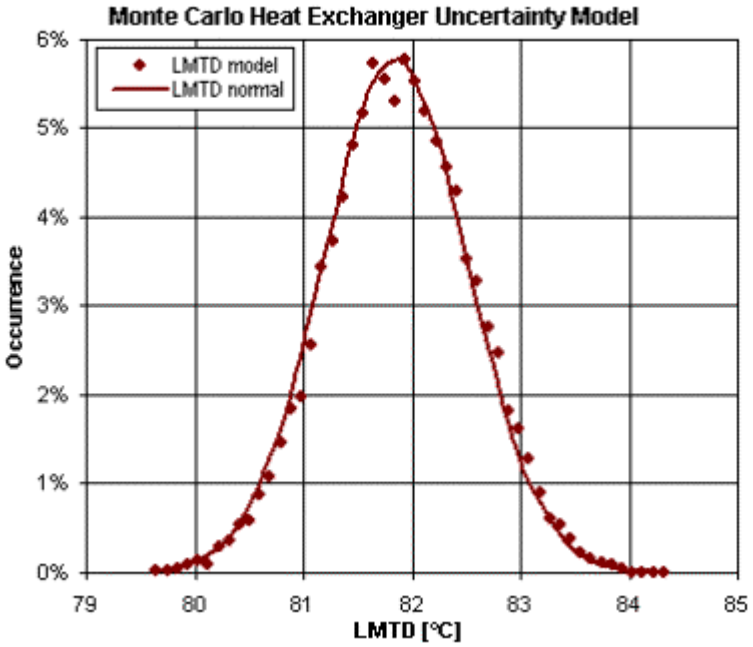

110
100
90
80
70
60
50
head [ft]
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000
flow [gpm]

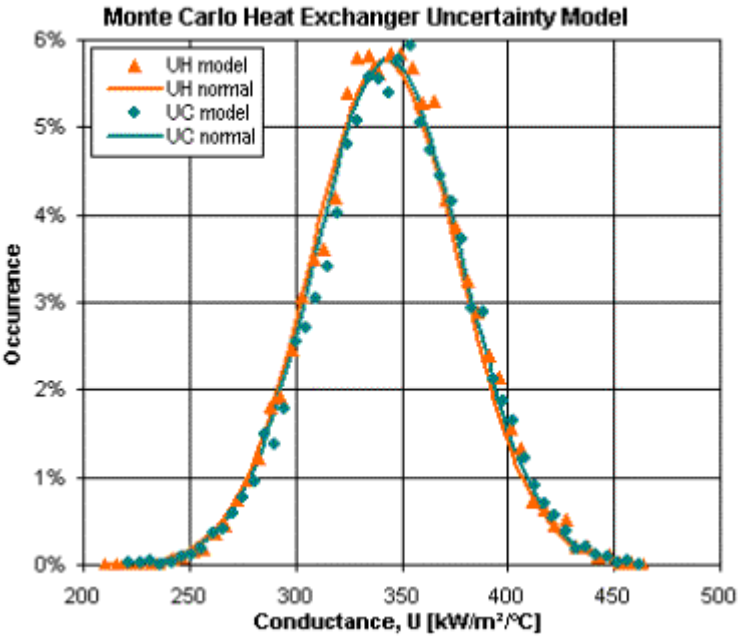

shell B
shell A
LMTD [°F]
14.5
14.0
13.5
13.0
12.5
12.0
11.5
8:24
9:36
10:48
12:00
13:12
14:24
15:36
16:48
18:00
19:12
20:24

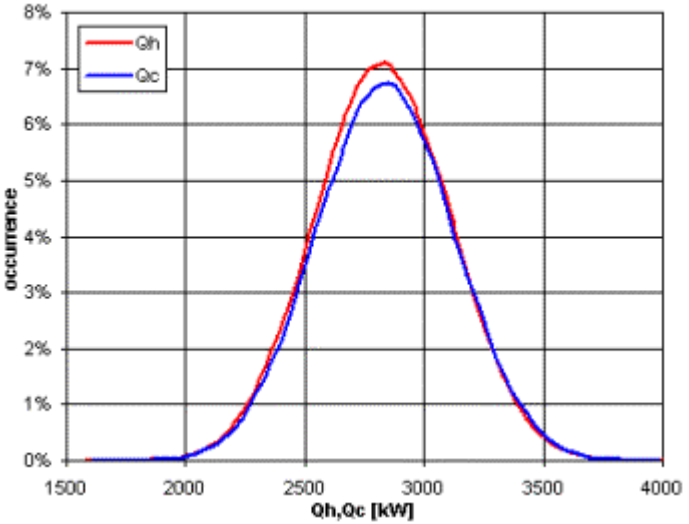

Conductance, U [BTU/hr/ft²/°F]
660
640
620
600
580
560
540
520
500
8:24
9:36
10:48
12:00
13:12
14:24
15:36
16:48
18:00
19:12
20:24
shell B
shell A

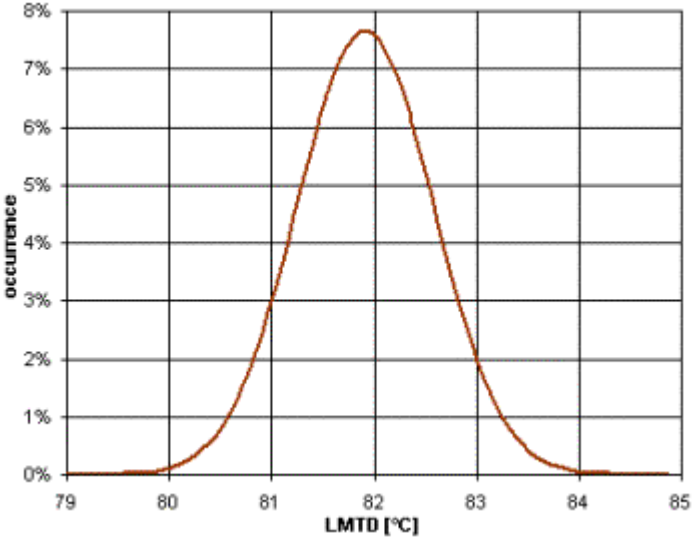

occurrence
25%
20%
15%
10%
5%
0%
500
520
540
560
580
600
620
640
660
conductance, U [BTU/hr/ft²/°F]
shell A data
shell A norm
shell B data
shell B norm

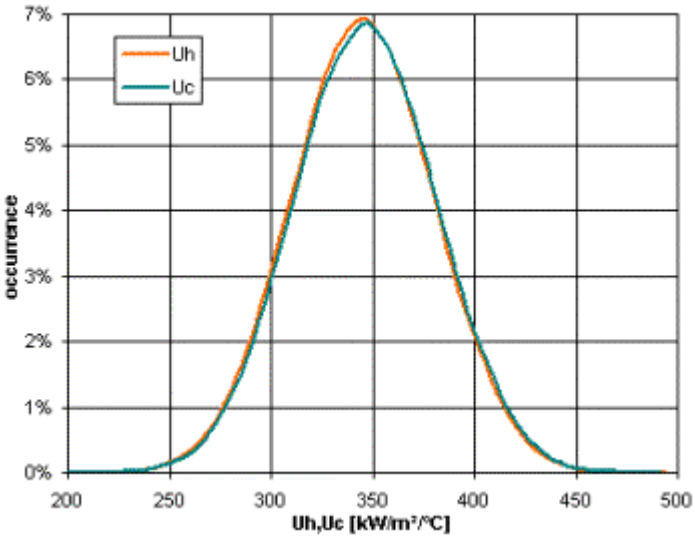

Monte Carlo Heat Exchanger Uncertainty Model
QH model
QH normal
QC model
QC normal
Occurrence
6%
5%
4%
3%
2%
1%
0%
1500
2000
2500
3000
3500
4000
Heat Transfer [kW]

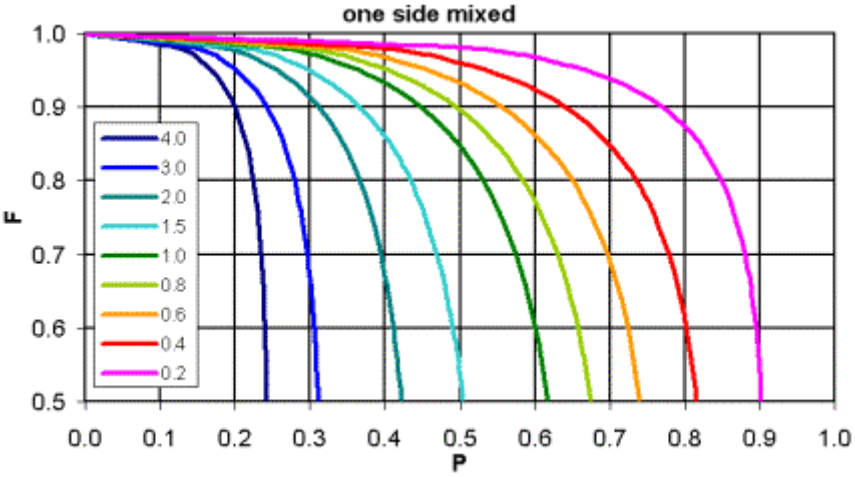

Monte Carlo Heat Exchanger Uncertainty Model
LMTD model
LMTD normal
Occurrence
6%
5%
4%
3%
2%
1%
0%
79
80
81
82
83
84
85
LMTD [°C]

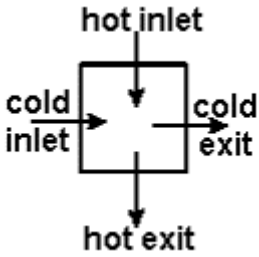

Monte Carlo Heat Exchanger Uncertainty Model
UH model
UH normal
UC model
UC normal
Occurrence
6%
5%
4%
3%
2%
1%
0%
200
250
300
350
400
450
500
Conductance, U [kW/m²/°C]


Qh
Qc
8%
7%
6%
5%
4%
3%
2%
1%
0%
occurrence
1500
2000
2500
3000
3500
4000
Qh,Qc [kW]

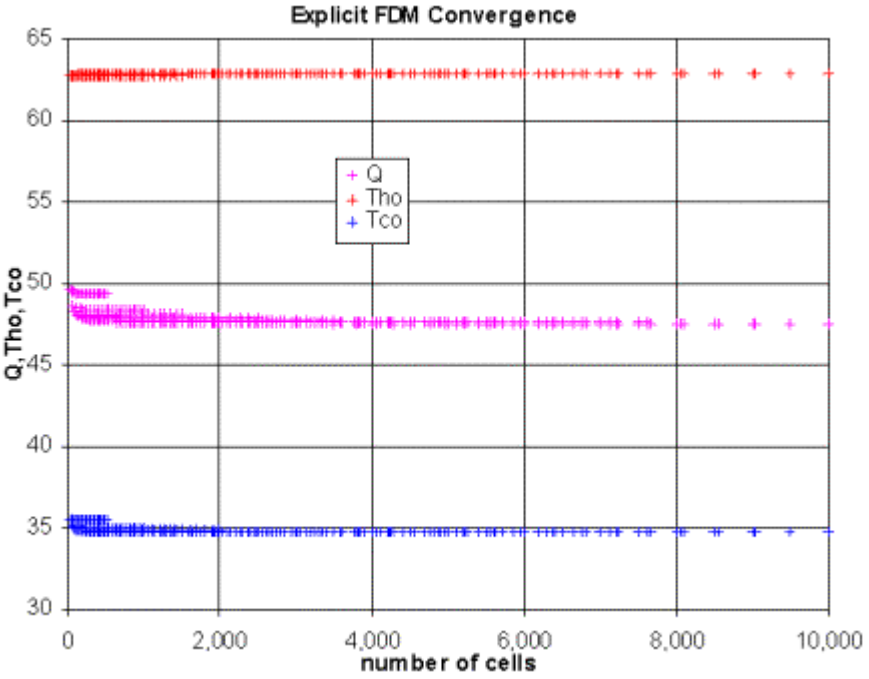

8%
7%
6%
5%
4%
3%
2%
1%
0%
occurrence
79
80
81
82
83
84
85
LMTD [°C]

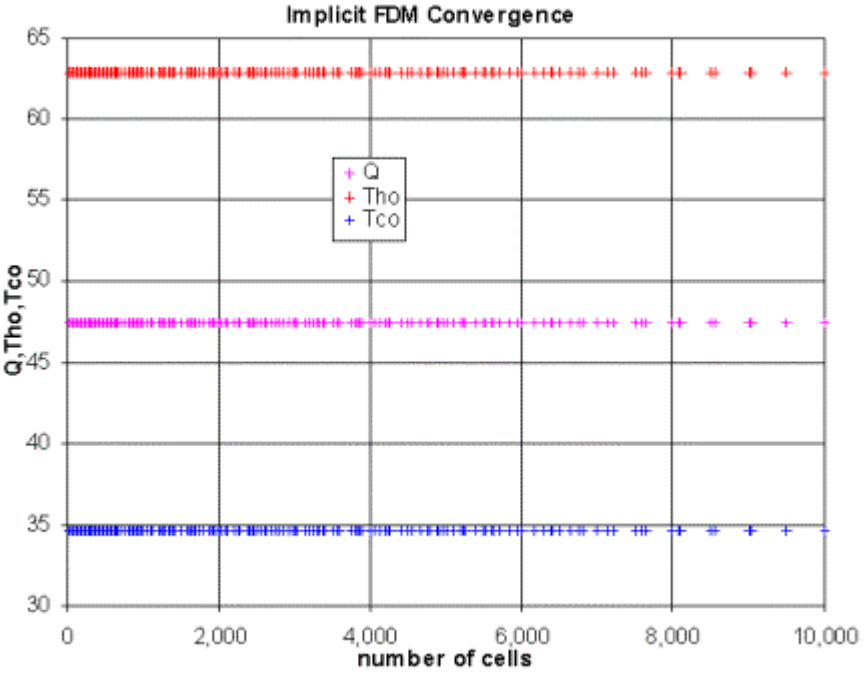

Uh
Uc
occurrence
7%
6%
5%
4%
3%
2%
1%
0%
200
250
300
350
400
450
500
Uh,Uc [kW/m²/°C]

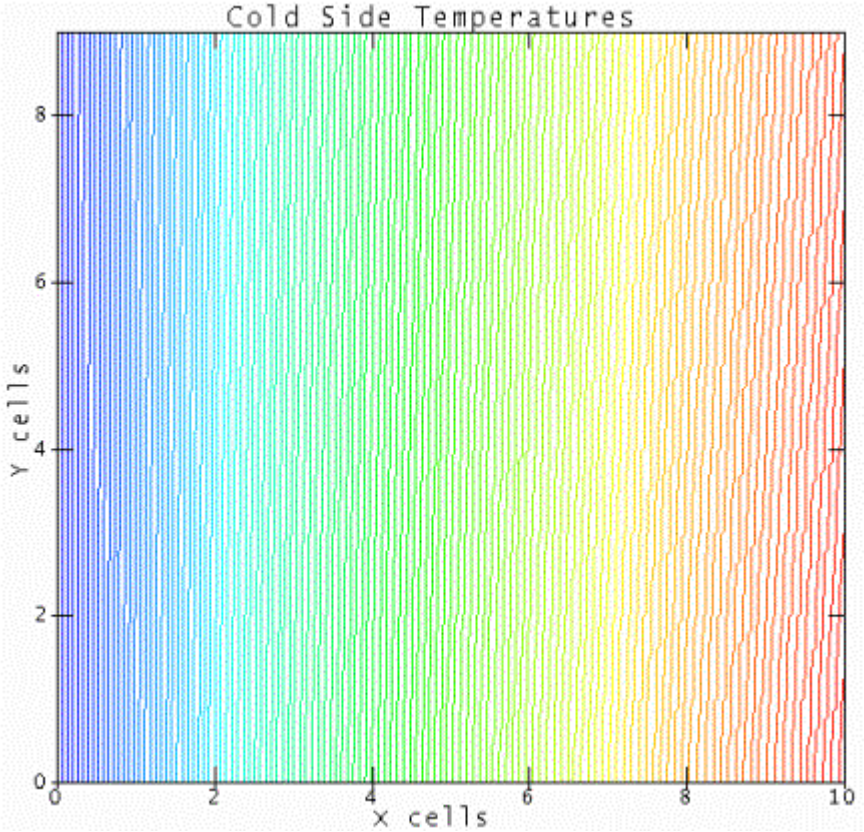

one side mixed
F
P
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
4.0
3.0
2.0
1.5
1.0
0.8
0.6
0.4
0.2

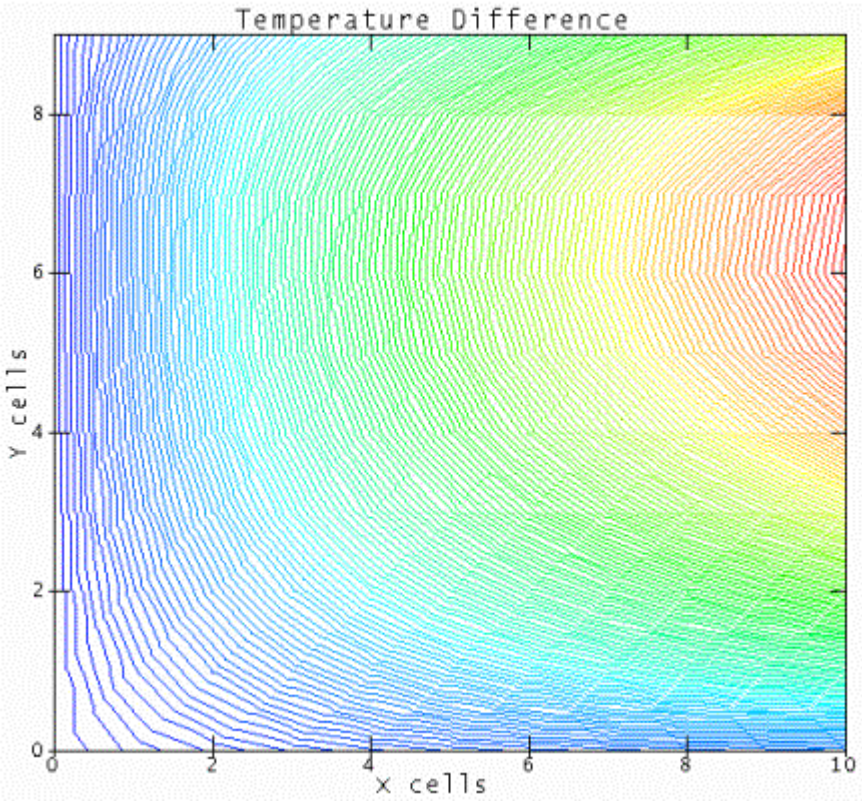


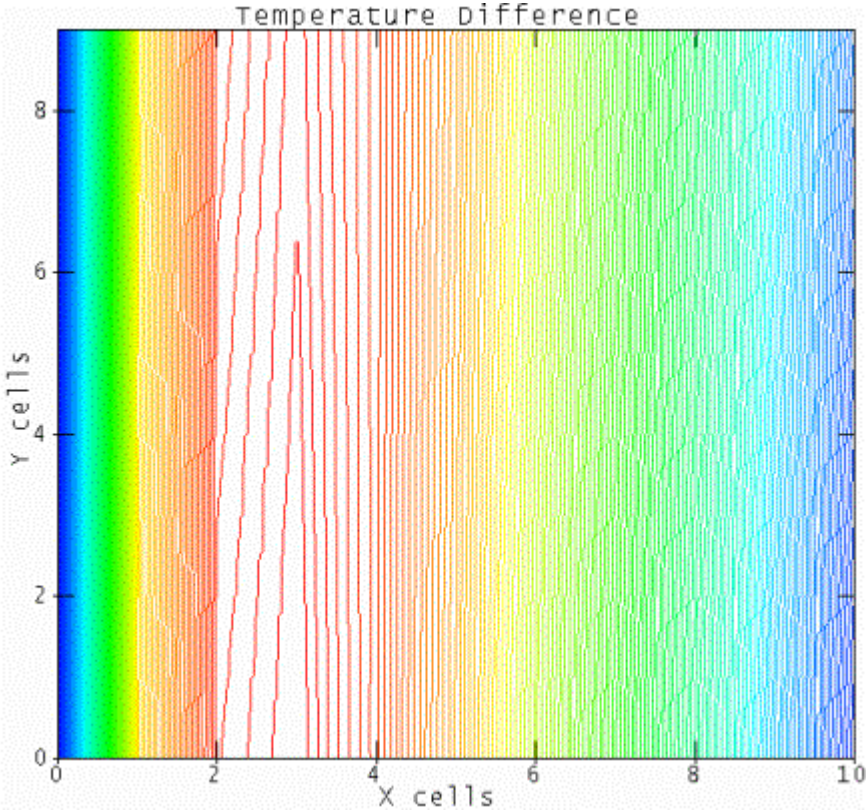
	A	B	C	D
1	**crossflow example 11-211**			
2	symbol	units	hot	cold
3	U	W/m²/°C	**205**	
4	Cp	kJ/kg/°C	**4.19**	**1.01**
5	m	kg/s	**5.25**	**2.39**
6	Tin	°C	**65.0**	**15.0**
7	Tout	°C	**62.9**	34.5
8	q	kW	47.1	
9	LMTD	°C	38.52	
10	P	-	0.043	0.390
11	R	-	9.113	0.110
12	symbol	units	one mixed	
13	F-LMTD method			
14	F	-	0.995	
15	UA	kW/°C	1.23	
16	A	m²	5.98	
17	P-NTU method			
18	NTU	-	0.0558	0.509
19	UA	kW/°C	1.23	1.23
20	A	m²	5.98	5.98
21	**user inputs in blue**			
22	calculations in orange			
23	**linked cells in green**			

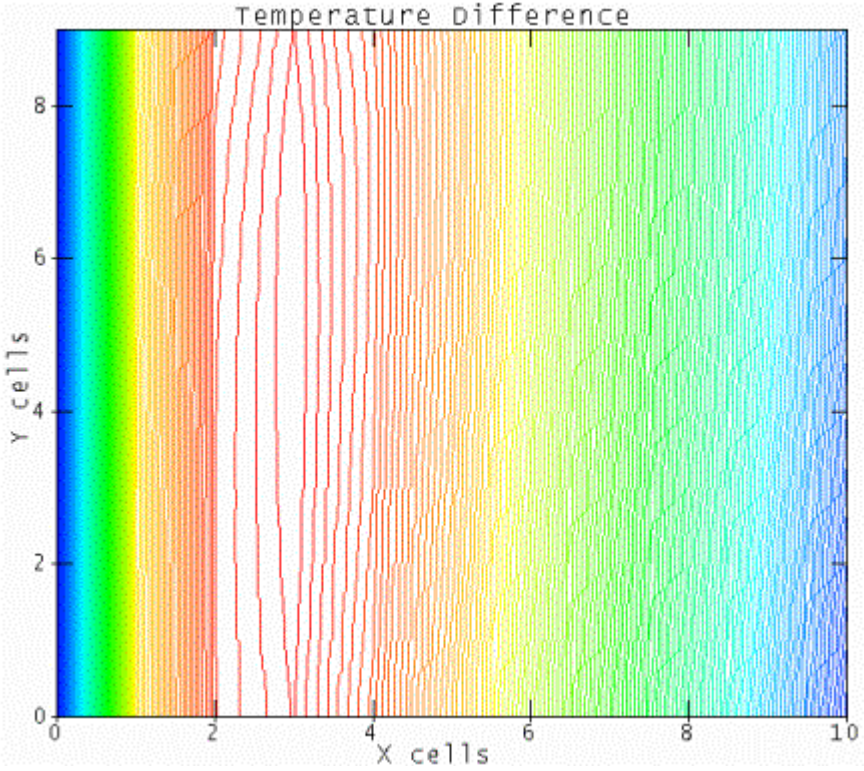

Explicit FDM Convergence
65
60
55
50
45
40
35
30
Q,Tho,Tco
Q
Tho
Tco
0
2,000
4,000
6,000
8,000
10,000
number of cells

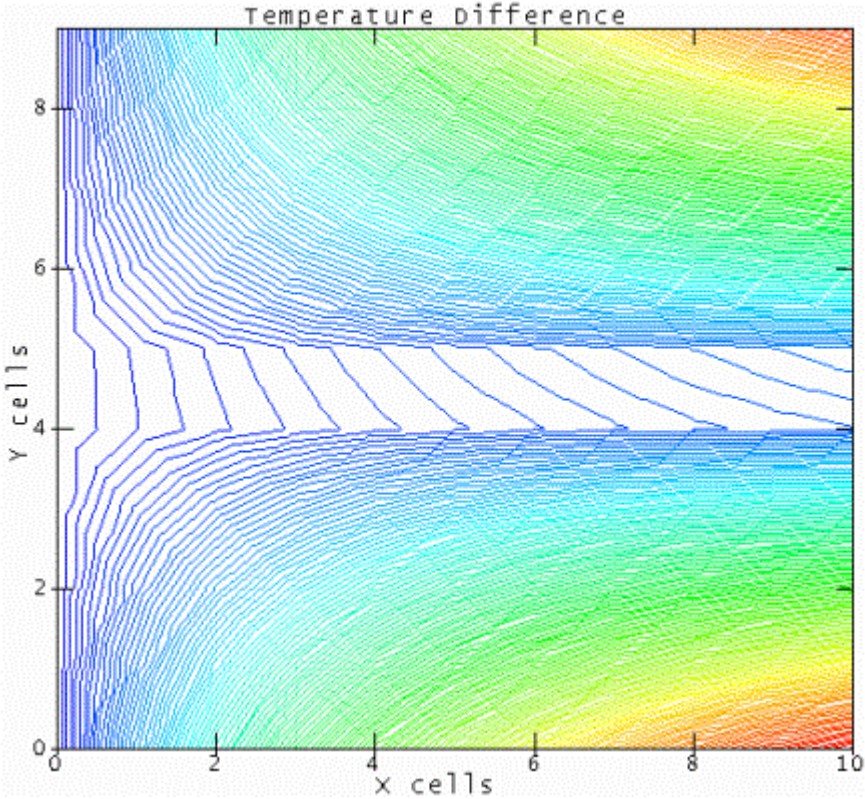

Implicit FDM Convergence
65
60
55
50
45
40
35
30
Q,Tho,Tco
Q
Tho
Tco
0
2,000
4,000
6,000
8,000
10,000
number of cells

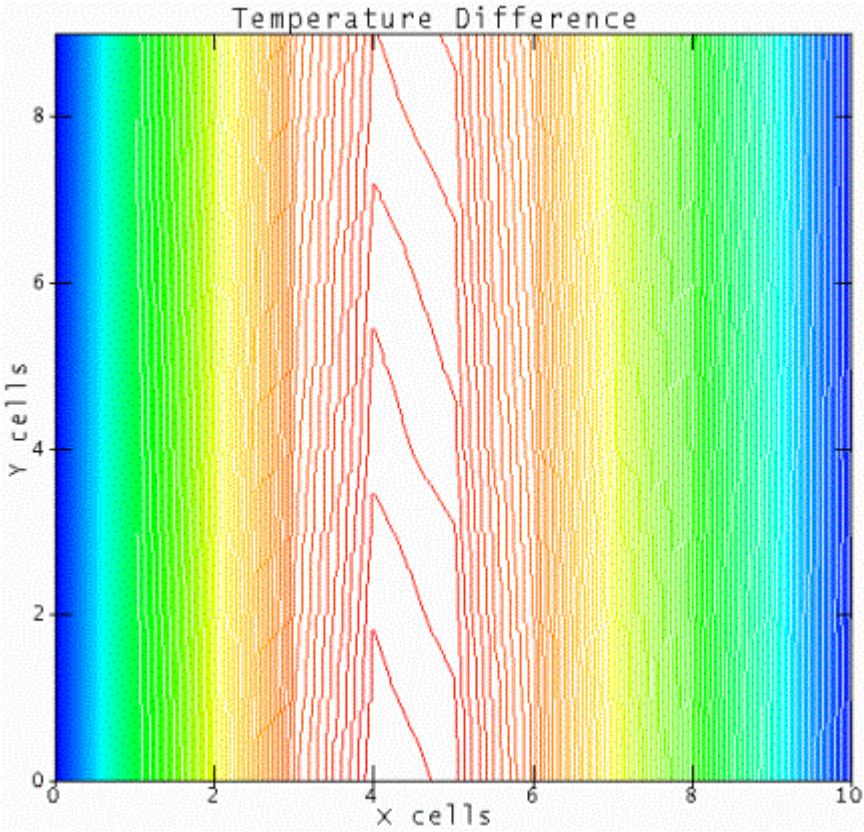

Cold Side Temperatures
Y cells
X cells
0
2
4
6
8
10

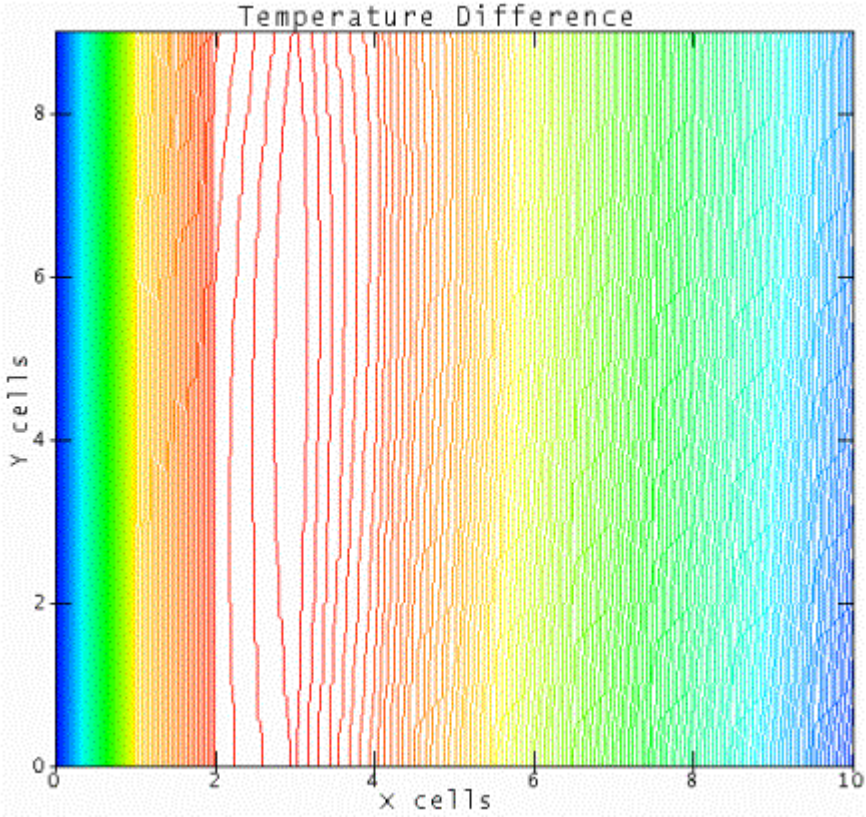

Temperature Difference
Y cells
X cells
0
2
4
6
8
10

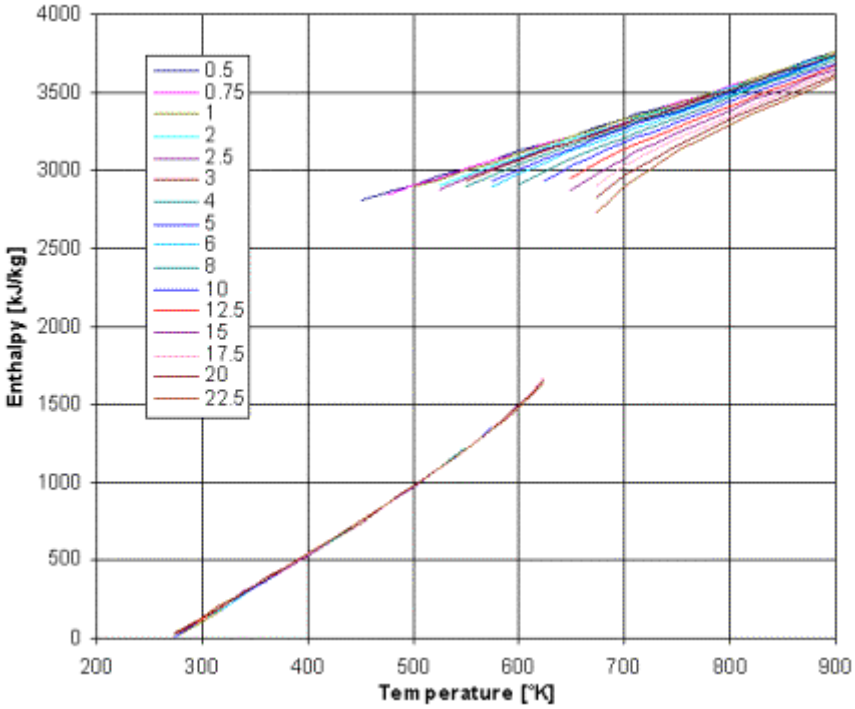

Temperature Difference
Y cells
X cells
0
2
4
6
8
10

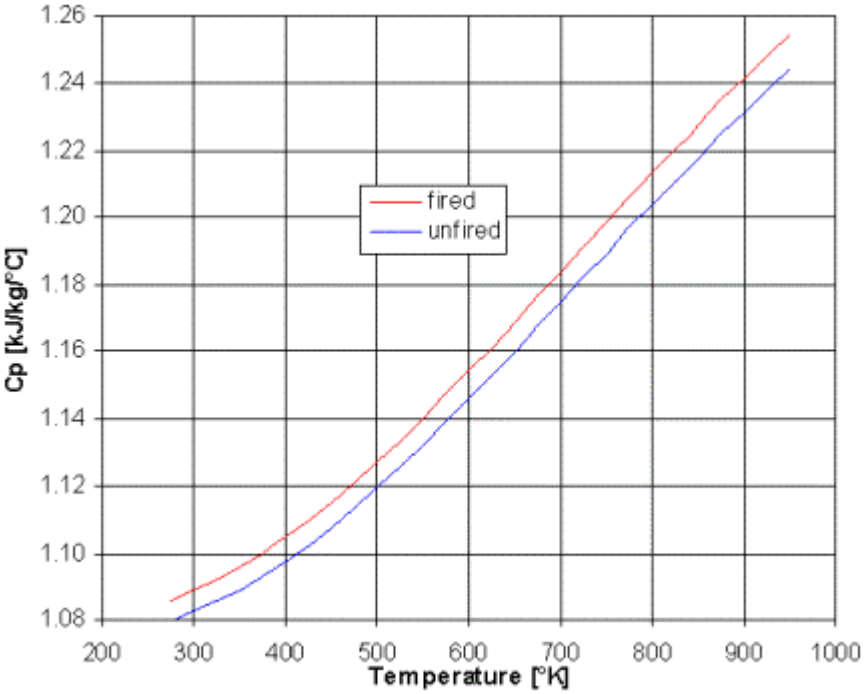

Temperature Difference
Y cells
X cells
0
2
4
6
8
10

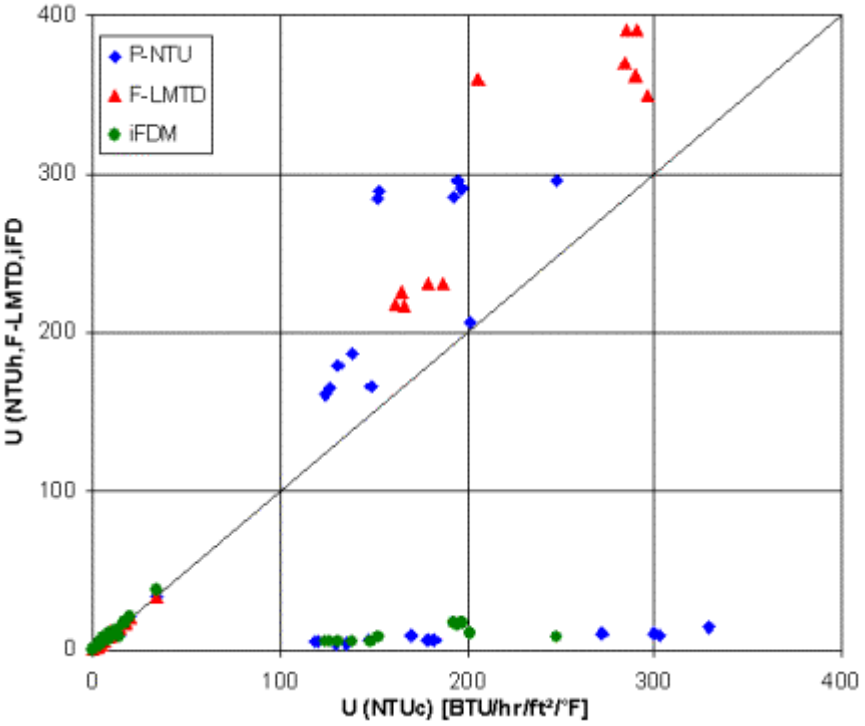

Temperature Difference
Y cells
X cells
0
2
4
6
8
10

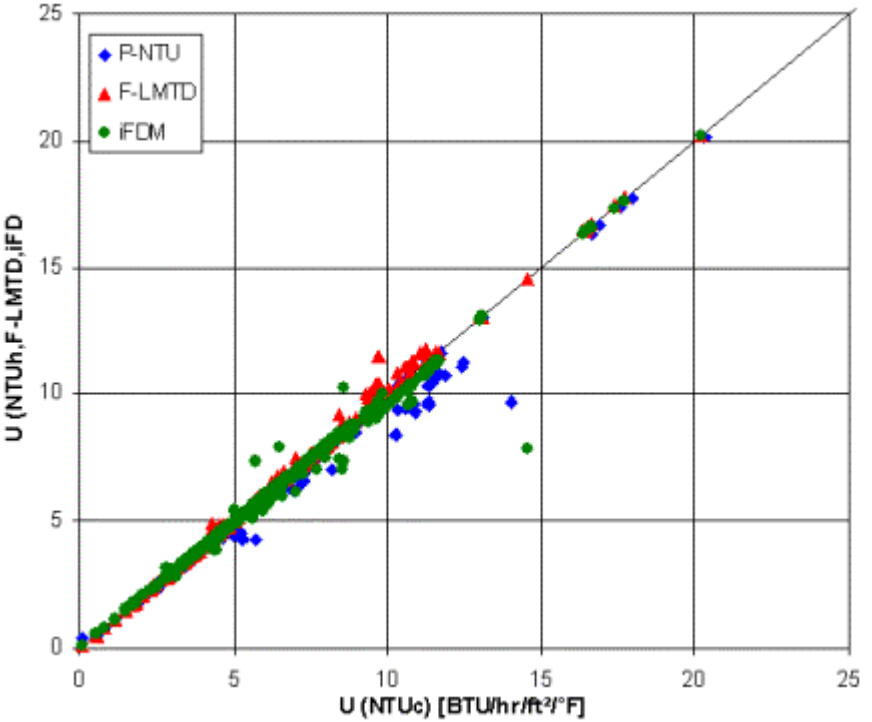

Temperature Difference
Y cells
X cells
0
2
4
6
8
10


Temperature Difference
Y cells
X cells
0
2
4
6
8
10


4000
3500
3000
2500
2000
1500
1000
500
0
Enthalpy [kJ/kg]
200
300
400
500
600
700
800
900
Temperature [°K]
0.5
0.75
1
2
2.5
3
4
5
6
8
10
12.5
15
17.5
20
22.5


1.26
1.24
1.22
1.20
1.18
1.16
1.14
1.12
1.10
1.08
Cp [kJ/kg/°C]
fired
unfired
200
300
400
500
600
700
800
900
1000
Temperature [°K]


P-NTU
F-LMTD
iFDM
U (NTUh,F-LMTD,iFD
U (NTUc) [BTU/hr/ft²/°F]
0
100
200
300
400


P-NTU
F-LMTD
iFDM
U (NTUh,F-LMTD,iFD
U (NTUc) [BTU/hr/ft²/°F]
0
5
10
15
20
25

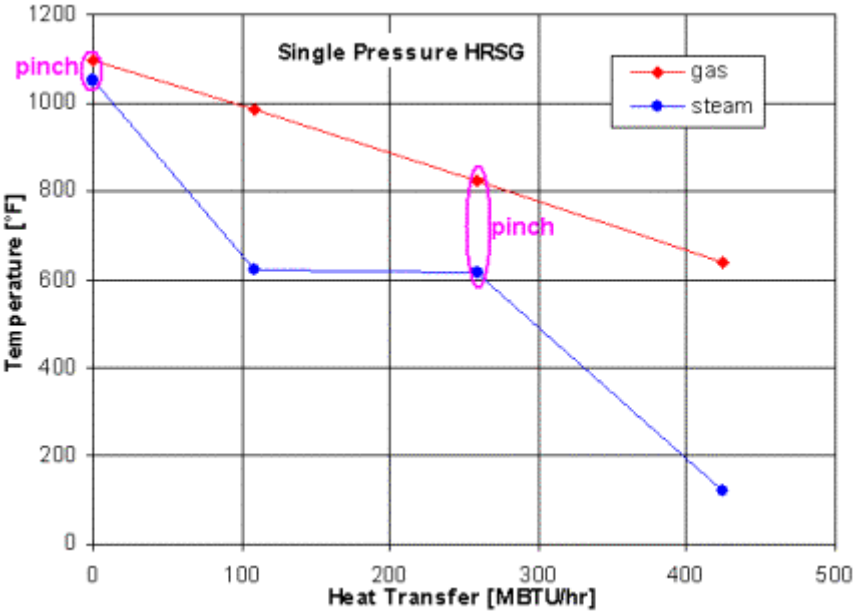
A	B	C	D	E	F	G	H	I
			Single Pressure HRSG					
case	mC	mH	Pci	Pco	Tci	Tco	Thi	Tho
name	lb/hr	lb/hr	psia	psia	°F	°F	°F	°F
SH	**300,000**	**3,000,000**	1800	1750	621	**1050**	**1100**	986
EV	300,000	3,000,000	**1800**	1800	621	621	986	824
EC	300,000	3,000,000	1950	1800	**120**	616	824	641

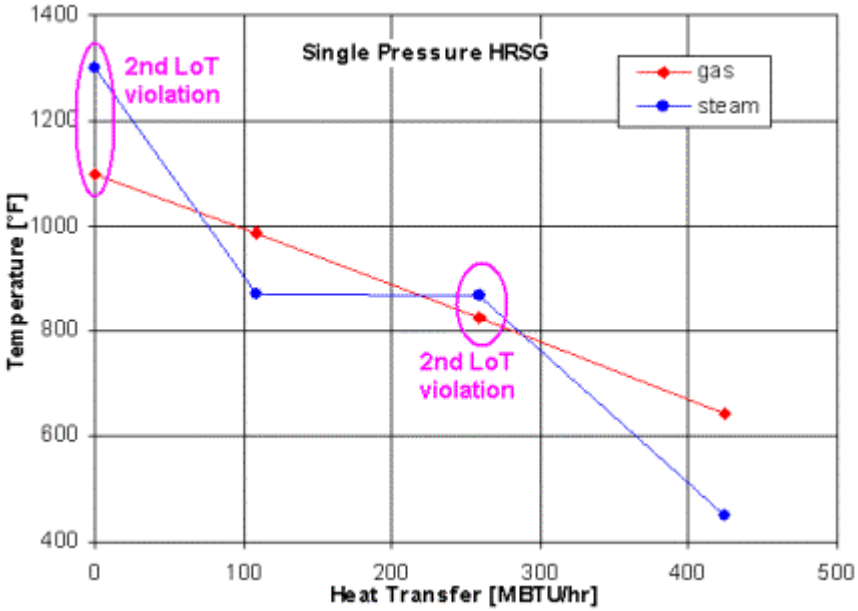
J	K	L	M	N	O	P	Q
				Single Pressure HRSG			
Q	CpC	CpH	Rc	Rh	Pc	Ph	NTUc
MBTU/hr	BTU/lb/°F	BTU/lb/°F	-	-	-	-	-
108.86	0.846	0.319	0.27	3.77	0.896	0.237	####
150.73	∞	0.310	∞	0.00	0.000	0.443	0.59
164.13	1.103	0.299	0.37	2.71	0.704	0.260	1.69

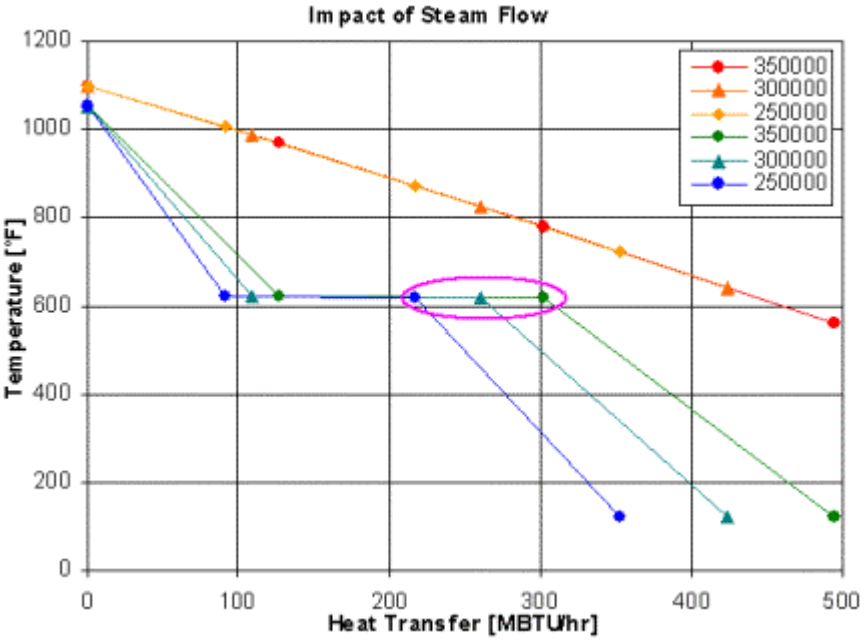
R	S	T	U	V	W	X
NTUh	LMTD	F	UA	ΣQ	Th	Tc
-	°F	-	MBTU/hr/°F	MBTU/hr	°F	°F
0.91	158.50	0.78	0.69	0.00	1100	1050
0.59	276.46	1.00	0.55	108.86	986	621
0.60	341.30	0.90	0.48	259.58	824	616
		total	1.71	423.71	641	120

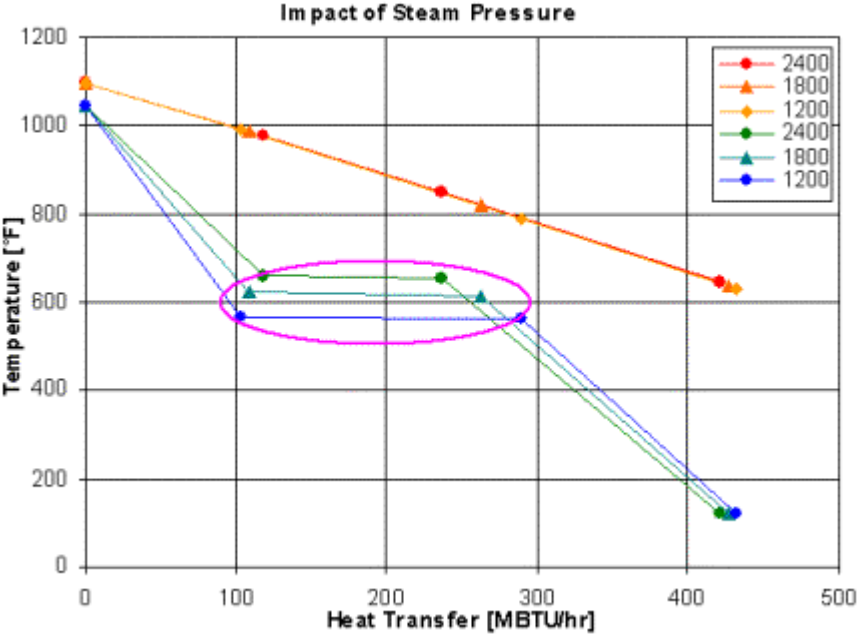
user inputs in blue

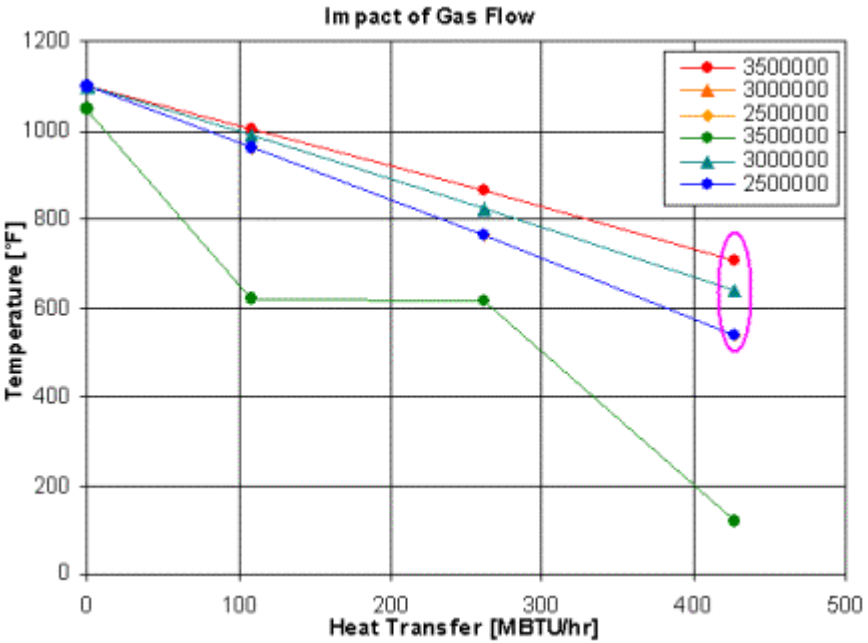
calculations in orange

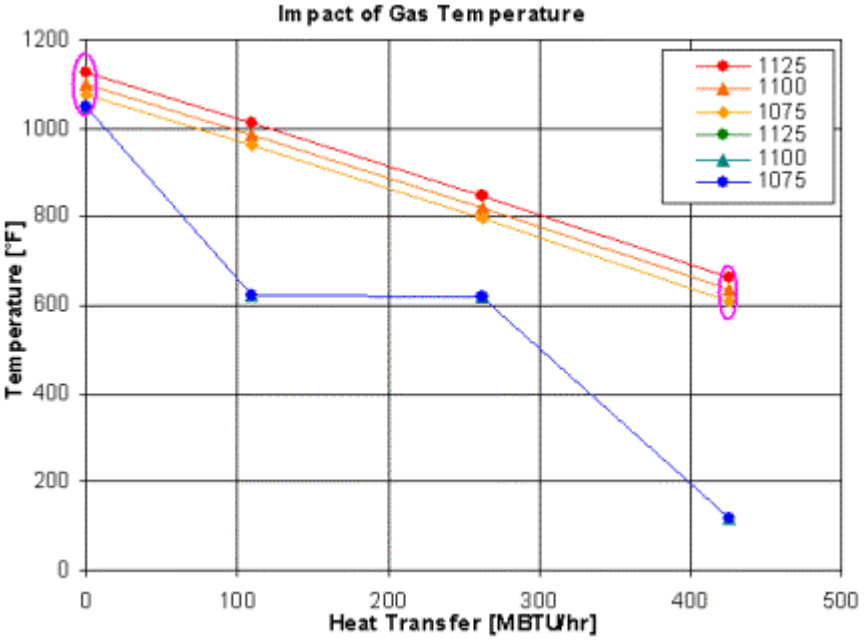

Single Pressure HRSG
gas
steam
pinch
pinch
Temperature [°F]
Heat Transfer [MBTU/hr]
0
200
400
600
800
1000
1200
0
100
200
300
400
500

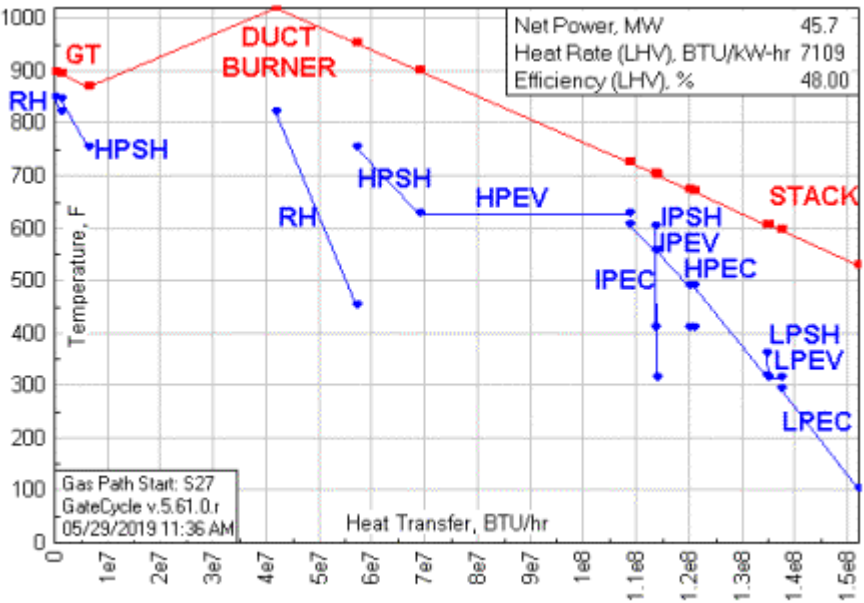

Single Pressure HRSG
gas
steam
2nd LoT violation
2nd LoT violation
Temperature [°F]
Heat Transfer [MBTU/hr]
400
600
800
1000
1200
1400
0
100
200
300
400
500

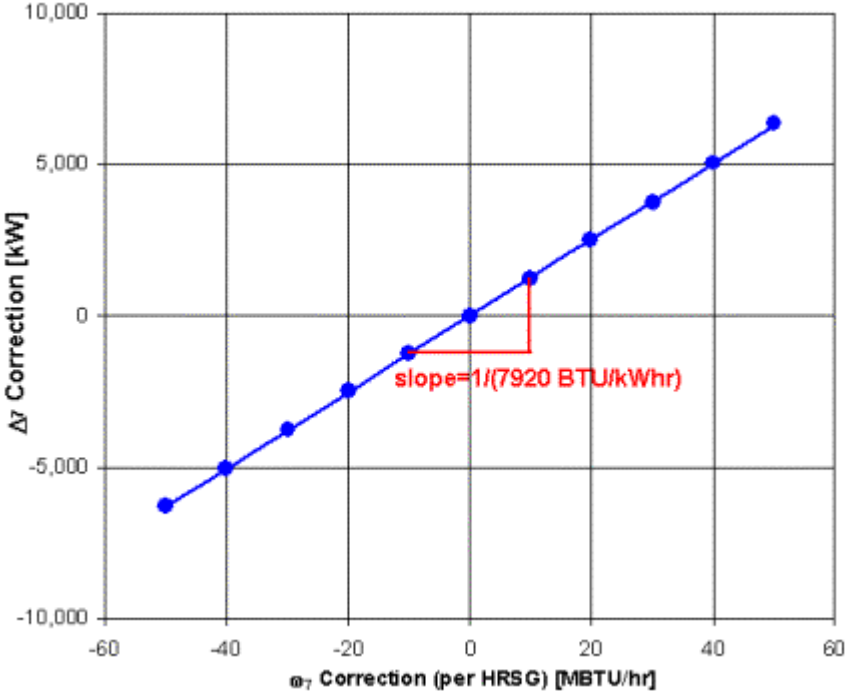

Impact of Steam Flow
Temperature [°F]
Heat Transfer [MBTU/hr]
0
200
400
600
800
1000
1200
0
100
200
300
400
500
350000
300000
250000
350000
300000
250000

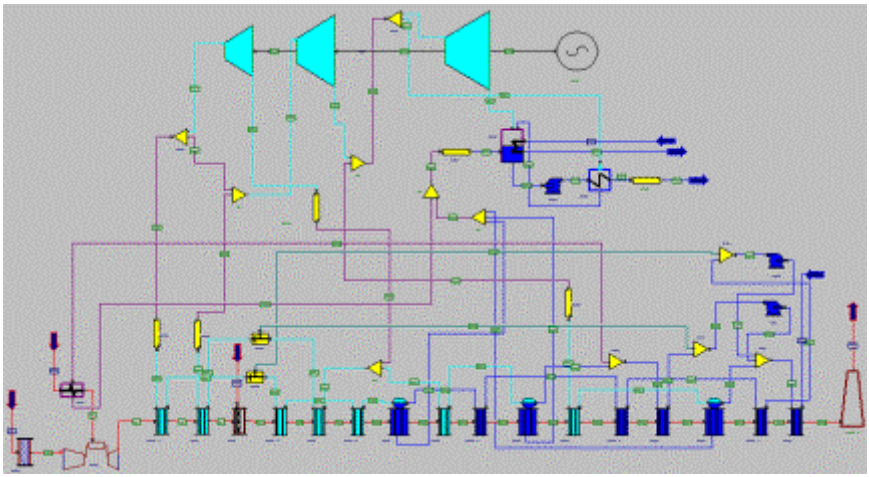

Impact of Steam Pressure
Temperature [°F]
Heat Transfer [MBTU/hr]
0
200
400
600
800
1000
1200
0
100
200
300
400
500
2400
1800
1200
2400
1800
1200

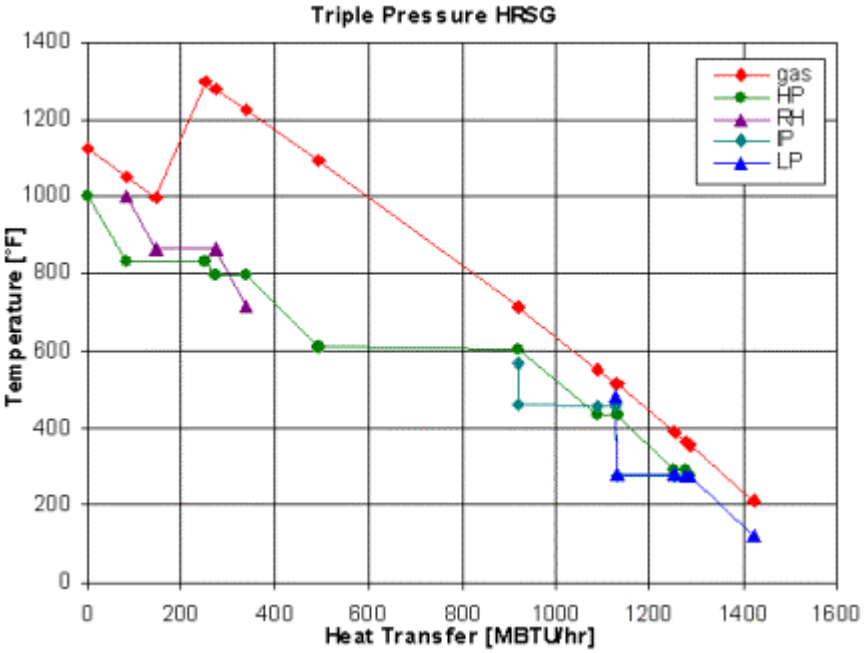

Impact of Gas Flow
Temperature [°F]
Heat Transfer [MBTU/hr]
0
200
400
600
800
1000
1200
0
100
200
300
400
500
3500000
3000000
2500000
3500000
3000000
2500000

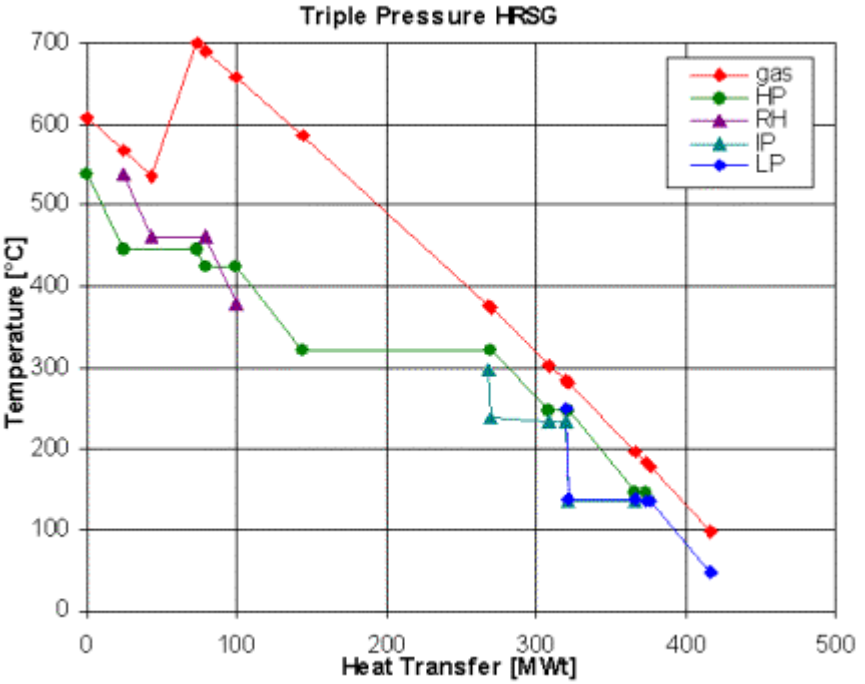

Impact of Gas Temperature
Temperature [°F]
Heat Transfer [MBTU/hr]
1125
1100
1075
1125
1100
1075
0
200
400
600
800
1000
1200
0
100
200
300
400
500

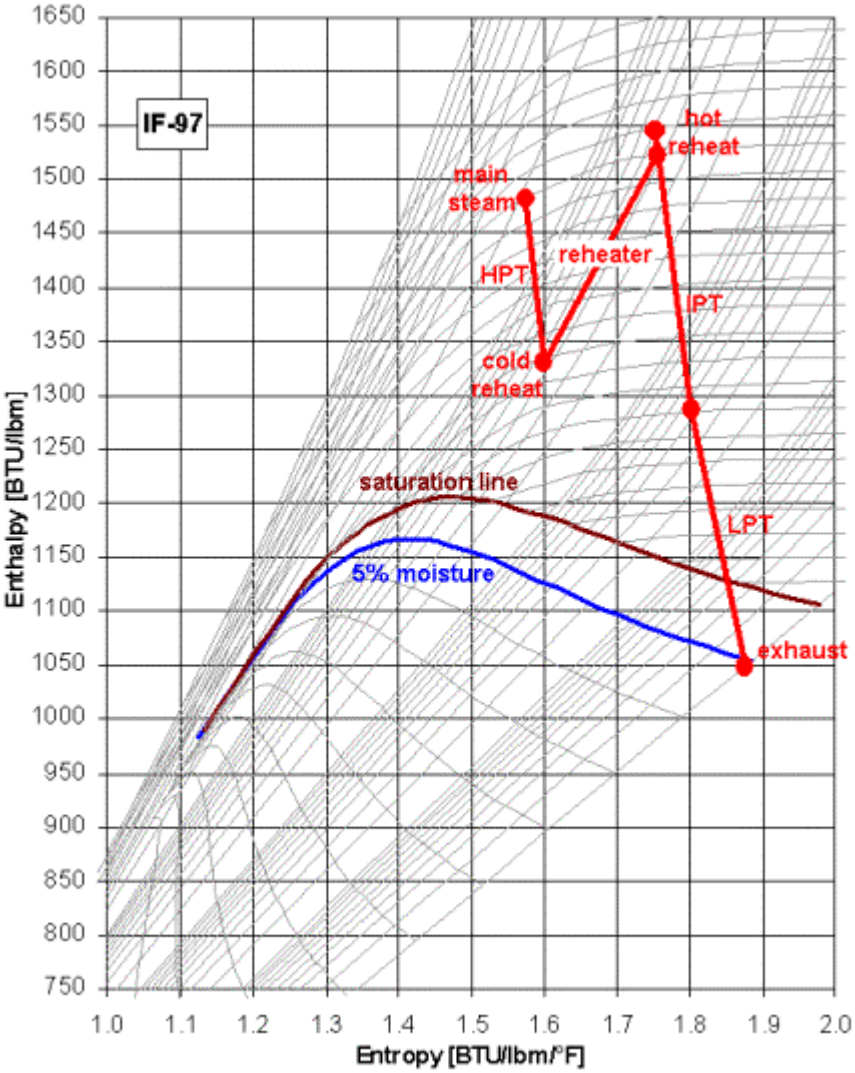

Net Power, MW 45.7
Heat Rate (LHV), BTU/kW-hr 7109
Efficiency (LHV), % 48.00
GT
DUCT BURNER
RH
HPSH
HPSH
RH
HPEV
STACK
IPSH
IPEV
IPEC
HPEC
LPSH
LPEV
LPEC
Temperature, F
Heat Transfer, BTU/hr
Gas Path Start: S27
GateCycle v.5.61.0.r
05/29/2019 11:36 AM
0
100
200
300
400
500
600
700
800
900
1000
0
1e7
2e7
3e7
4e7
5e7
6e7
7e7
8e7
9e7
1e8
1.1e8
1.2e8
1.3e8
1.4e8
1.5e8

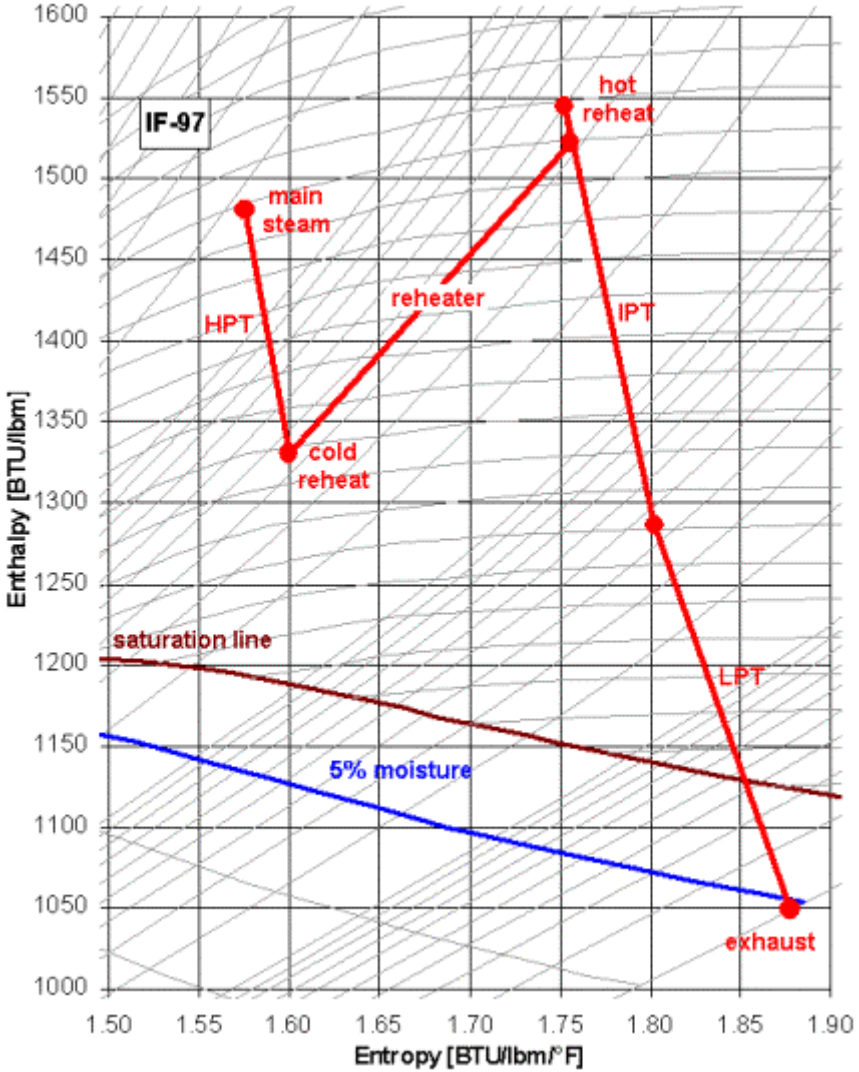

10,000
5,000
0
-5,000
-10,000
-60
-40
-20
0
20
40
60
Δγ Correction [kW]
ω7 Correction (per HRSG) [MBTU/hr]
slope=1/(7920 BTU/kWhr)

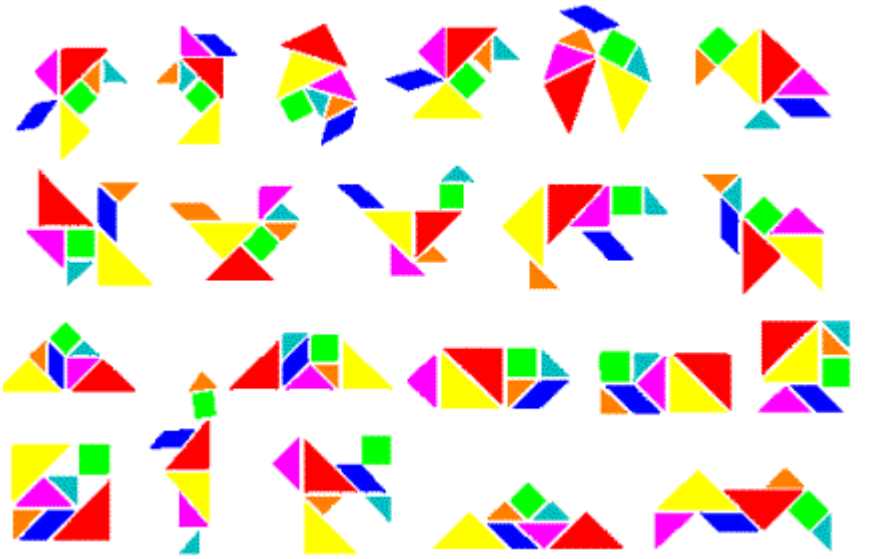


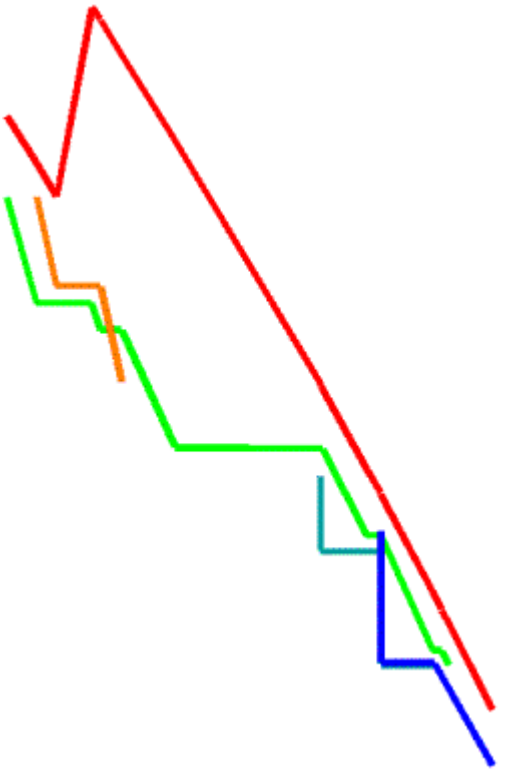

Triple Pressure HRSG
Temperature [°F]
Heat Transfer [MBTU/hr]
gas
HP
RH
IP
LP
0
200
400
600
800
1000
1200
1400
1600

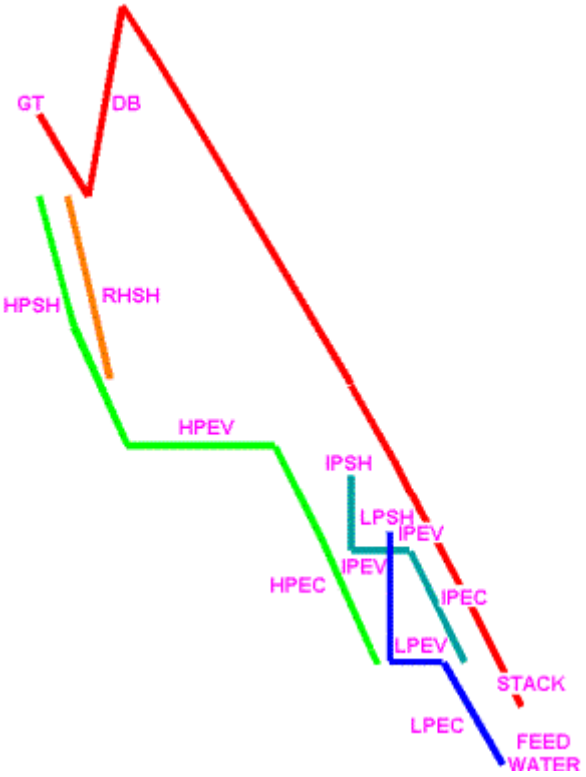

Triple Pressure HRSG
Temperature [°C]
Heat Transfer [MWt]
gas
HP
RH
IP
LP
0
100
200
300
400
500
600
700

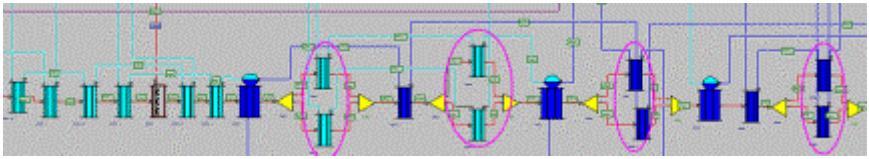

IF-97
hot reheat
main steam
reheater
HPT
IPT
cold reheat
saturation line
LPT
5% moisture
exhaust
Enthalpy [BTU/lbm]
Entropy [BTU/lbm/°F]
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0

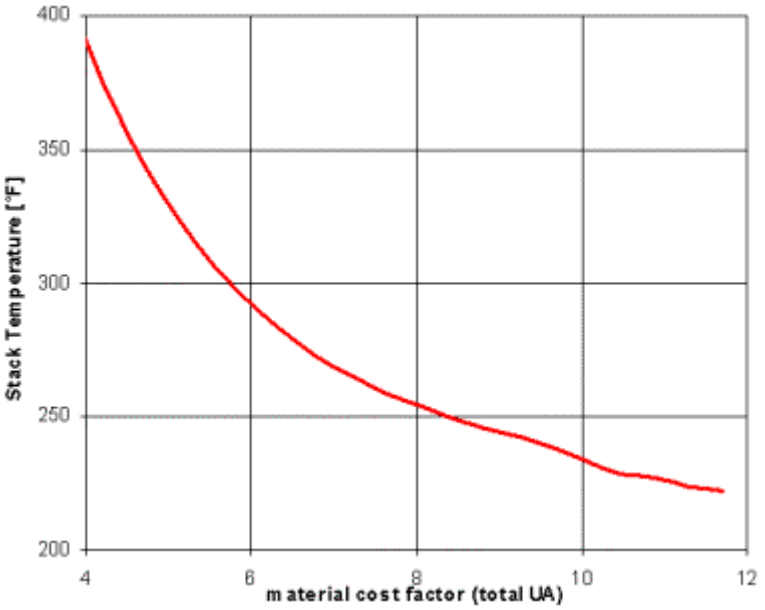

IF-97
hot reheat
main steam
HPT
reheater
IPT
cold reheat
saturation line
LPT
5% moisture
exhaust
Enthalpy [BTU/lbm]
Entropy [BTU/lbm/°F]
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
1.50
1.55
1.60
1.65
1.70
1.75
1.80
1.85
1.90

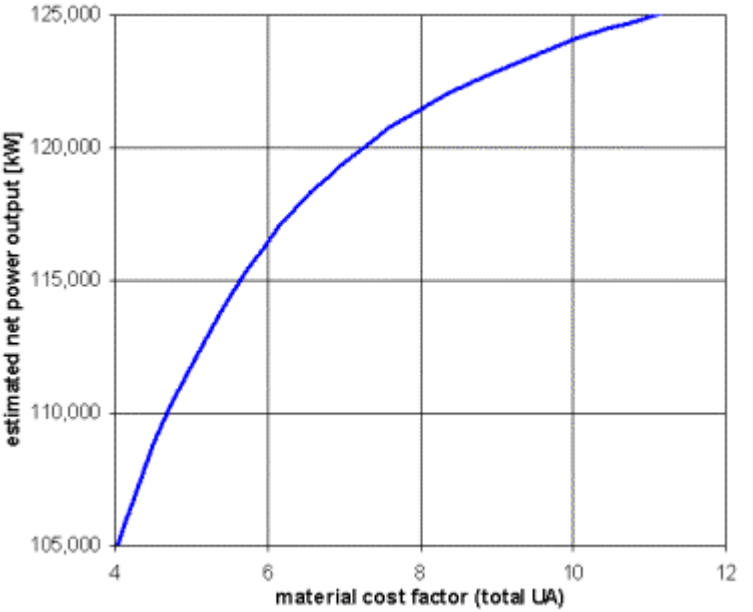


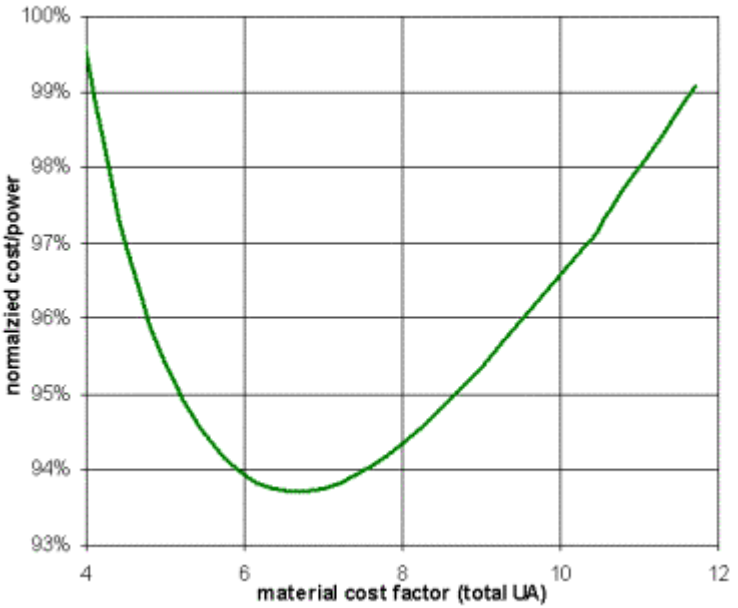



GT
DB
HPSH
RHSH
HPEV
IPSH
LPSH
IPEV
IPEV
HPEC
IPEC
LPEV
STACK
LPEC
FEED
WATER

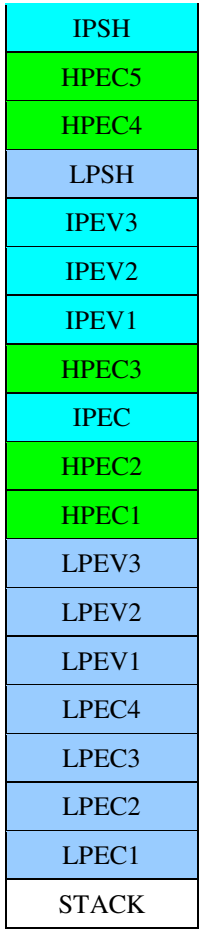


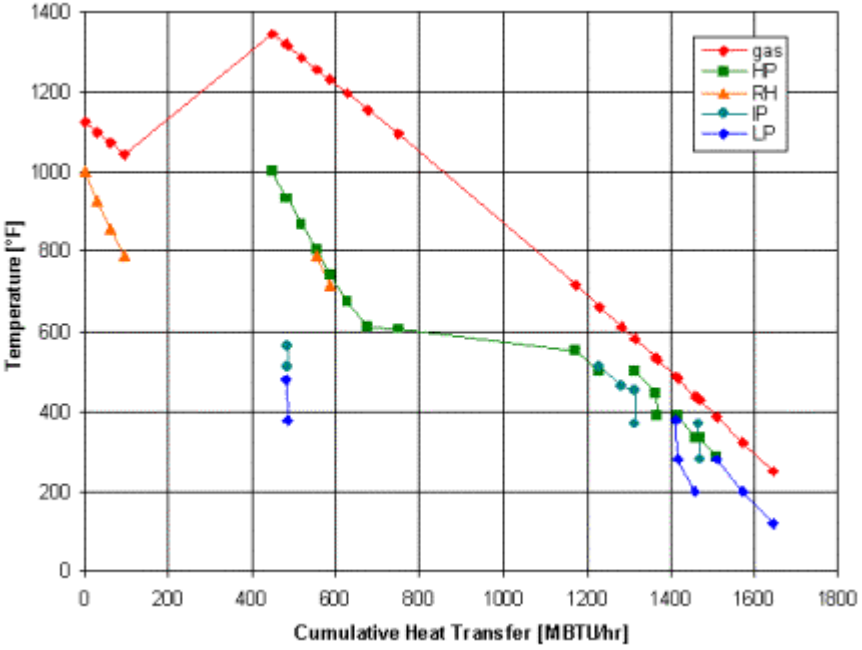

400
350
300
250
200
Stack Temperature [°F]
4
6
8
10
12
material cost factor (total UA)

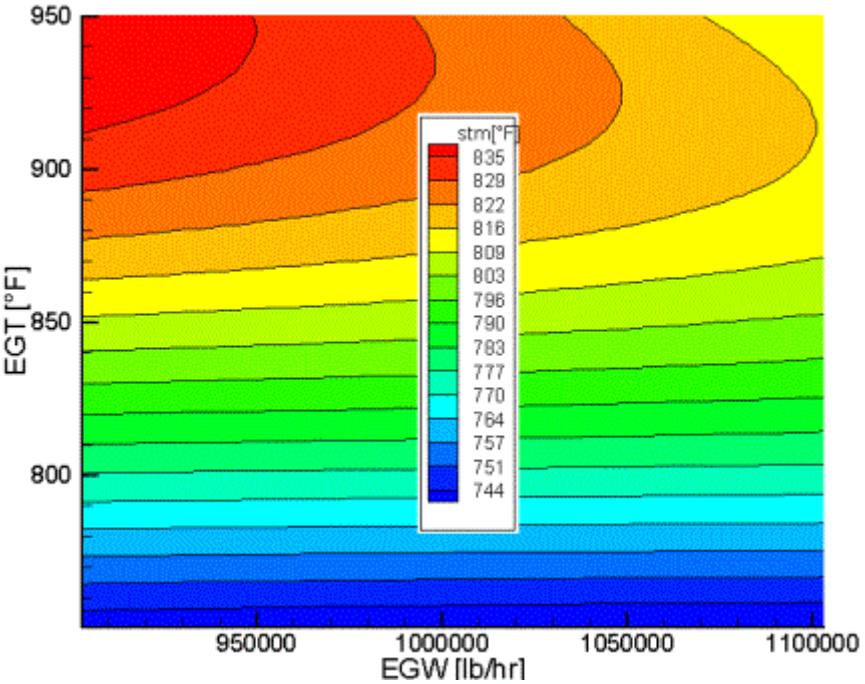

125,000
120,000
115,000
110,000
105,000
estimated net power output [kW]
4
6
8
10
12
material cost factor (total UA)

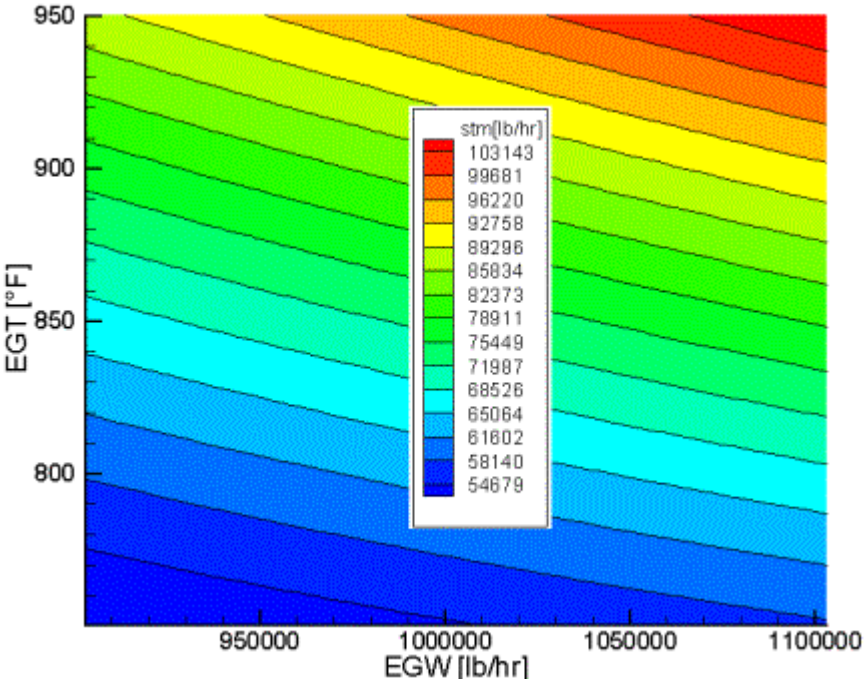


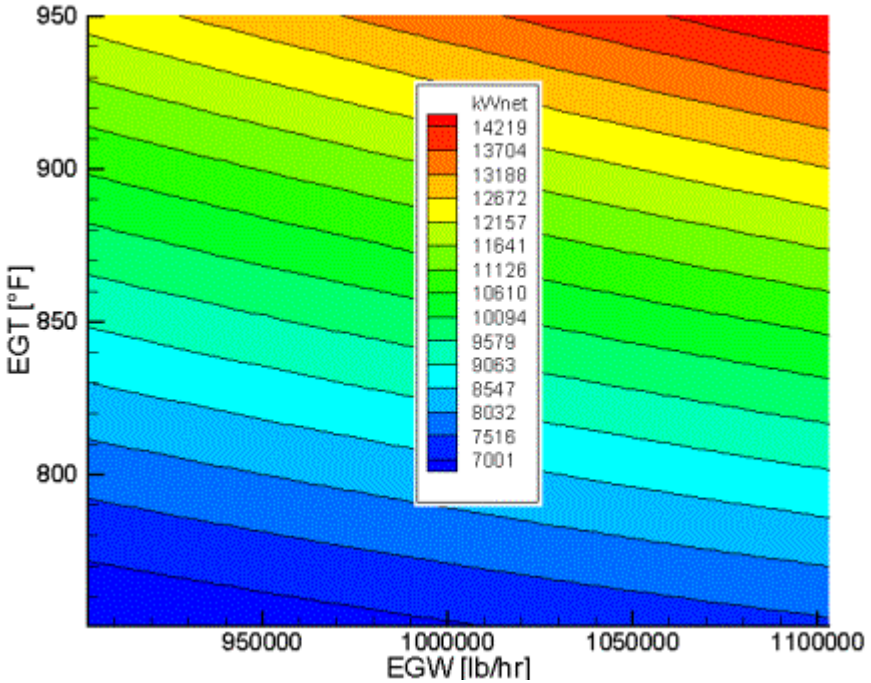
GT
HPSH4
RH3
HPSH3
RH2
DB
HPSH2
HPSH1
RH1
HPEV4
HPEV3
HPEV2
HPEV1
HPEC6
SCR

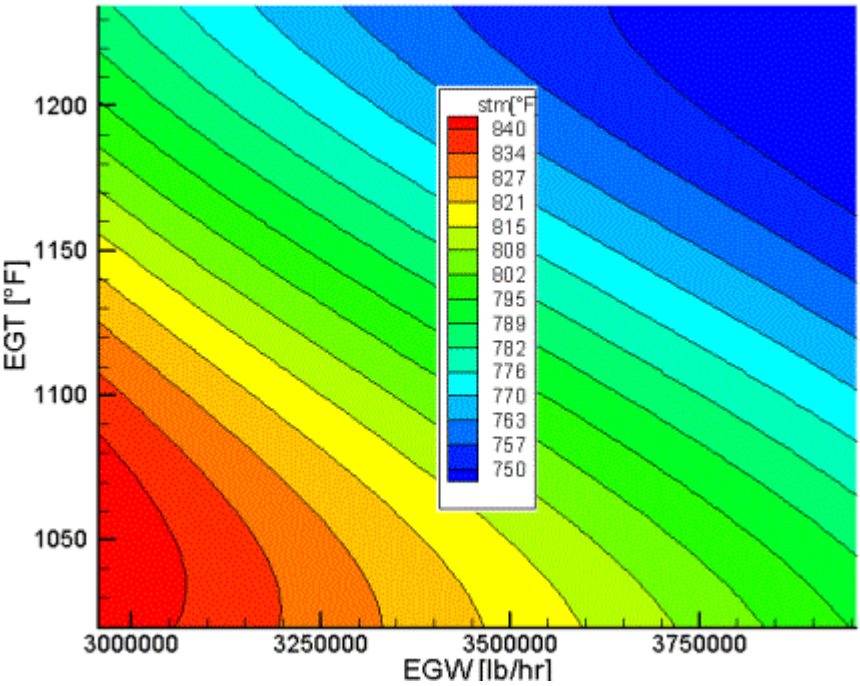

IPSH
HPEC5
HPEC4
LPSH
IPEV3
IPEV2
IPEV1
HPEC3
IPEC
HPEC2
HPEC1
LPEV3
LPEV2
LPEV1
LPEC4
LPEC3
LPEC2
LPEC1
STACK

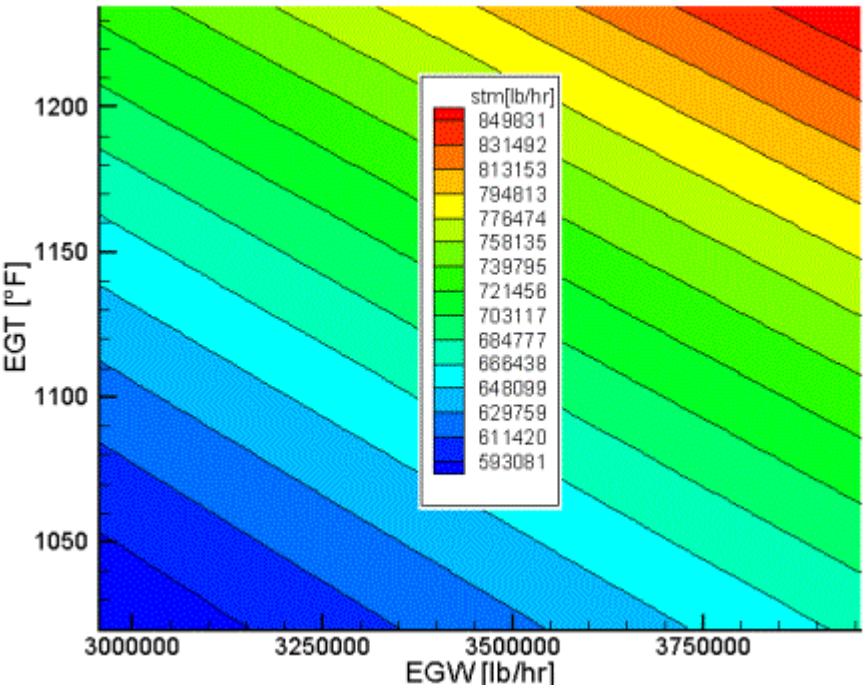

gas
HP
RH
IP
LP
Temperature [°F]
Cumulative Heat Transfer [MBTU/hr]
0
200
400
600
800
1000
1200
1400
1600
1800

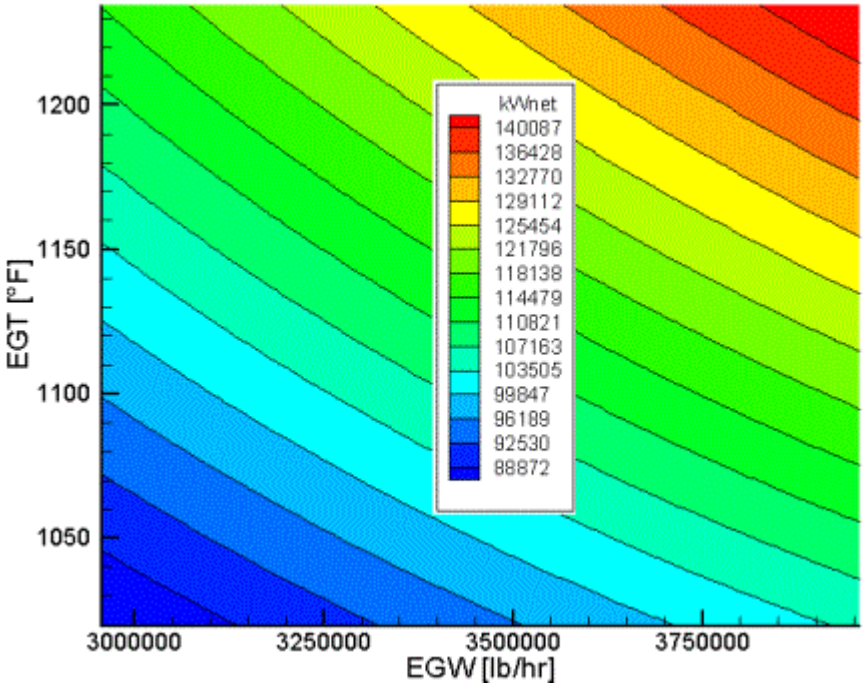

950
900
850
800
EGT [°F]
stm[°F]
835
829
822
816
809
803
796
790
783
777
770
764
757
751
744
950000
1000000
1050000
1100000
EGW [lb/hr]

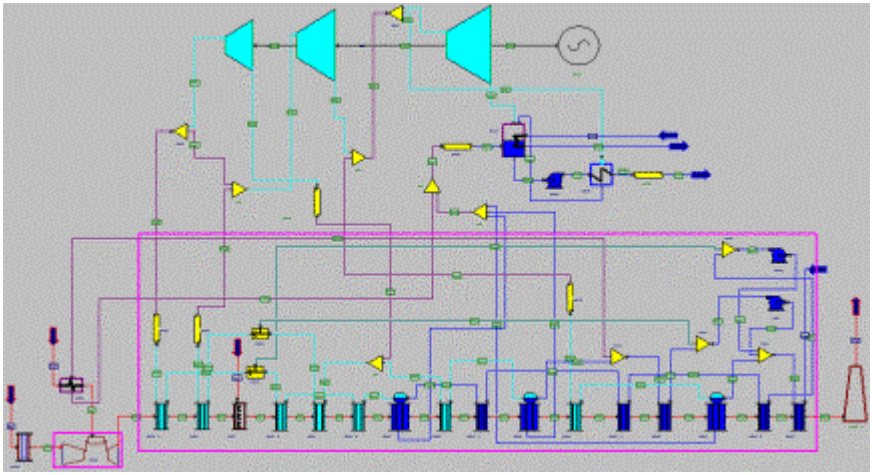

950
900
850
800
EGT [°F]
950000
1000000
1050000
1100000
EGW [lb/hr]
stm[lb/hr]
103143
99681
96220
92758
89296
85834
82373
78911
75449
71987
68526
65064
61602
58140
54679

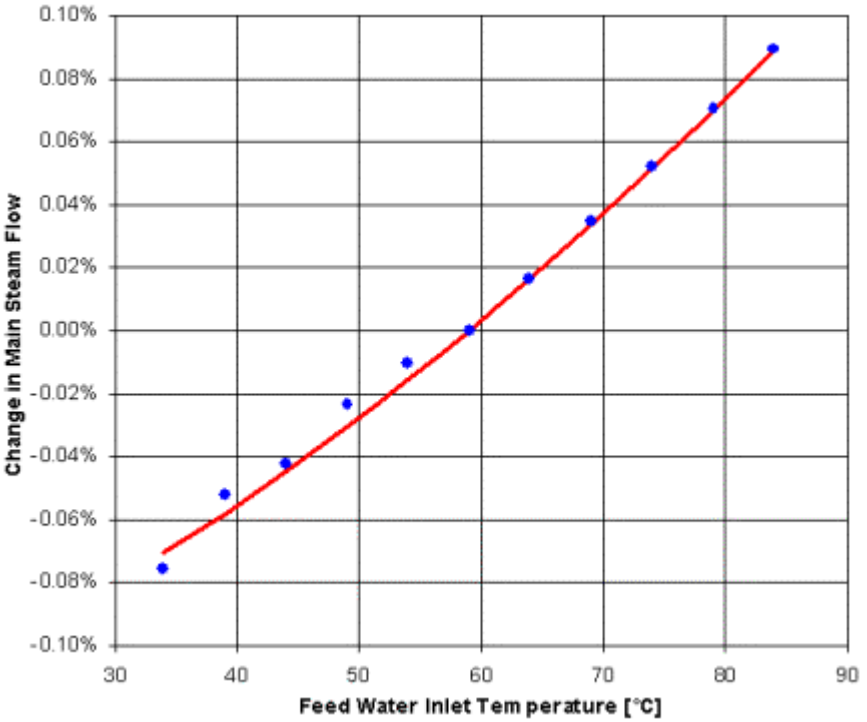

950
900
850
800
EGT [°F]
950000
1000000
1050000
1100000
EGW [lb/hr]
kWnet
14219
13704
13188
12672
12157
11641
11126
10610
10094
9579
9063
8547
8032
7516
7001

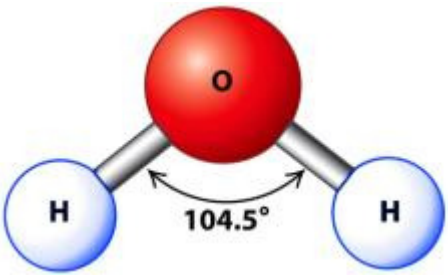

stm[°F
840
834
827
821
815
808
802
795
789
782
776
770
763
757
750
1200
1150
1100
1050
EGT [°F]
3000000
3250000
3500000
3750000
EGW [lb/hr]

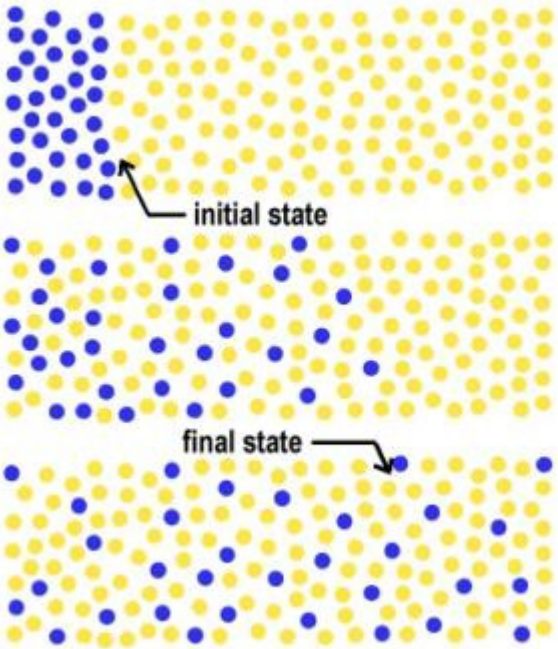

stm[lb/hr]
849831
831492
813153
794813
776474
758135
739795
721456
703117
684777
666438
648099
629759
611420
593081
1200
1150
1100
1050
EGT [°F]
3000000
3250000
3500000
3750000
EGW [lb/hr]


kWnet
140087
136428
132770
129112
125454
121796
118138
114479
110821
107163
103505
99847
96189
92530
88872
1200
1150
1100
1050
EGT [°F]
3000000
3250000
3500000
3750000
EGW [lb/hr]



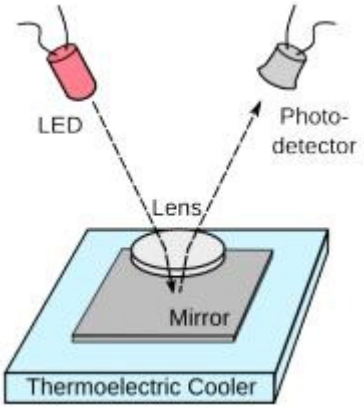

0.10%
0.08%
0.06%
0.04%
0.02%
0.00%
-0.02%
-0.04%
-0.06%
-0.08%
-0.10%
Change in Main Steam Flow
30
40
50
60
70
80
90
Feed Water Inlet Temperature [°C]

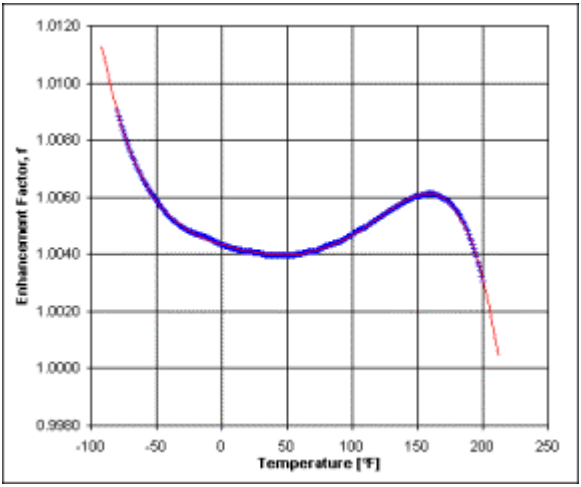

O
H
H
104.5°

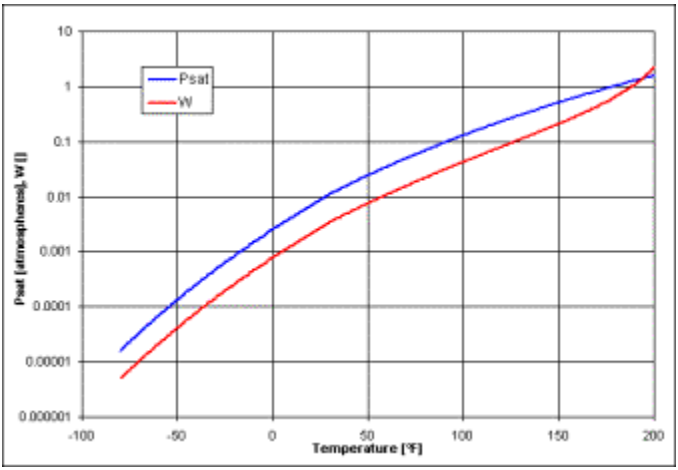

initial state
final state

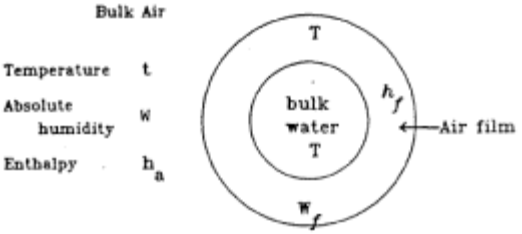

wick
water bottle
wet RTD
dry RTD

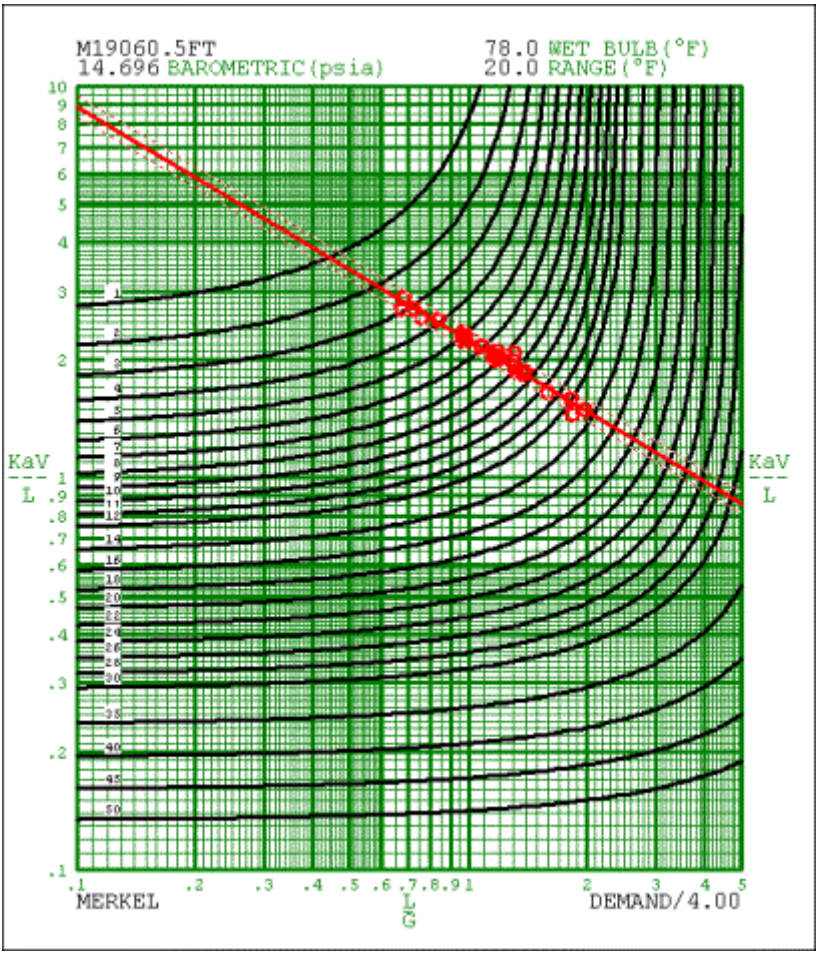

insulation
fan

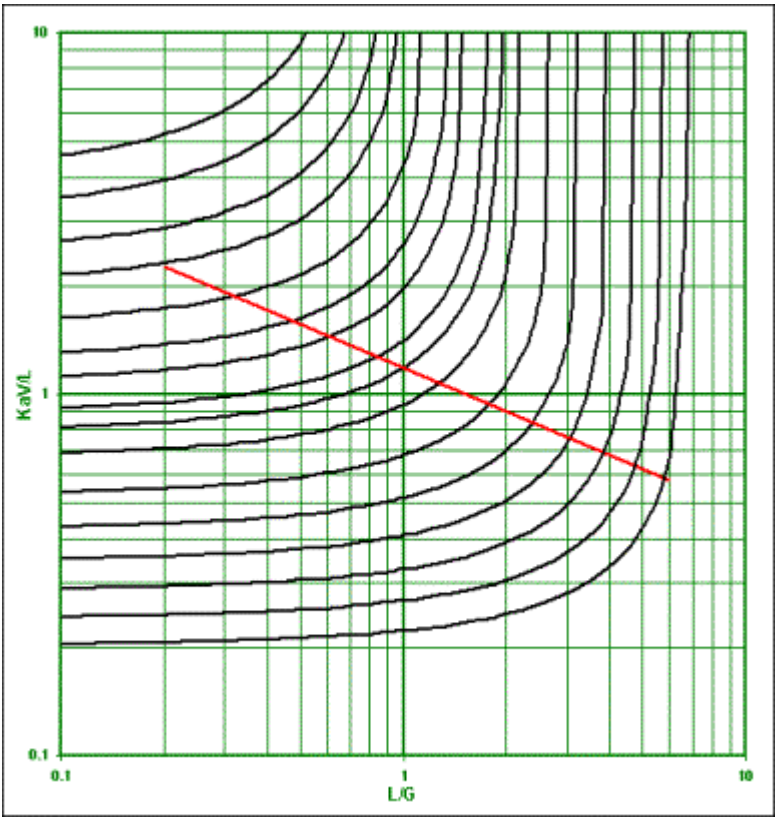

LED
Photo-
detector
Lens
Mirror
Thermoelectric Cooler

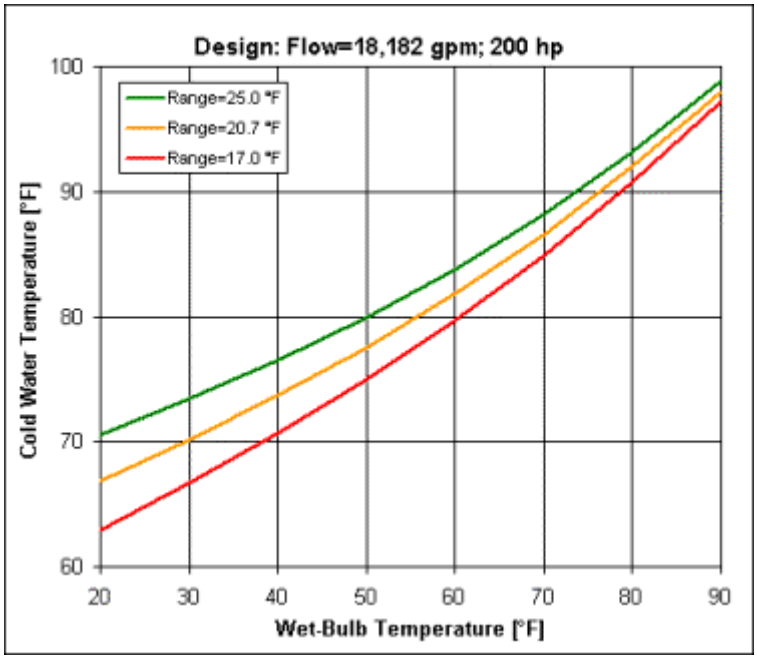

1.0120
1.0100
1.0080
1.0060
1.0040
1.0020
1.0000
0.9980
Enhancement Factor, f
-100
-50
0
50
100
150
200
250
Temperature [°F]


Psat
W
Psat [atmospheres], W [-]
Temperature [°F]
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
-100
-50
0
50
100
150
200


Bulk Air
Temperature t
Absolute humidity W
Enthalpy h_a
T
bulk water
T
h_f
Air film
W_f


M19060.5FT
14.696 BAROMETRIC(psia)
78.0 WET BULB(°F)
20.0 RANGE(°F)
KaV / L
KaV / L
MERKEL
L / G
DEMAND/4.00


10
1
0.1
KaV/L
0.1
1
10
L/G

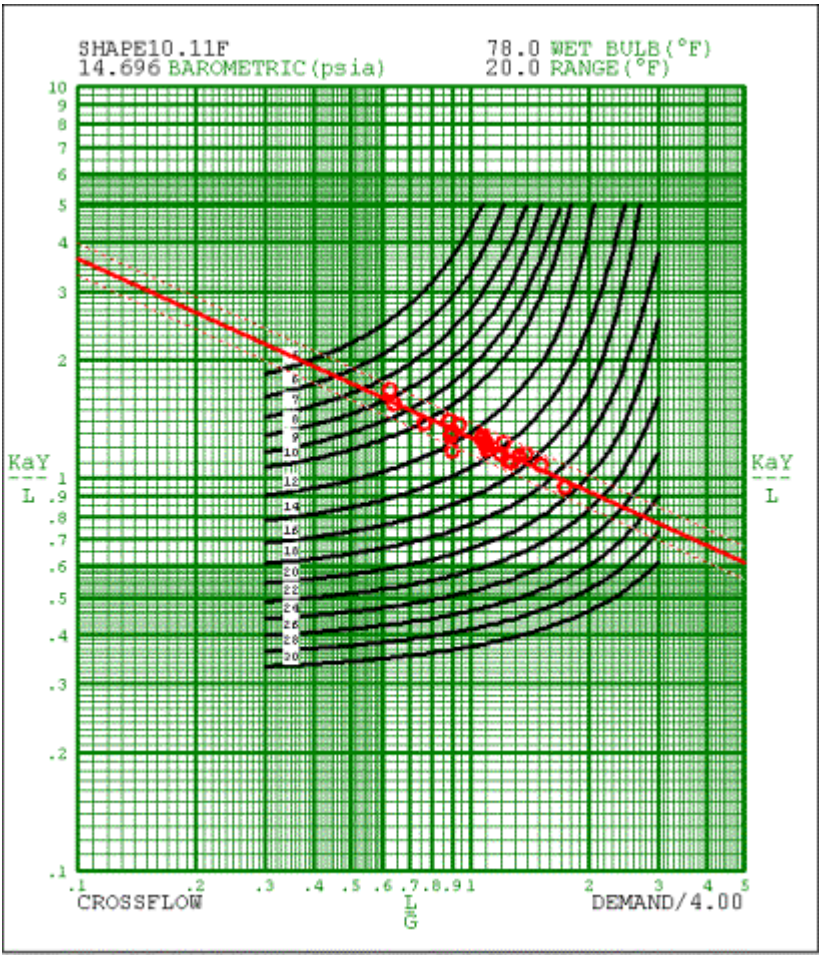


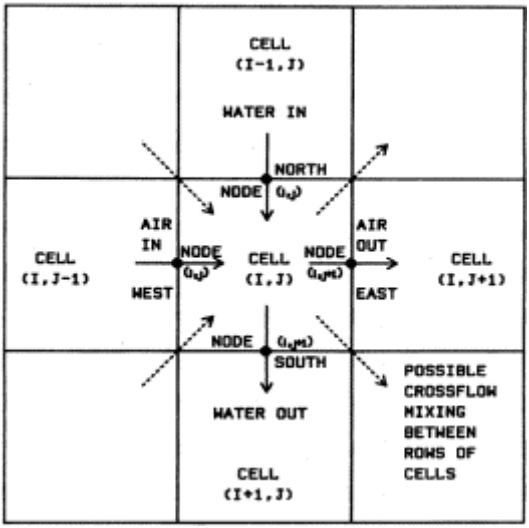
CrossflowCooling Tower Demand Calculations

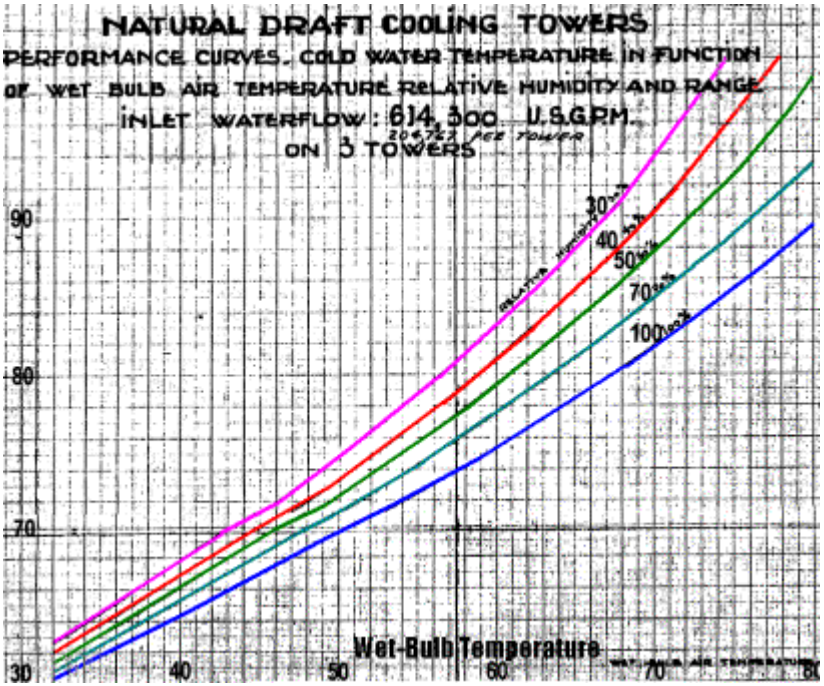
user inputs
50 Twb
120 Thw
2.00 L/G
1.38 KaY
calculations
83.2 Tcw
36.8 range
33.2 approach

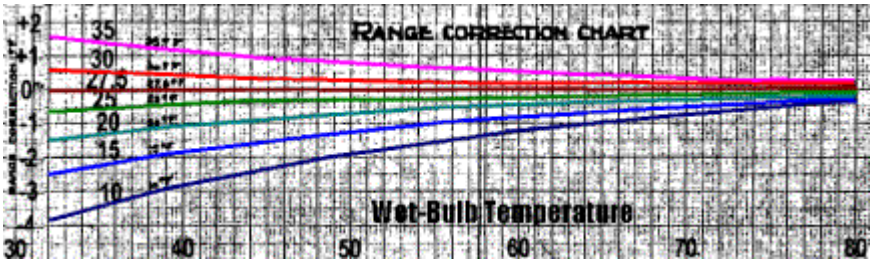
Ta						Tw				
						120.0	120.0	120.0	120.0	120.0
50	102	113	117	119	119	92.6	107.7	114.5	117.5	118.9
50	78	97	108	113	117	81.7	95.2	104.3	110.6	114.7
50	70	86	97	105	111	74.7	87.1	96.2	103.2	108.5
50	65	79	89	98	104	69.8	81.1	89.9	96.9	102.6
50	62	74	83	91	98	66.0	76.4	84.7	91.7	97.4

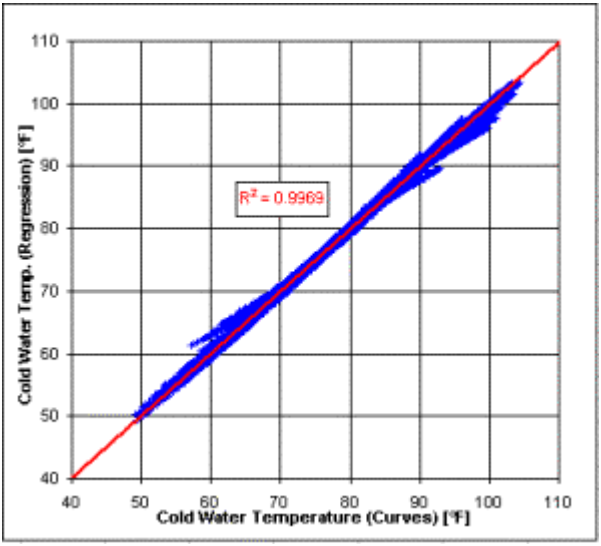
Ha						Hw				
						119.7	119.7	119.7	119.7	119.7
20.3	75.2	99.7	110.7	115.7	117.9	59.6	87.2	103.7	112.2	116.3
20.3	42.0	66.9	87.2	101.0	109.4	45.6	63.7	80.1	93.9	104.2
20.3	34.3	50.5	66.8	81.8	94.2	38.4	52.1	65.3	77.7	88.9
20.3	30.3	42.3	55.0	67.5	79.3	33.9	44.9	55.8	66.4	76.6
20.3	27.8	37.2	47.5	57.9	68.2	30.8	39.9	49.1	58.3	67.3

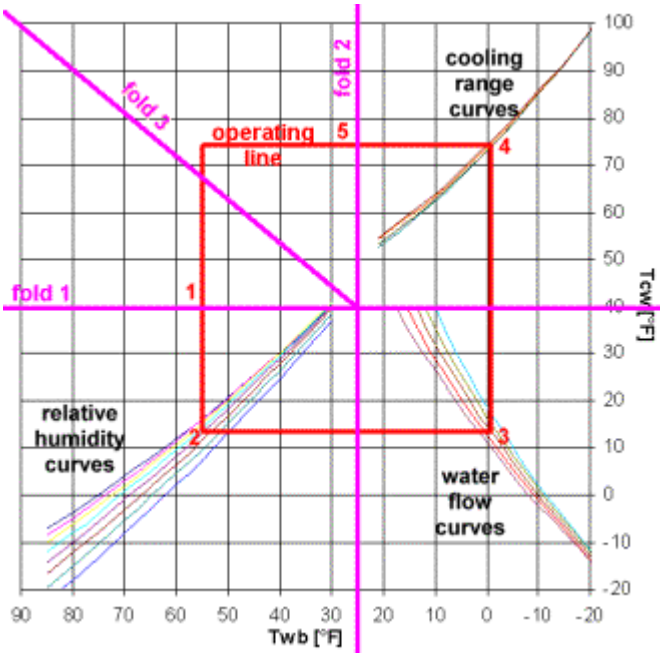

SHAPE10.11F
14.696 BAROMETRIC(psia)
78.0 WET BULB(°F)
20.0 RANGE(°F)
KaY / L
KaY / L
CROSSFLOW
L/G
DEMAND/4.00

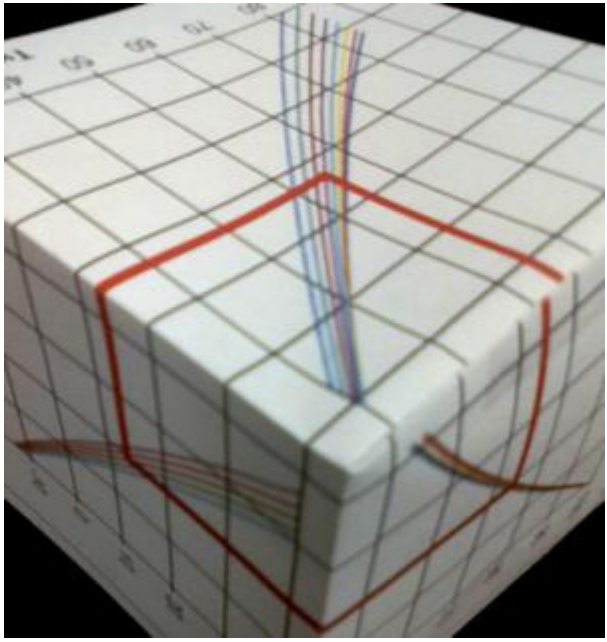

CELL
(I-1,J)
WATER IN
NORTH
NODE
AIR
IN
NODE
CELL
(I,J-1)
WEST
CELL
(I,J)
NODE
AIR
OUT
CELL
(I,J+1)
EAST
NODE
SOUTH
WATER OUT
CELL
(I+1,J)
POSSIBLE
CROSSFLOW
MIXING
BETWEEN
ROWS OF
CELLS

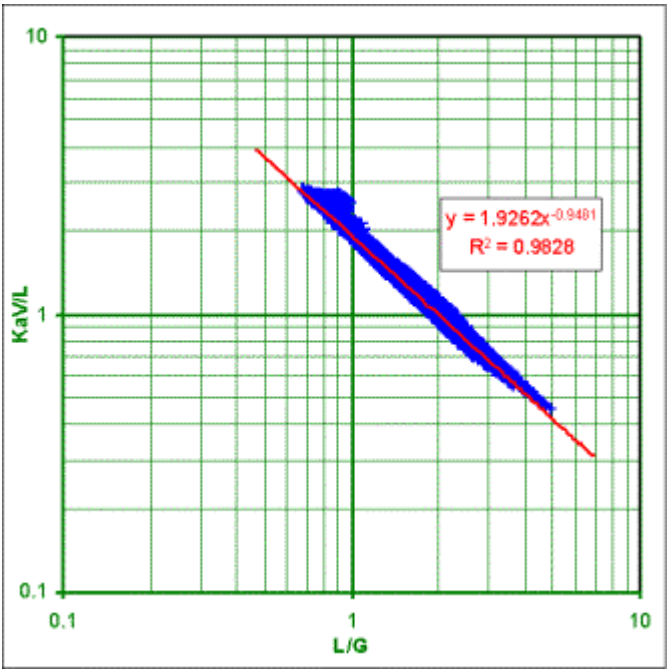

NATURAL DRAFT COOLING TOWERS
PERFORMANCE CURVES. COLD WATER TEMPERATURE IN FUNCTION
OF WET BULB AIR TEMPERATURE RELATIVE HUMIDITY AND RANGE
INLET WATERFLOW: 614,300 U.S.G.P.M.
ON 3 TOWERS
90
80
70
30
40
50
60
70
Wet-Bulb Temperature

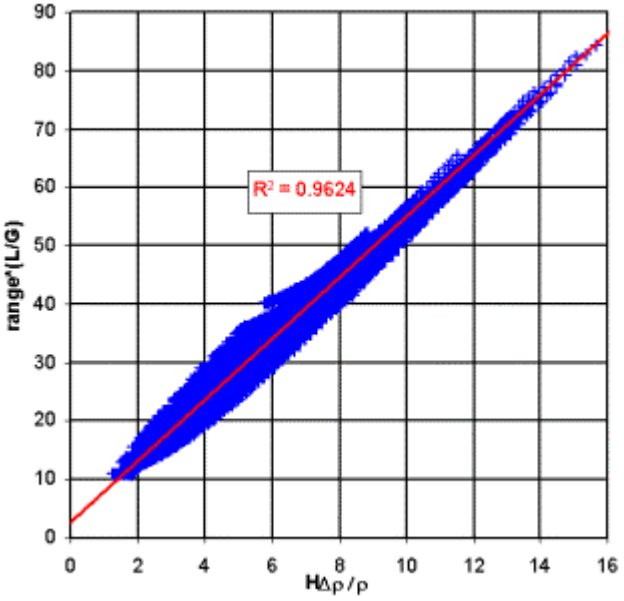

RANGE CORRECTION CHART
Wet-Bulb Temperature
35
30
25
20
15
10
30
40
50
60
70
80

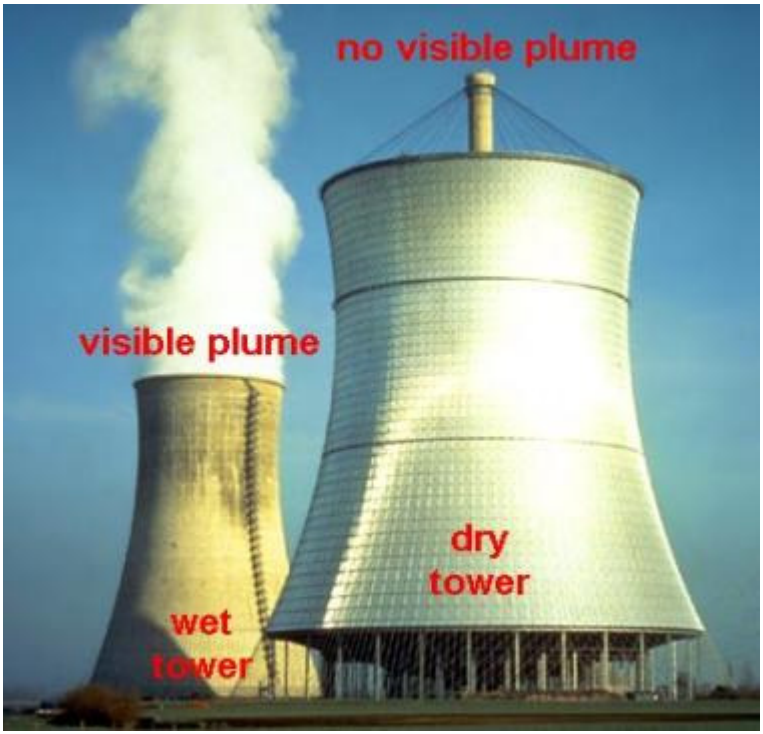

Cold Water Temp. (Regression) [°F]
Cold Water Temperature (Curves) [°F]
R² = 0.9969
110
100
90
80
70
60
50
40
40
50
60
70
80
90
100
110

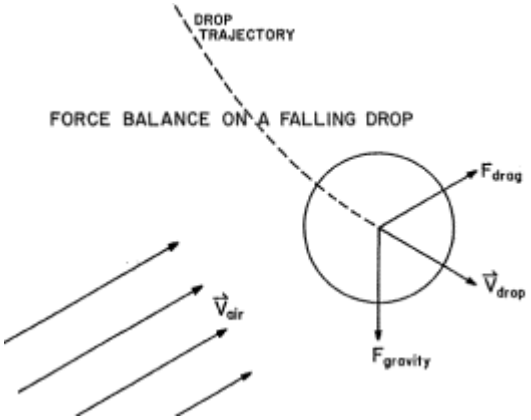

fold 3
fold 2
fold 1
operating line
1
2
3
4
5
cooling range curves
relative humidity curves
water flow curves
100
90
80
70
60
50
40
30
20
10
0
-10
-20
Tcw [°F]
90
80
70
60
50
40
30
20
10
0
-10
-20
Twb [°F]

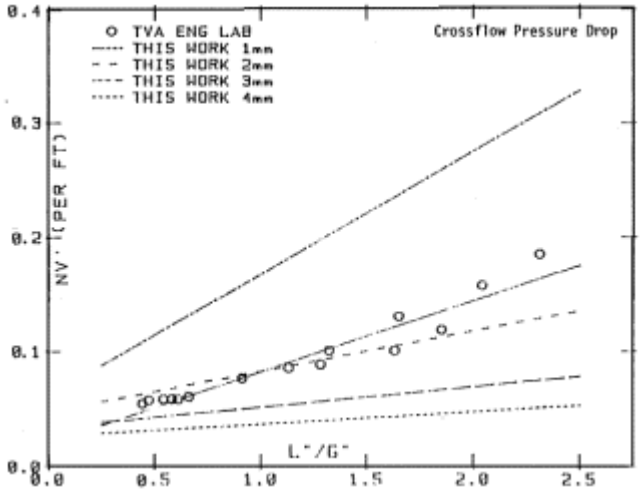


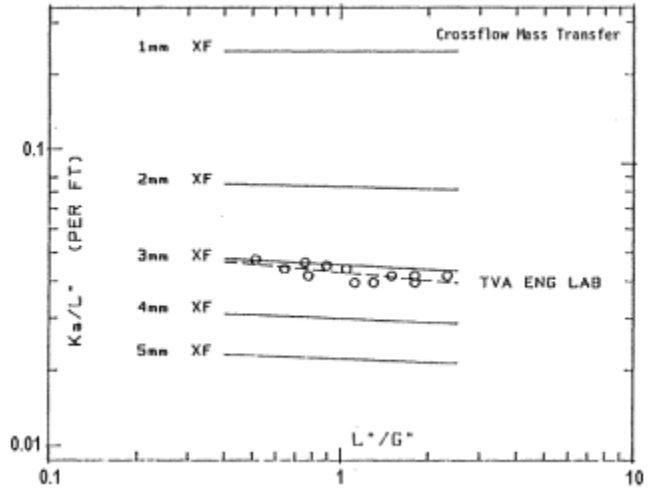

10
1
0.1
KaV/L
0.1
1
10
L/G
y = 1.9262x-0.9481
R2 = 0.9828

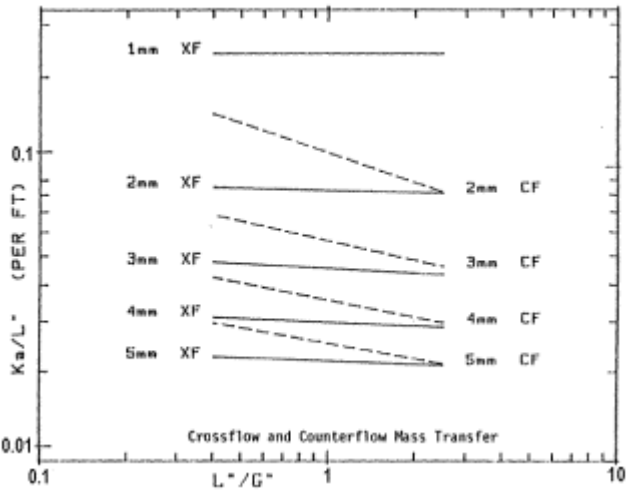

R² = 0.9624
range*(L/G)
HΔρ/ρ
0
10
20
30
40
50
60
70
80
90
0
2
4
6
8
10
12
14
16

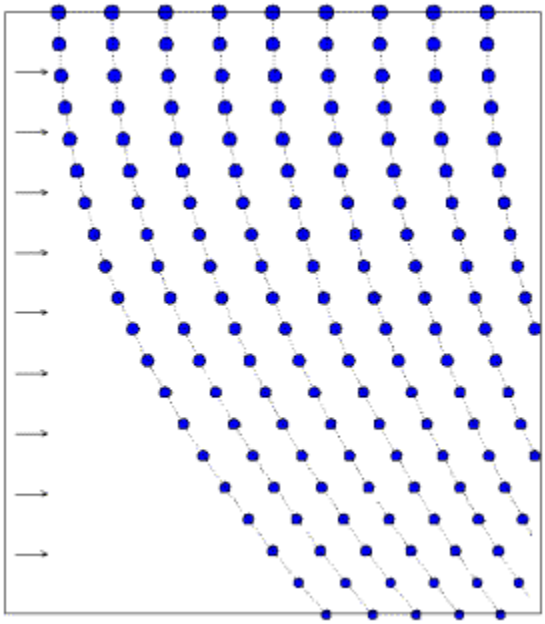

no visible plume
visible plume
dry
tower
wet
tower

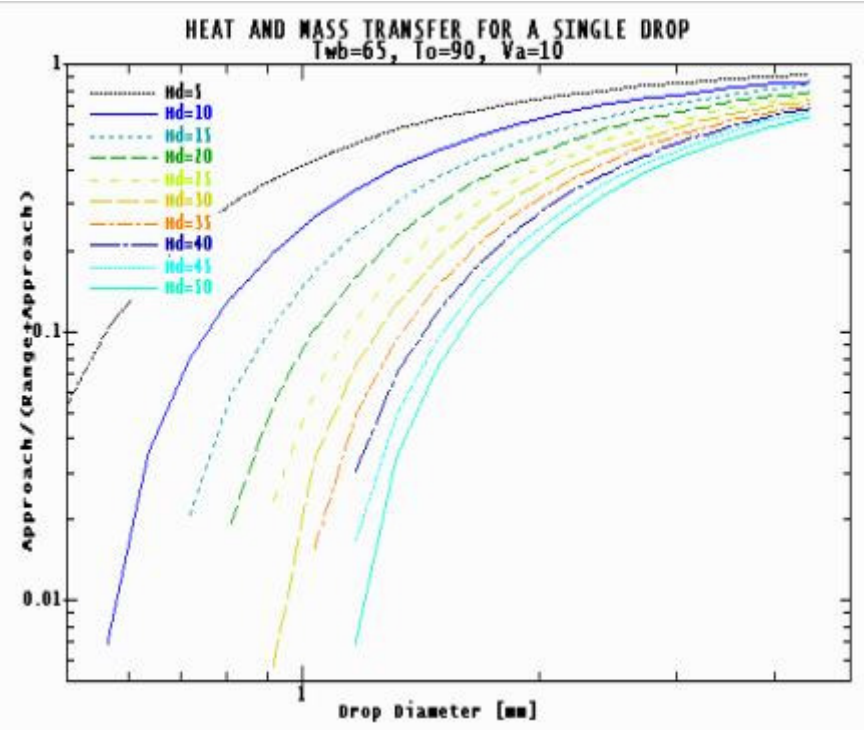

DROP
TRAJECTORY
FORCE BALANCE ON A FALLING DROP
F_{drag}
$\vec{V}_{drop}$
$\vec{V}_{air}$
$F_{gravity}$

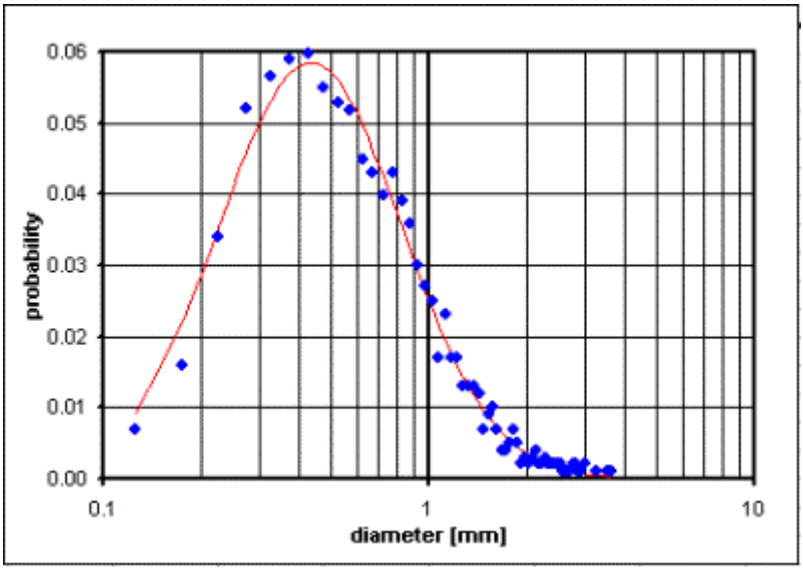

Crossflow Pressure Drop
TVA ENG LAB
THIS WORK 1mm
THIS WORK 2mm
THIS WORK 3mm
THIS WORK 4mm
NV'(PER FT)
L'/G'
0.0
0.1
0.2
0.3
0.4
0.5
1.0
1.5
2.0
2.5

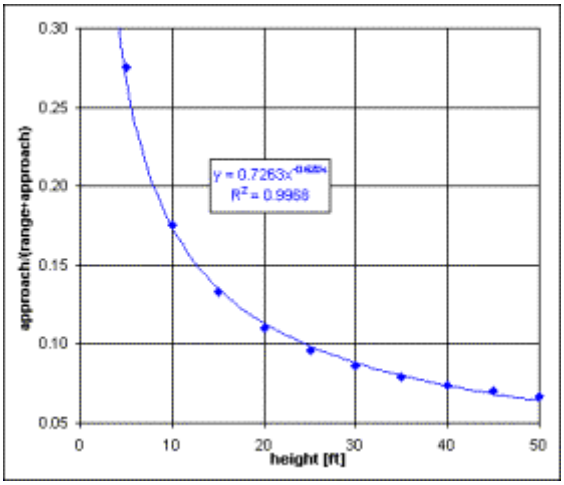

Crossflow Mass Transfer
1mm XF
2mm XF
3mm XF
4mm XF
5mm XF
TVA ENG LAB
Ka/L' (PER FT)
L'/G'
0.01
0.1
1
10

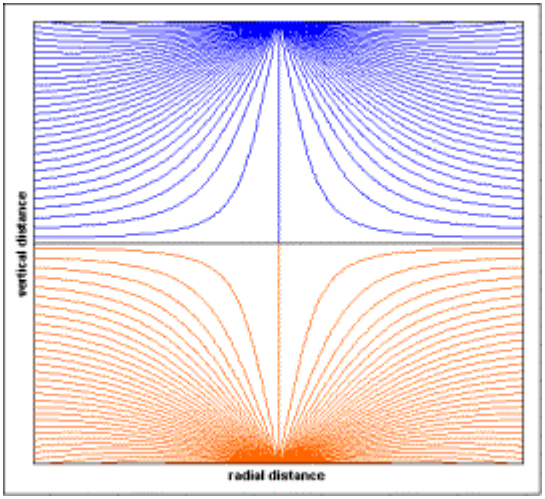

1mm XF
2mm XF
2mm CF
3mm XF
3mm CF
4mm XF
4mm CF
5mm XF
5mm CF
0.1
0.01
Ka/L" (PER FT)
Crossflow and Counterflow Mass Transfer
0.1
L"/G"
1
10

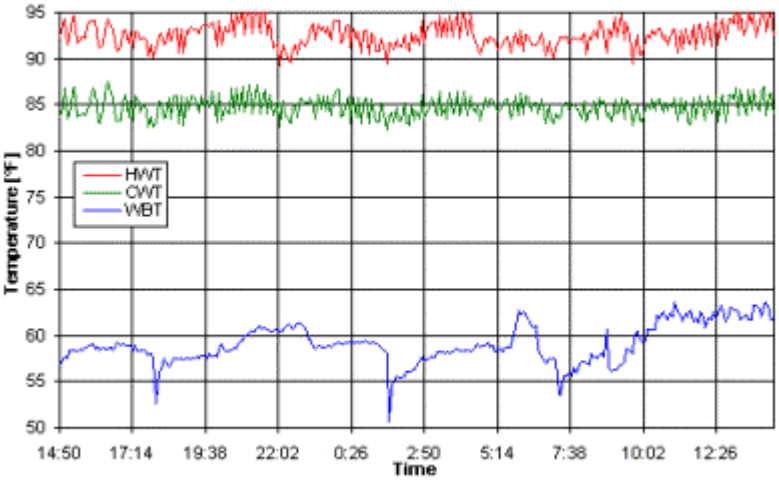


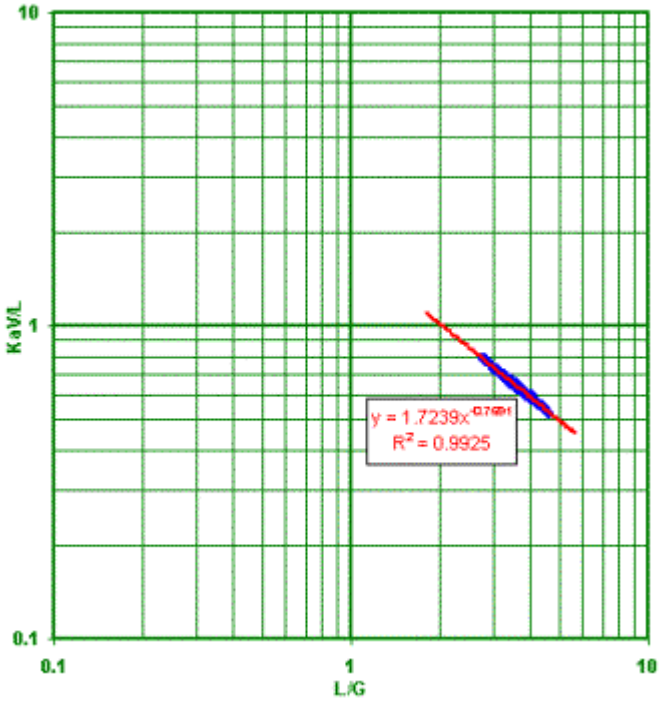

HEAT AND MASS TRANSFER FOR A SINGLE DROP
Twb=65, To=90, Va=10
Approach/(Range+Approach)
Drop Diameter [mm]
1
0.1
0.01
1
Nd=5
Nd=10
Nd=15
Nd=20
Nd=25
Nd=30
Nd=35
Nd=40
Nd=45
Nd=50

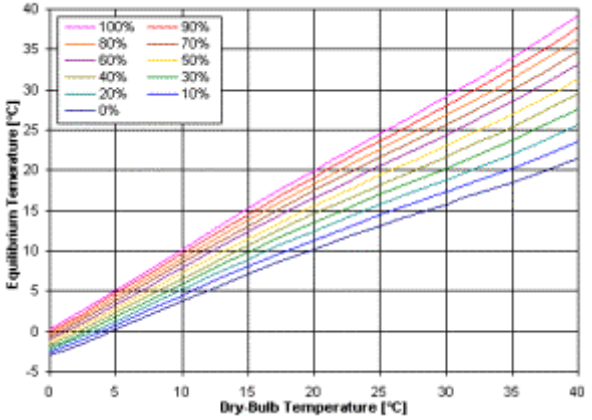

0.06
0.05
0.04
0.03
0.02
0.01
0.00
probability
0.1
1
10
diameter [mm]

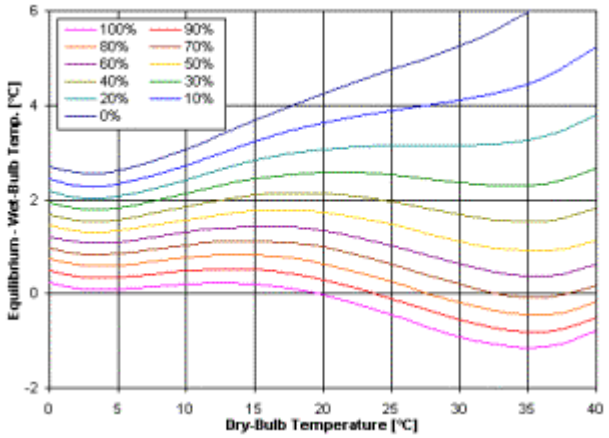

0.30
0.25
0.20
0.15
0.10
0.05
approach/(range+approach)
y = 0.7263x^-0.4654
R² = 0.9968
0
10
20
30
40
50
height [ft]

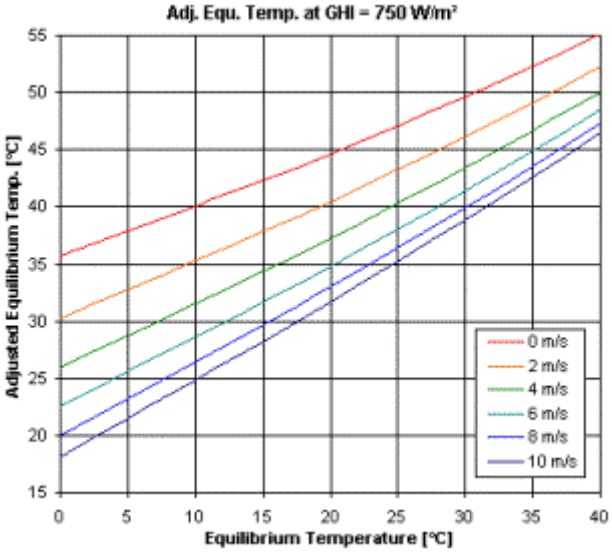

vertical distance
radial distance

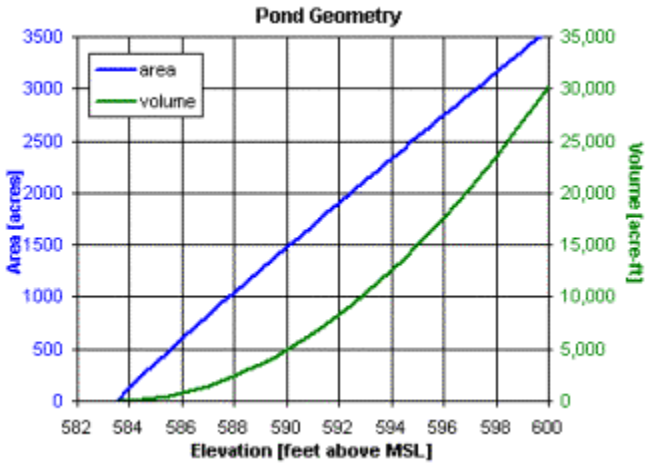

95
90
85
80
75
70
65
60
55
50
Temperature [°F]
HWT
CWT
WBT
14:50
17:14
19:38
22:02
0:26
2:50
5:14
7:38
10:02
12:26
Time

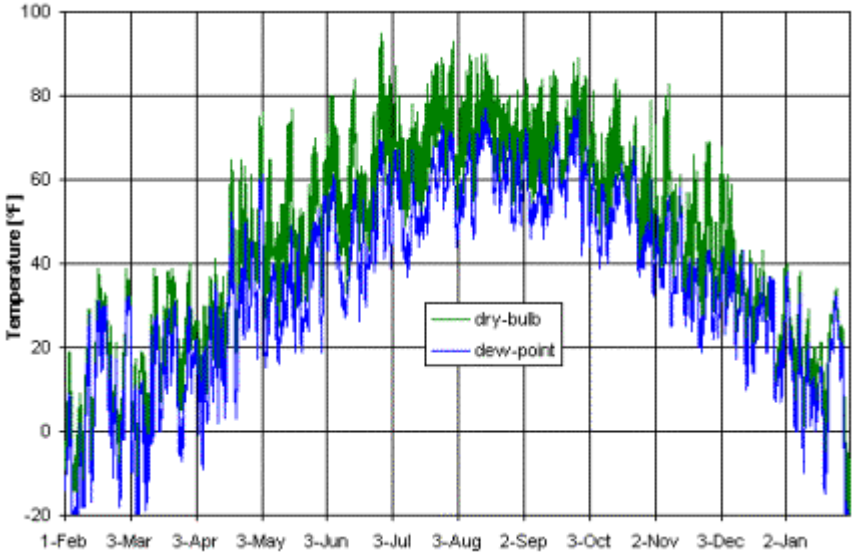

10
1
0.1
KaV/L
0.1
1
10
L/G
y = 1.7239x^-0.7691
R² = 0.9925

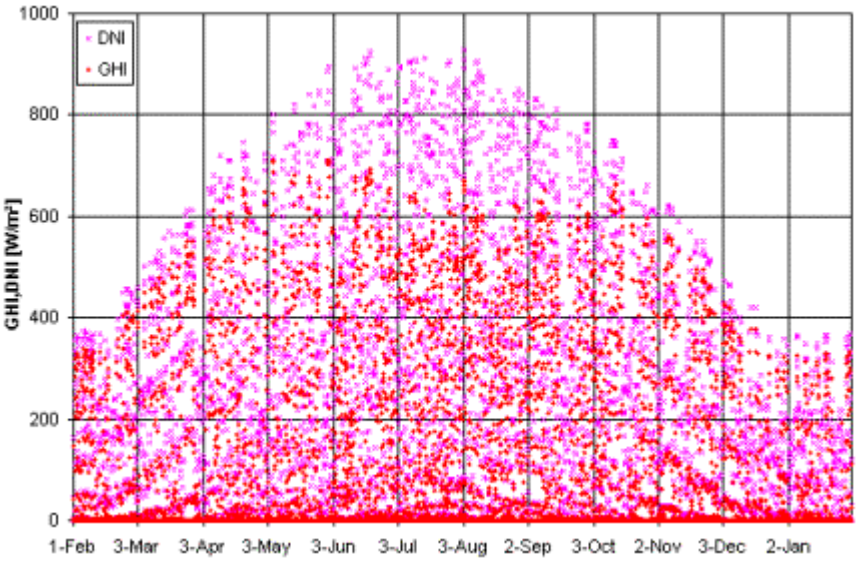

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Equilibrium Temperature [°C]
Dry-Bulb Temperature [°C]
40
35
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
30
35
40

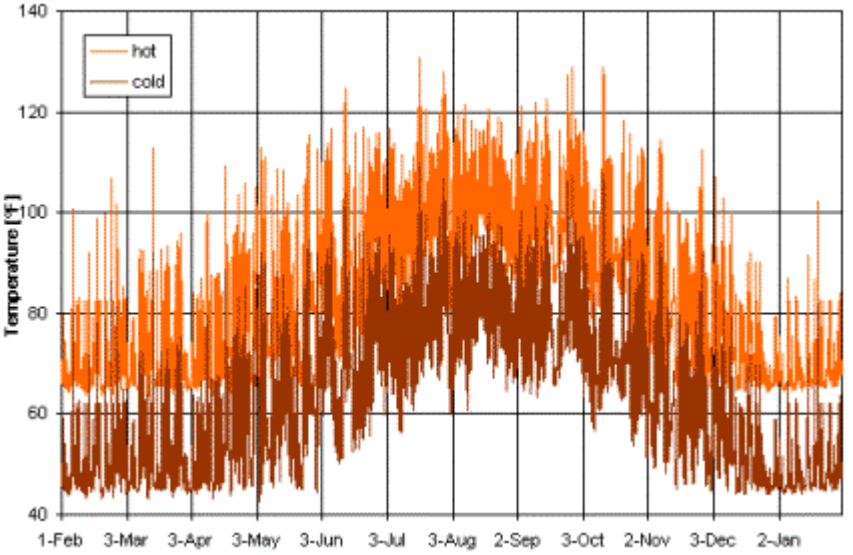

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Equilibrium - Wet-Bulb Temp. [°C]
Dry-Bulb Temperature [°C]

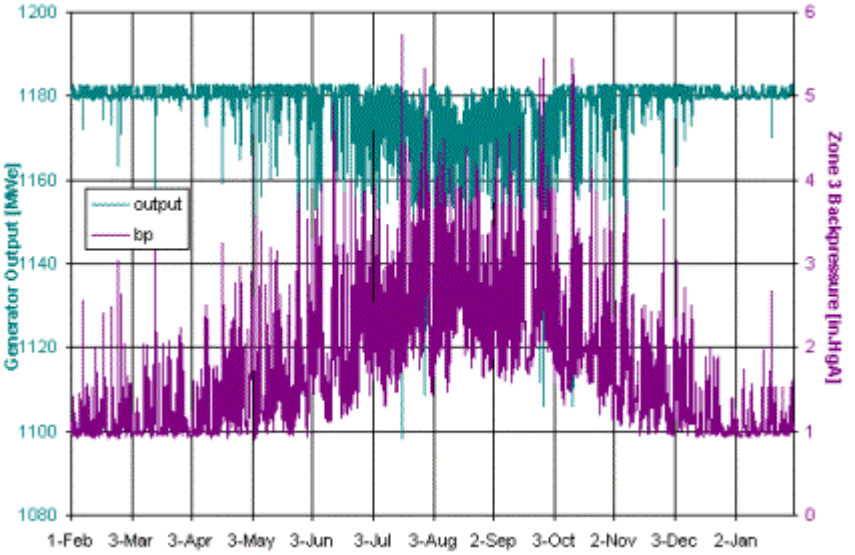

Adj. Equ. Temp. at GHI = 750 W/m²
0 m/s
2 m/s
4 m/s
6 m/s
8 m/s
10 m/s
Adjusted Equilibrium Temp. [°C]
Equilibrium Temperature [°C]

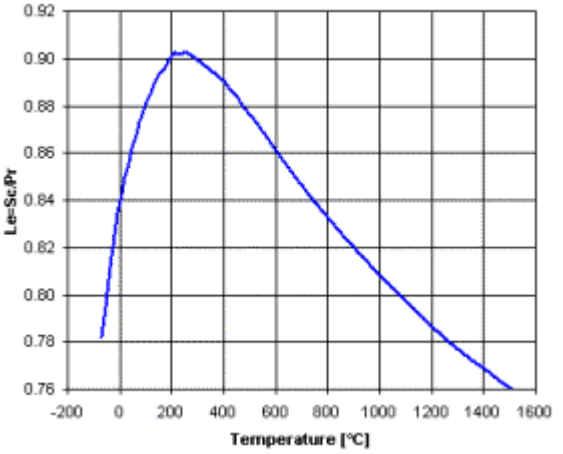

Pond Geometry
area
volume
Area [acres]
Volume [acre-ft]
Elevation [feet above MSL]
3500
3000
2500
2000
1500
1000
500
0
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
582
584
586
588
590
592
594
596
598
600

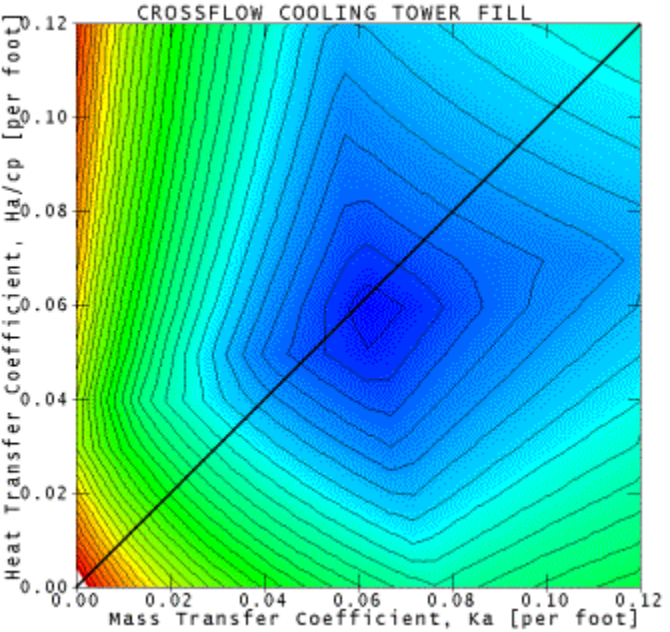

Temperature [°F]
dry-bulb
dew-point
100
80
60
40
20
0
-20
1-Feb
3-Mar
3-Apr
3-May
3-Jun
3-Jul
3-Aug
2-Sep
3-Oct
2-Nov
3-Dec
2-Jan

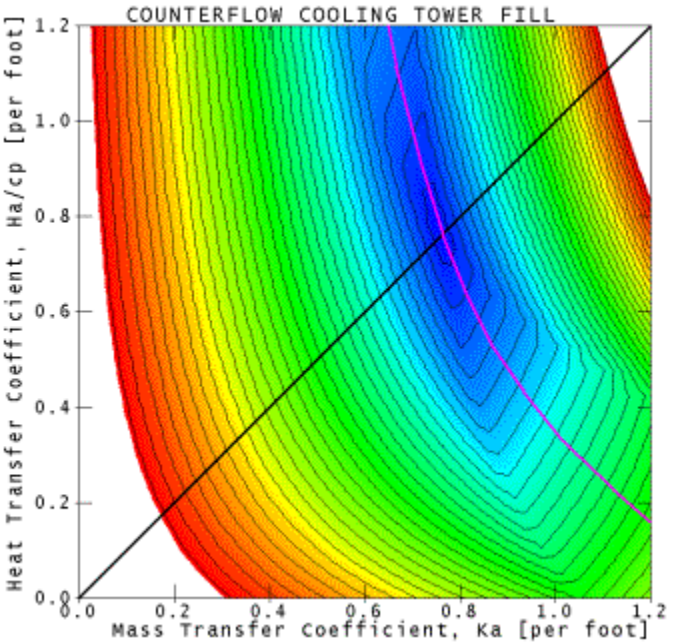

DNI
GHI
GHI,DNI [W/m²]
1000
800
600
400
200
0
1-Feb
3-Mar
3-Apr
3-May
3-Jun
3-Jul
3-Aug
2-Sep
3-Oct
2-Nov
3-Dec
2-Jan

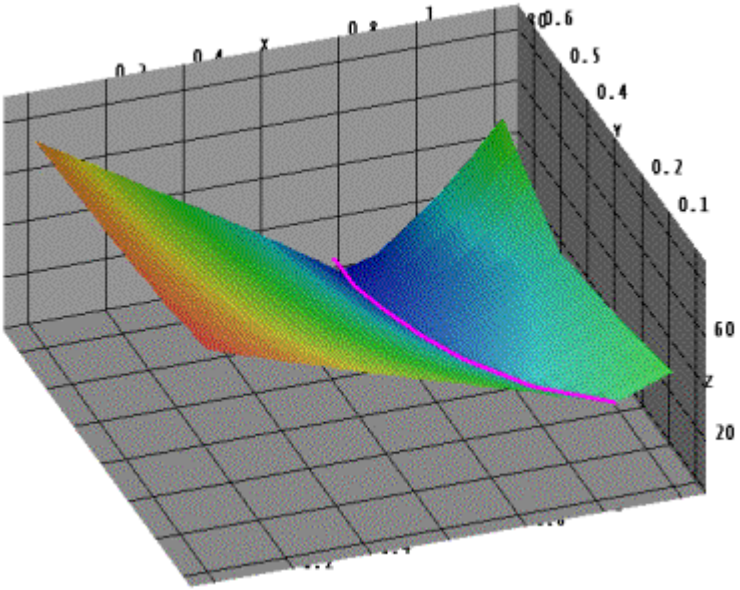

hot
cold
Temperature [°F]
140
120
100
80
60
40
1-Feb
3-Mar
3-Apr
3-May
3-Jun
3-Jul
3-Aug
2-Sep
3-Oct
2-Nov
3-Dec
2-Jan

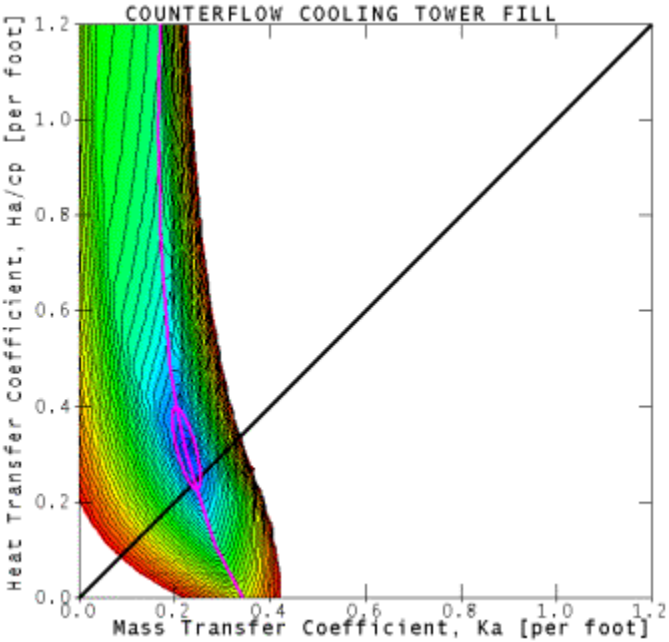

Generator Output [MWe]
Zone 3 Backpressure [in.HgA]
output
bp
1200
1180
1160
1140
1120
1100
1080
6
5
4
3
2
1
0
1-Feb
3-Mar
3-Apr
3-May
3-Jun
3-Jul
3-Aug
2-Sep
3-Oct
2-Nov
3-Dec
2-Jan

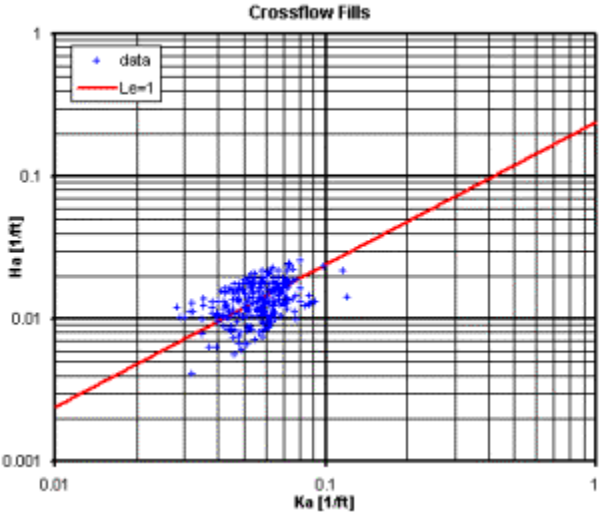

Le-Sc/Pr
Temperature [°C]
0.92
0.90
0.88
0.86
0.84
0.82
0.80
0.78
0.76
-200
0
200
400
600
800
1000
1200
1400
1600

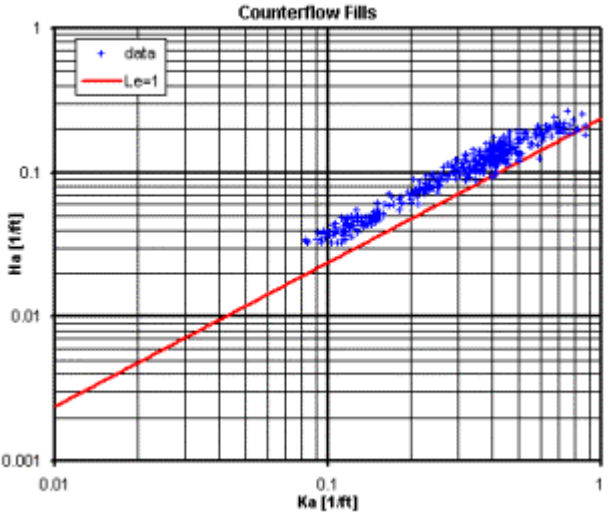

CROSSFLOW COOLING TOWER FILL
Heat Transfer Coefficient, Ha/cp [per foot]
0.00
0.02
0.04
0.06
0.08
0.10
0.12
Mass Transfer Coefficient, Ka [per foot]

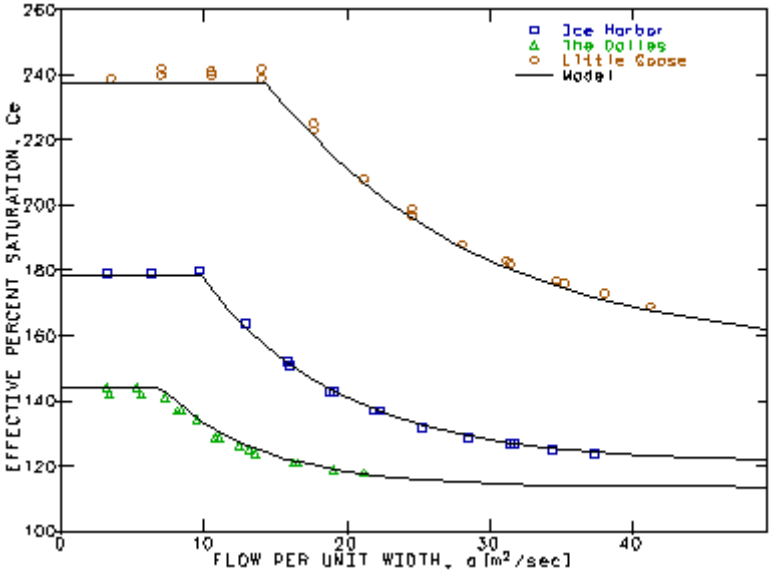

COUNTERFLOW COOLING TOWER FILL
Heat Transfer Coefficient, Ha/cp [per foot]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Mass Transfer Coefficient, Ka [per foot]

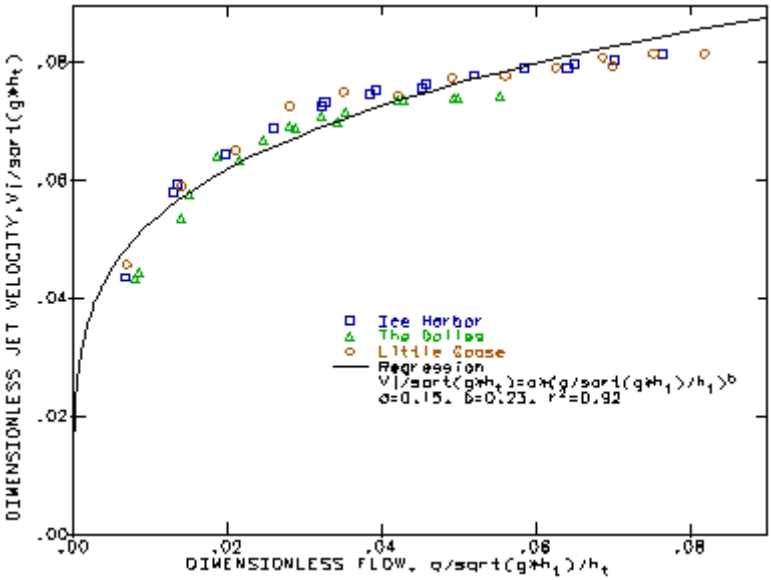

0.6
0.5
0.4
Y
0.2
0.1
60
Z
20

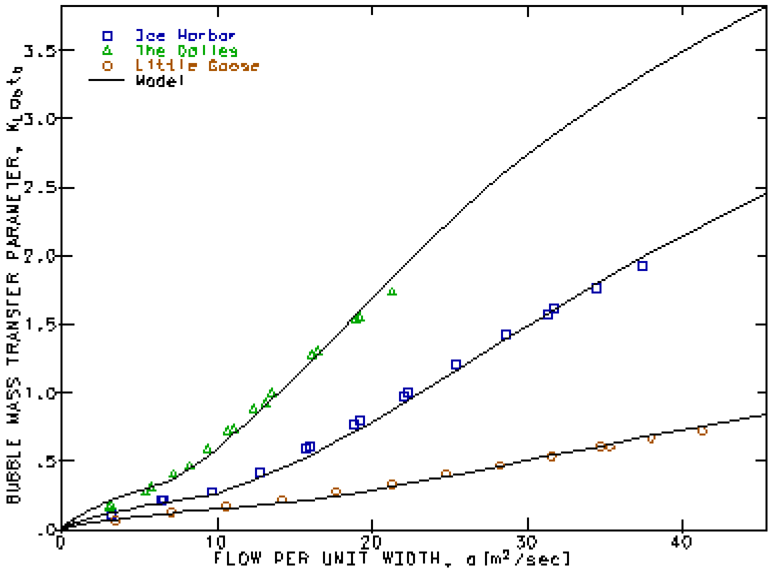

COUNTERFLOW COOLING TOWER FILL
Heat Transfer Coefficient, Ha/cp [per foot]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Mass Transfer Coefficient, Ka [per foot]

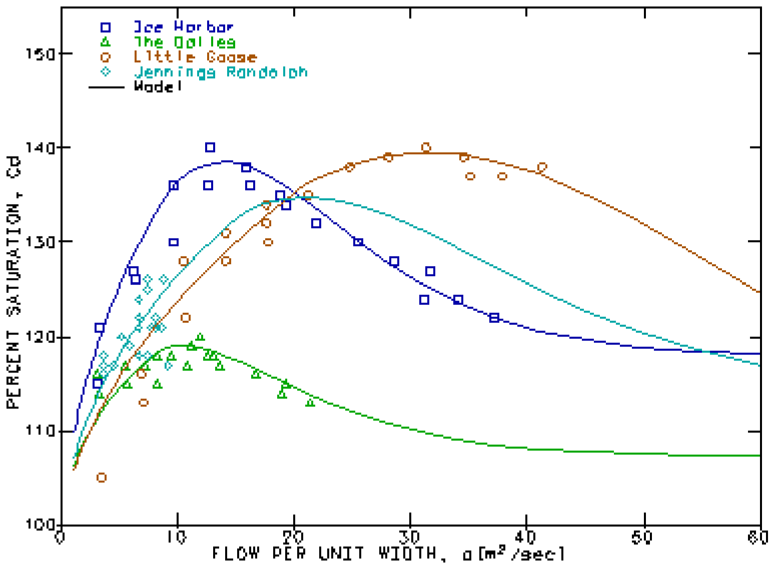

Crossflow Fills
data
Le=1
1
0.1
0.01
0.001
Ha [1/ft]
0.01
0.1
1
Ka [1/ft]

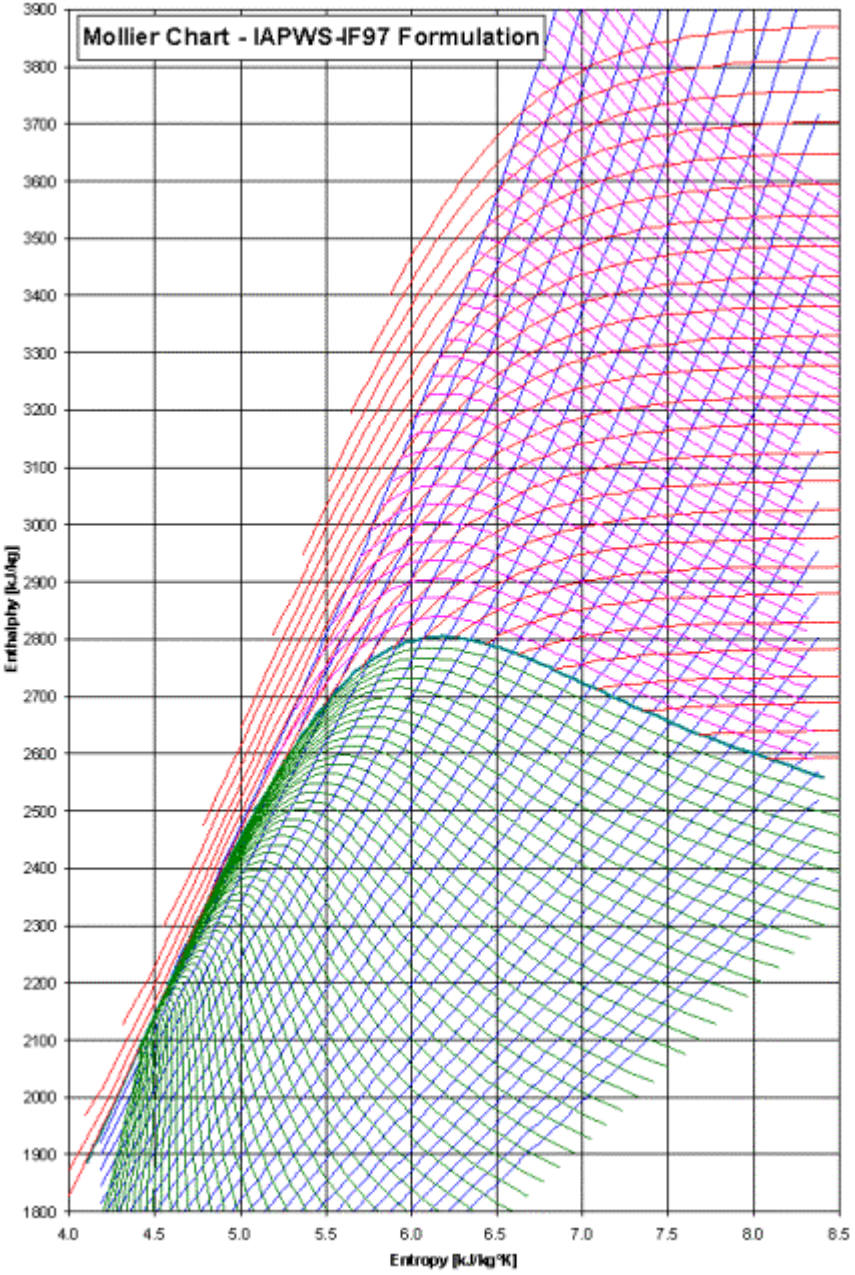

Counterflow Fills
data
Le=1
1
0.1
0.01
0.001
Ha [1/ft]
0.01
0.1
1
Ka [1/ft]

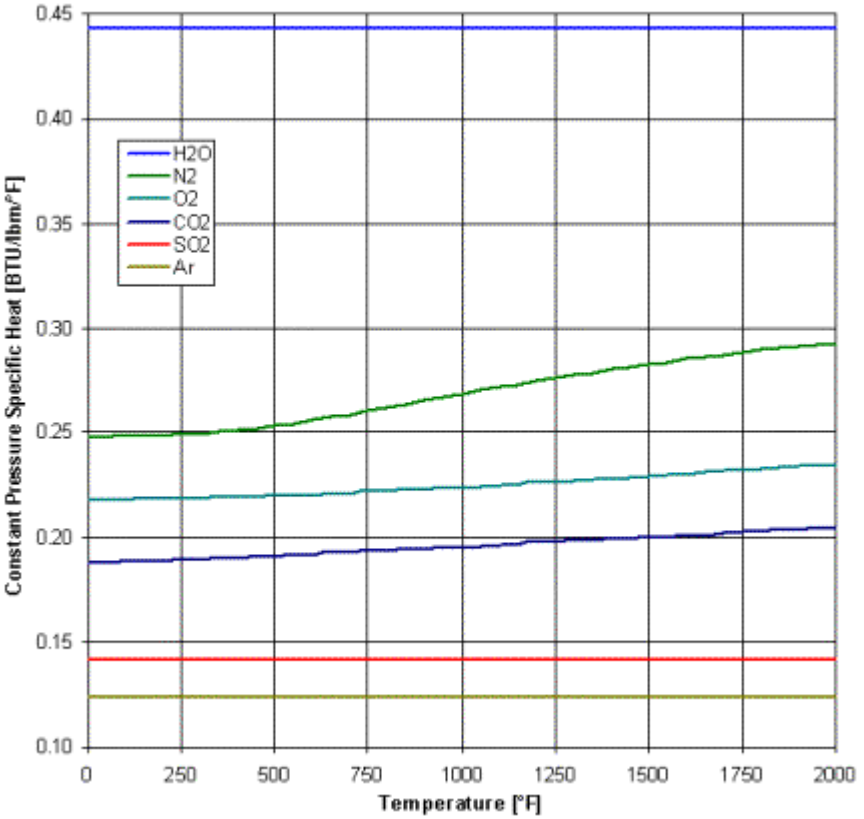

Ice Harbor
The Dalles
Little Goose
Model
EFFECTIVE PERCENT SATURATION, Ce
FLOW PER UNIT WIDTH, q [m²/sec]
260
240
220
200
180
160
140
120
100
0
10
20
30
40


Ice Harbor
The Dalles
Little Goose
Regression
V|/sqrt(g*h_t)=a*(q/sqrt(g*h_1)/h_1)^b
a=0.15, b=0.23, r²=0.92
DIMENSIONLESS JET VELOCITY, V|/sqrt(g*h_t)
DIMENSIONLESS FLOW, q/sqrt(g*h_1)/h_t
.08
.06
.04
.02
.00
.00
.02
.04
.06
.08


Joe Harbor
The Dalles
Little Goose
Model
BUBBLE MASS TRANSFER PARAMETER, $K_L a_b t_b$
FLOW PER UNIT WIDTH, q [m²/sec]

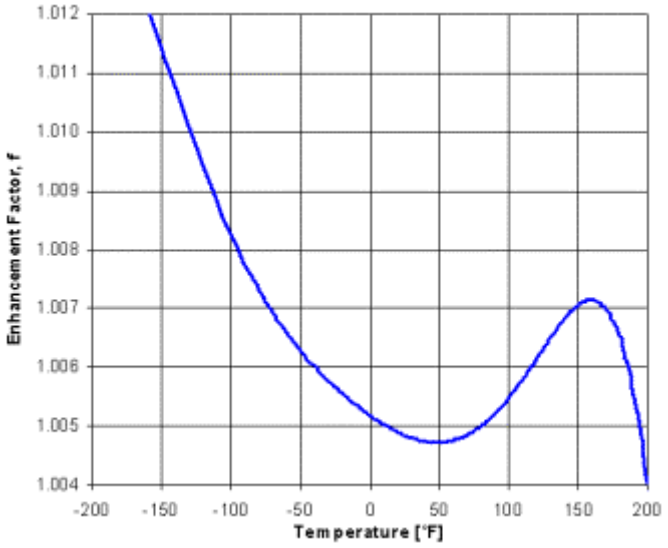

Joe Harbor
The Dalles
Little Goose
Jennings Randolph
Model
PERCENT SATURATION, Cd
FLOW PER UNIT WIDTH, q [m²/sec]

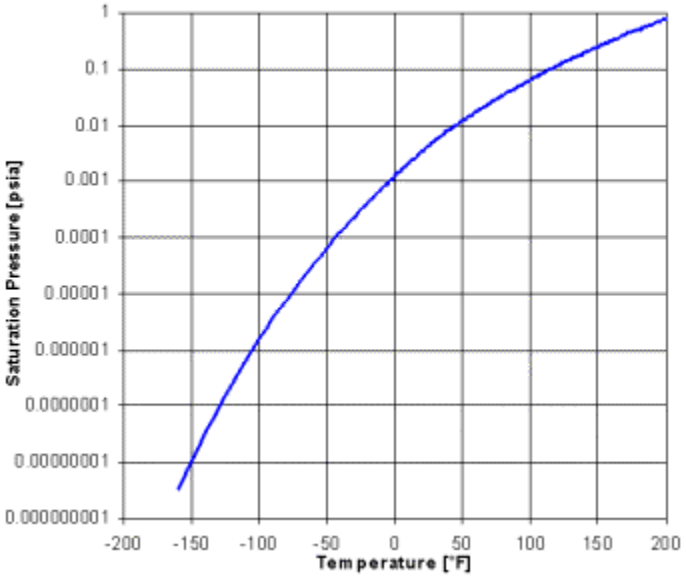

Mollier Chart - IAPWS-IF97 Formulation
Enthalpy [kJ/kg]
3900
3800
3700
3600
3500
3400
3300
3200
3100
3000
2900
2800
2700
2600
2500
2400
2300
2200
2100
2000
1900
1800
Entropy [kJ/kg*K]
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5

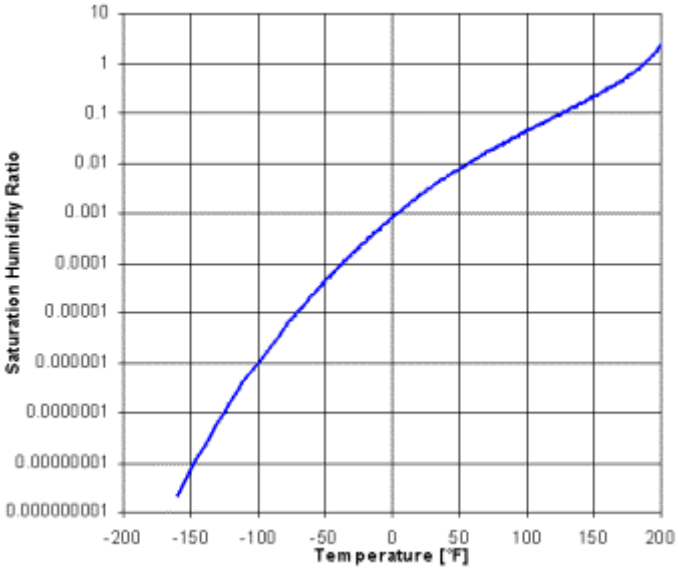


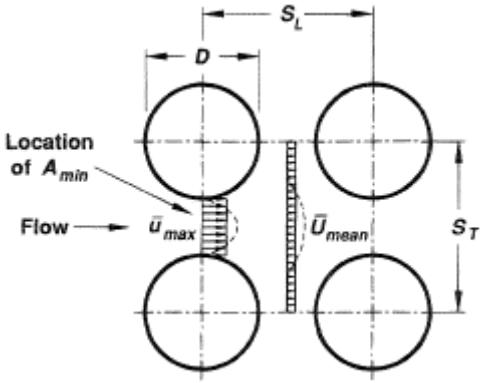
	NASA Glenn Properties												
				specific heat [kJ/kg/℃]					enthalpy [kJ/kg]				
	°K	℃	°F	N2	O2	CO2	H2O	Ar	N2	O2	CO2	H2O	Ar
	275	2	35	1.04	0.92	0.82	1.86	0.52	-24	-21	-8961	-13466	-12
	300	27	80	1.04	0.92	0.85	1.86	0.52	2	2	-8940	-13420	1
ambient	325	52	125	1.04	0.92	0.87	1.87	0.52	28	25	-8918	-13373	14
HRSG gas	350	77	170	1.04	0.93	0.89	1.88	0.52	54	48	-8896	-13326	27
	375	102	215	1.04	0.93	0.92	1.89	0.52	80	71	-8874	-13279	40
	400	127	260	1.04	0.94	0.94	1.90	0.52	106	95	-8850	-13232	53
	425	152	305	1.05	0.95	0.96	1.91	0.52	132	118	-8827	-13184	66
	450	177	350	1.05	0.96	0.98	1.93	0.52	158	142	-8803	-13136	79

	475	202	395	1.05	0.96	1.00	1.94	0.52	185	166	-8778	-13088	92
	500	227	440	1.06	0.97	1.01	1.96	0.52	211	190	-8753	-13039	105
	525	252	485	1.06	0.98	1.03	1.97	0.52	237	215	-8727	-12990	118
	550	277	530	1.06	0.99	1.05	1.99	0.52	264	239	-8701	-12940	131
	575	302	575	1.07	1.00	1.06	2.00	0.52	291	264	-8675	-12891	144
	600	327	620	1.07	1.00	1.08	2.02	0.52	317	289	-8648	-12840	157
	625	352	665	1.08	1.01	1.09	2.03	0.52	344	314	-8621	-12790	170
	650	377	710	1.09	1.02	1.10	2.05	0.52	372	339	-8594	-12739	183
	675	402	755	1.09	1.02	1.11	2.06	0.52	399	365	-8566	-12687	196
	700	427	800	1.10	1.03	1.13	2.08	0.52	426	391	-8538	-12636	209
GT exhaust	725	452	845	1.10	1.04	1.14	2.10	0.52	454	416	-8510	-12583	222
	750	477	890	1.11	1.04	1.15	2.12	0.52	481	443	-8481	-12531	235
	775	502	935	1.12	1.05	1.16	2.13	0.52	509	469	-8452	-12478	248
	800	527	980	1.12	1.05	1.17	2.15	0.52	537	495	-8423	-12424	261
	825	552	1025	1.13	1.06	1.18	2.17	0.52	565	521	-8394	-12370	274
	850	577	1070	1.13	1.06	1.19	2.18	0.52	593	548	-8364	-12316	287
	875	602	1115	1.14	1.07	1.20	2.20	0.52	622	575	-8334	-12261	300
	900	627	1160	1.15	1.07	1.20	2.22	0.52	650	601	-8304	-12206	313

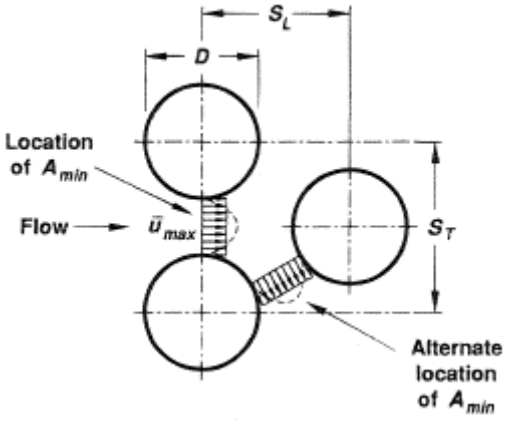

1.012
1.011
1.010
1.009
1.008
1.007
1.006
1.005
1.004
Enhancement Factor, f
-200
-150
-100
-50
0
50
100
150
200
Temperature [°F]


1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
Saturation Pressure [psia]
-200
-150
-100
-50
0
50
100
150
200
Temperature [°F]



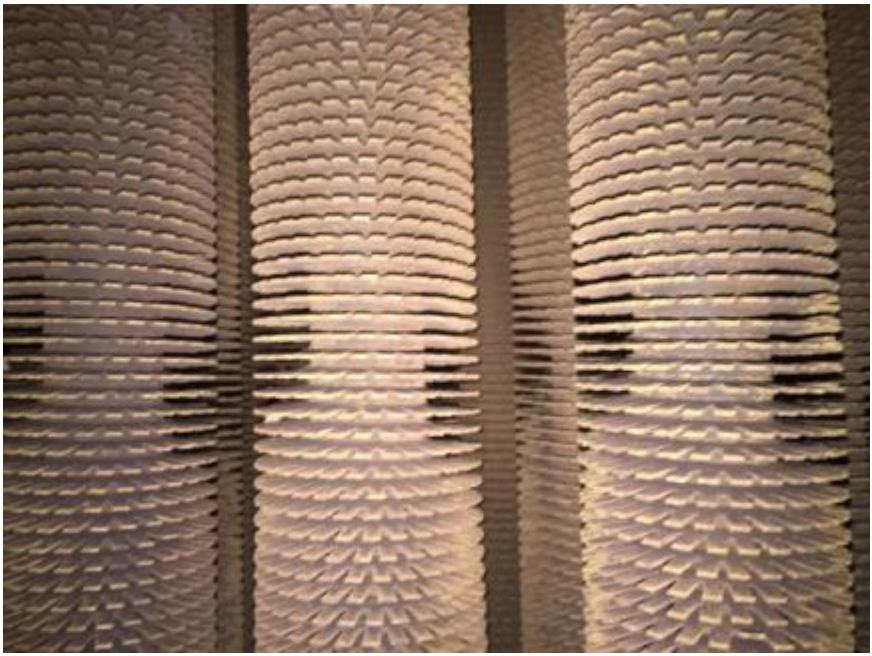


Inline Tube Bank



Staggered Tube Bundle

Various Tube Bundles



Finned Tubes