Fermilab

Particle Physics Division
Mechanical Department Engineering Note

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Project: NOvA

Title: IPND chiller system/A-Block

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Reviewer(s):

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Applicable Codes:

Abstract Summary:

The IPND used in the NOVA experiment will use thermoelectric coolers (TEC's) in order to cool the APD's. The TEC's will be connected to a chiller system which pumps water through the piping and hoses. The proper diameters, flow rate, pressure loss, and heat transfer of the piping have been determined for an A-block.

Discussion/Summary of Flow Calculations

The following is for the IPND chiller system and pertains to 1 chiller supplying 1 A-block. The system was designed with the 4 distribution manifolds connected in series (2 in series with the in pipe, and 2 in series with the out pipe) coming from the chiller. The 10 hose manifolds (5 pairs, each pair in series connected by hoses) are parallel to each other and connected to the distribution manifolds, with three on the first distribution manifold and two on the second. The hoses are connected parallel to each other from each pair of hose manifolds, with 16 on the horizontal plains and 15 on the vertical plains (Configuration seen in *Diagram*). The system is reverse return to help keep the pressure drops equal through all routes.

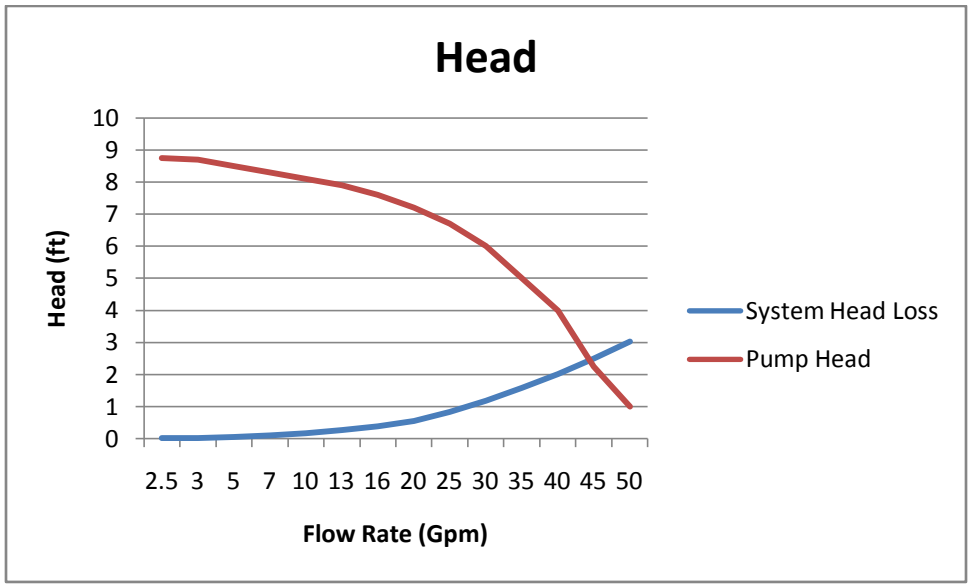


Chart: Operating rate has been determined at about 42 Gpm with the head loss of the system slightly higher than shown when considering the outer components such as the filter, which have not been factored in above.

Total system flow rate must remain above 2.5 Gpm in order to supply a minimum of 2 mL/s to each of the TEC's.

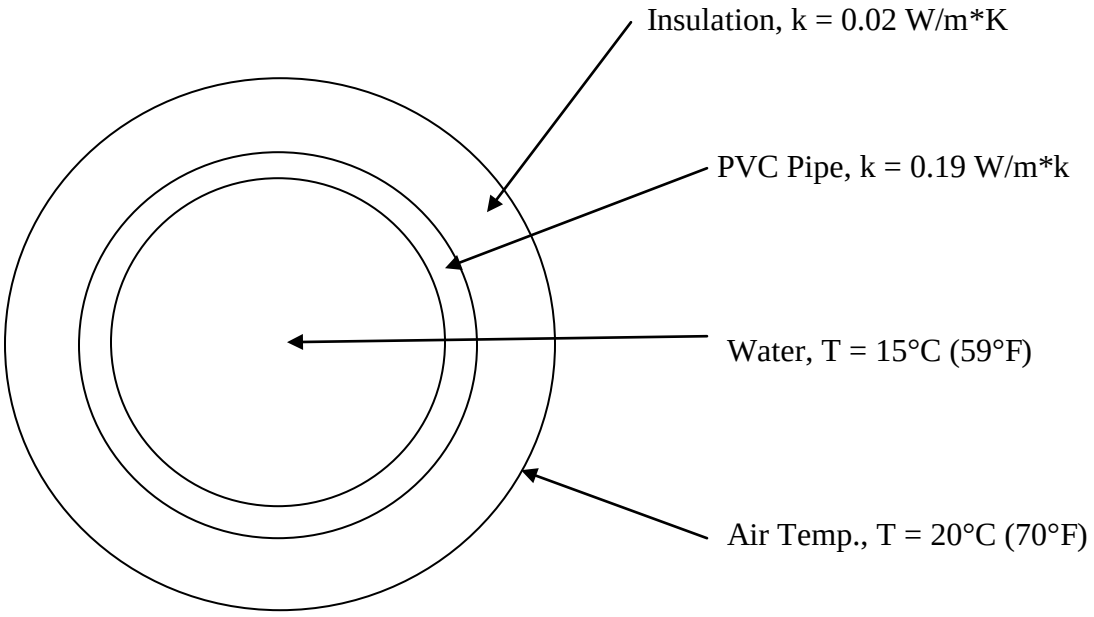
Also worth noting: In a separate note it was determined that a minimum of about 0.4 feet (4.8 inches) of head is required to drive 2 mL/s through the TEC.

Discussion/Summary of Heat Transfer Calculations

The following assumptions will be made when calculating the total heat transfer:

1.) T(inner wall) = T(bulk fluid) = 59°F (15°C); or internal convection = 0
2.) T(outer insulation wall) = fixed air temperature = 70°F (21°C); or external convection = 0
3.) Bulk fluid temperature is constant
4.) Each TEC contributes 2.54 Watts, with 78 TEC's present in the block
5.) Heat gain from the ambient air is the other energy source

Therefore, the total heat transfer is the total heat transfer from the 78 TEC's plus the total heat transfer to the pipes from the air; qTotal = qTEC's + qPipes.



(Figure: PVC pipe with 3/8'' foam insulation)

Properties used in calculations

Dynamic viscosity of water (cp)	1.5
Density of water (lbs/ft^3)	62.4

NOvA IPND
A Block Analysis

Pipe Sizing

In/Out Pipe

*Length assumed at 10 feet

Diameter (in)	Pressure Loss (psi)	% Improvement
1 1/4	0.698	-
1 1/2	0.339	51.4
2	0.102	69.9
2 1/2	0.0438	57
3	0.0154	64.8

A 2'' pipe will be used to minimize pressure losses

Distribution Manifold

Diameter (in)	Pressure Loss (psi)	% Improvement
0.75	3.85	-
1	1.16	69.8
1 1/2	0.152	86.9
2	0.046	69.7
2 1/2	0.0197	57.2
3	0.0072	63.5

2'' Pipe will be used

Hose Manifold

Diameter (in)	max/min/avg ΔP Across APD's (psi)	% diff.
0.50	4.722/3.743/4.438	20
0.75	1.27/1.017/1.198	19.9
1	0.467/0.3862/0.445 1	17.4
1 1/2	0.141/0.130/0.138	7.9
2'	0.107/0.103/0.106	3.3
2 1/2	0.0979/0.0963/0.09	1.6
3	0.0934/0.0928/0.09	0.6

A 1 1/2'' pipe will be used to keep the pressure losses across APD's low and within 10% of each other

Hose

Diameter	Pressure Loss (psi)	Velocity (in/s)
1/8''	0.0124	84.88
1/4''	0.0417	21.22

Flow/Pressure Loss Analysis

in/out/reverse return

*Length (ft)	30.00
inner diameter (in)	2.07
outer diameter (in)	2.35
flow (Gpm)	42.00
RE	42771.32
friction factor	0.021
Pressure Loss (psi)	0.40

Distribution Manifold 1

section 1		*section 2*	
Length (ft)	0.61	Length (ft)	4.1667
inner diameter (in)	2.07	inner diameter (in)	2.067
outer diameter (in)	2.35	outer diameter (in)	2.345
flow (Gpm)	42.00	flow (Gpm)	32.9448
RE	42771.32	RE	33549.8
friction factor	0.021	friction factor	0.0225
Pressure Loss (psi)	0.0080	Pressure Loss (psi)	0.03639

Tee 1 branch

inner diameter (in)	1.61
flow (Gpm)	9.06
friction factor	0.021
K factor	1.26
Pressure Loss (psi)	0.0173

Tee 2 branch

inner diameter (in)	1.6100
flow (Gpm)	8.0797
friction factor	0.0210
K factor	1.2600
Pressure Loss (psi)	0.0137

Tee 1 run

inner diameter (in)	2.07
flow avg (Gpm)	37.47
friction factor	0.019
K factor	0.38
Pressure Loss (psi)	0.0328

Tee 2 run

inner diameter (in)	2.067
flow avg (Gpm)	28.90
friction factor	0.019
K factor	0.38
Pressure Loss (psi)	0.0198

section 3

Length (ft)	3.757
inner diameter (in)	2.067
outer diameter (in)	2.345
flow (Gpm)	24.86
RE	25321.73
friction factor	0.024
Pressure Loss (psi)	0.0199

Tee 3 branch

inner diameter (in)	1.61
flow (Gpm)	7.907
friction factor	0.021
K factor	1.26
Pressure Loss (psi)	0.0131

Tee 3 run

inner diameter (in)	2.0670
flow avg (Gpm)	20.9115
friction factor	0.0190
K factor	0.3800
Pressure Loss (psi)	0.0102

Distribution Manifold 2

section 1	
Length (ft)	3.7566
inner diameter (in)	2.0670
outer diameter (in)	2.3450
flow (Gpm)	16.9580
RE	17269.4196
friction factor	0.0260
Pressure Loss (psi)	0.0100

Tee 1 branch	
inner diameter (in)	1.6100
flow (Gpm)	8.0890
friction factor	0.0210
K factor	1.2600
Pressure Loss (psi)	0.0138

Tee 1 run	
inner diameter (in)	2.0670
flow avg (Gpm)	12.9135
friction factor	0.0190
K factor	0.3800
Pressure Loss (psi)	0.0039

Elbow 1	
inner diameter (in)	2.0670
flow (Gpm)	16.9580
friction factor	0.0190
K factor	0.5700
Pressure Loss (psi)	0.0101

section 2	
Length (ft)	4.1667
inner diameter (in)	2.0670
outer diameter (in)	2.3450
flow (Gpm)	8.8690
RE	9031.906
friction factor	0.0310
Pressure Loss (psi)	0.0036

Elbow 2	
inner diameter (in)	1.6100
flow (Gpm)	8.8690
friction factor	0.0210
K factor	1.2600
Pressure Loss (psi)	0.0166

Distribution Manifold 3

section 1

Length (ft)	4.1667
inner diameter (in)	2.0670
outer diameter (in)	2.3450
flow (Gpm)	9.0552
RE	9221.4968
friction factor	0.0300
Pressure Loss (psi)	0.0037

Elbow 1

inner diameter (in)	2.0670
flow (Gpm)	9.0552
friction factor	0.0190
K factor	1.1400
Pressure Loss (psi)	0.0057

section 2

Length (ft)	3.7566
inner diameter (in)	2.0670
outer diameter (in)	2.3450
flow (Gpm)	17.1349
RE	17449.59
friction factor	0.0260
Pressure Loss (psi)	0.0102

Tee 1 branch

inner diameter (in)	1.6100
flow (Gpm)	8.0797
friction factor	0.0210
K factor	1.2600
Pressure Loss (psi)	0.0137

Tee 1 run

inner diameter (in)	2.0670
flow avg (Gpm)	13.0951
friction factor	0.0190
K factor	0.3800
Pressure Loss (psi)	0.0040

Tee 2 branch

inner diameter (in)	1.6100
flow (Gpm)	7.9071
friction factor	0.0210
K factor	1.2600
Pressure Loss (psi)	0.0132

Tee 2 run

inner diameter (in)	2.0670
flow avg (Gpm)	21.0885
friction factor	0.0190
K factor	0.3800
Pressure Loss (psi)	0.0104

Distribution Manifold 4

section 1

Length (ft)	3.7566
inner diameter (in)	2.0670
outer diameter (in)	2.3450
flow (Gpm)	25.0420
RE	25501.9011
friction factor	0.0240
Pressure Loss (psi)	0.0202

Tee 1 branch

inner diameter (in)	1.6100
flow (Gpm)	8.0890
friction factor	0.0210
K factor	1.2600
Pressure Loss (psi)	0.0138

Tee 1 run

inner diameter (in)	2.0670
flow avg (Gpm)	29.0865
friction factor	0.0190
K factor	0.3800
Pressure Loss (psi)	0.0198

Elbow 1

inner diameter (in)	2.0670
flow (Gpm)	25.0420
friction factor	0.0190
K factor	0.5700
Pressure Loss (psi)	0.0220

section 2

Length (ft)	4.1667
inner diameter (in)	2.0670
outer diameter (in)	2.3450
flow (Gpm)	33.1310
RE	33739.414
friction factor	0.0220
Pressure Loss (psi)	0.0359

Tee 2 branch

inner diameter (in)	1.6100
flow (Gpm)	8.8690
friction factor	0.0210
K factor	1.2600
Pressure Loss (psi)	0.0166

Tee 2 run

inner diameter (in)	2.0670
flow avg (Gpm)	37.5655
friction factor	0.0190
K factor	0.3800
Pressure Loss (psi)	0.0330

section 3

Length (ft)	0.6070
inner diameter (in)	2.0670
outer diameter (in)	2.3450
flow (Gpm)	42.0000
RE	42771.3208
friction factor	0.0210
Pressure Loss (psi)	0.0080

→Each hose manifold set contains: 2 hose manifolds (with 15 [HM4, HM5] or 16 sections [HM1, HM2, HM3]), a contraction, an expansion, 2 hose 1's, 2 hose 2's, and 2 valves (?).

Hose Manifold set 1 Full Breakdown

Flow in (Gpm)	9.06	% P. Loss diff	% Flow diff
TEC flow (Gpm)	0.57	3.40	1.84
Length per sec. (ft)	0.72		
inner diameter (in)	1.61	TEC Flow (mL/s)	35.71

section	*flow (Gpm)*	*P. Loss/section(psi)*	*P. Loss/other (psi)*	*P. Loss total (psi)*
1	9.0552	0.0021	0.3047	0.3252
2	8.4893	0.0021	0.3033	0.3260
3	7.9233	0.0021	0.3021	0.3267
4	7.3574	0.0020	0.3009	0.3273
5	6.7914	0.0018	0.2998	0.3277
6	6.2255	0.0017	0.2989	0.3278
7	5.6595	0.0015	0.2980	0.3277
8	5.0936	0.0013	0.2971	0.3273
9	4.5276	0.0011	0.2964	0.3266
10	3.9617	0.0009	0.2958	0.3256
11	3.3957	0.0007	0.2953	0.3242
12	2.8298	0.0005	0.2948	0.3208
13	2.2638	0.0003	0.2944	0.3167
14	1.6979	0.0002	0.2942	0.3167
15	1.1319	0.0001	0.2940	0.3145
16	0.5660	0.0000	0.2939	0.3145

Hose Manifold set 2 Full Breakdown

Flow in (Gpm)	8.24	% P. Loss diff	% Flow diff
TEC flow (Gpm)	0.52	3.32	1.82
Length per sec. (ft)	0.72		
inner diameter (in)	1.61	TEC Flow (mL/s)	32.49

section	*flow (Gpm)*	*P. Loss/section(psi)*	*P. Loss/other (psi)*	*P. Loss total (psi)*
1	8.2404	0.0018	0.2574	0.2755
2	7.7254	0.0018	0.2563	0.2762
3	7.2104	0.0018	0.2552	0.2768
4	6.6953	0.0017	0.2543	0.2774
5	6.1803	0.0016	0.2534	0.2778
6	5.6653	0.0015	0.2526	0.2780
7	5.1503	0.0013	0.2518	0.2780
8	4.6352	0.0012	0.2512	0.2777
9	4.1202	0.0010	0.2506	0.2771
10	3.6052	0.0008	0.2500	0.2762
11	3.0902	0.0006	0.2496	0.2750
12	2.5751	0.0005	0.2492	0.2720
13	2.0601	0.0003	0.2489	0.2685
14	1.5451	0.0002	0.2487	0.2685
15	1.0301	0.0001	0.2485	0.2666
16	0.5150	0.0000	0.2486	0.2667

Hose Manifold set 3 Full Breakdown

Flow in (Gpm)	8.01	% P. Loss diff	% Flow diff
TEC flow (Gpm)	0.50	4.14	2.03
Length per sec. (ft)	0.72		
inner diameter (in)	1.61	TEC Flow (mL/s)	31.60

section	*flow (Gpm)*	*P. Loss/section(psi)*	*P. Loss/other (psi)*	*P. Loss total (psi)*
1	8.0136	0.0017	0.2434	0.2607
2	7.5128	0.0017	0.2424	0.2614
3	7.0119	0.0017	0.2414	0.2620
4	6.5111	0.0017	0.2405	0.2626
5	6.0102	0.0016	0.2396	0.2630
6	5.5094	0.0014	0.2389	0.2632
7	5.0085	0.0013	0.2382	0.2632
8	4.5077	0.0011	0.2375	0.2629
9	4.0068	0.0009	0.2370	0.2623
10	3.5060	0.0008	0.2365	0.2615
11	3.0051	0.0006	0.2360	0.2604
12	2.5043	0.0004	0.2357	0.2575
13	2.0034	0.0003	0.2354	0.2541
14	1.5026	0.0002	0.2352	0.2541
15	1.0017	0.0001	0.2351	0.2523
16	0.5009	0.0000	0.2351	0.2524

Hose Manifold set 4 Full Breakdown

Flow in (Gpm)	8.01	% P. Loss diff	% Flow diff
TEC flow (Gpm)	0.53	3.45	1.86
Length per sec. (ft)	0.72		
inner diameter (in)	1.61	TEC Flow (mL/s)	33.70

section	*flow (Gpm)*	*P. Loss/section(psi)*	*P. Loss/other (psi)*	*P. Loss total (psi)*
1	8.0136	0.0017	0.2758	0.2917
2	7.4794	0.0017	0.2746	0.2923
3	6.9451	0.0017	0.2736	0.2928
4	6.4109	0.0016	0.2726	0.2933
5	5.8766	0.0015	0.2718	0.2935
6	5.3424	0.0013	0.2710	0.2936
7	4.8082	0.0012	0.2702	0.2934
8	4.2739	0.0010	0.2696	0.2929
9	3.7397	0.0008	0.2690	0.2922
10	3.2054	0.0006	0.2686	0.2912
11	2.6712	0.0005	0.2682	0.2899
12	2.1370	0.0003	0.2678	0.2885
13	1.6027	0.0002	0.2676	0.2851

14	1.0685	0.0001	0.2674	0.2851
15	0.5342	0.0000	0.2675	0.2835

Hose Manifold set 5 Full Breakdown

Flow in (Gpm)	8.68	% P. Loss diff	% Flow diff
TEC flow (Gpm)	0.58	3.44	1.85
Length per sec. (ft)	0.72		
inner diameter (in)	1.61	TEC Flow (mL/s)	36.50

section	*flow (Gpm)*	*P. Loss/section(psi)*	*P. Loss/other (psi)*	*P. Loss total (psi)*
1	8.6772	0.0020	0.3169	0.3348
2	8.0987	0.0020	0.3156	0.3354
3	7.5202	0.0019	0.3144	0.3360
4	6.9418	0.0018	0.3133	0.3364
5	6.3633	0.0016	0.3122	0.3367
6	5.7848	0.0015	0.3113	0.3367
7	5.2063	0.0013	0.3104	0.3365
8	4.6278	0.0011	0.3097	0.3359
9	4.0494	0.0009	0.3090	0.3351
10	3.4709	0.0007	0.3085	0.3339
11	2.8924	0.0005	0.3080	0.3325
12	2.3139	0.0003	0.3076	0.3308
13	1.7354	0.0002	0.3073	0.3270
14	1.1570	0.0001	0.3072	0.3270
15	0.5785	0.0000	0.3073	0.3251

Example: Hose Manifold/Other Components factored into P. Loss Total

Hose1		*Contraction*	
Length (ft)	1.00	Flow (Gpm)	0.57
inner diameter (in)	0.36	ratio	0.74
outer diameter (in)	0.54	angle	45.00
flow (Gpm)	0.57	K	0.59
		Pressure Loss	
RE	3272.81	(psi)	0.0121
friction factor	0.042		
Pressure Loss (psi)	0.0284		

#	2

Expansion

Flow (Gpm)	0.57
ratio	0.74
angle	45.00
K	0.87
Pressure Loss (psi)	0.0179

Hose2

Length (ft)	0.50
inner diameter (in)	0.27
outer diameter (in)	0.41
flow (Gpm)	0.57
RE	4428.63
friction factor	0.038
Pressure Loss (psi)	0.0582
#	2

Valves

inner diameter (in)	0.57
flow (Gpm)	0.27
friction factor	0.035
K factor	0.11
Pressure Loss (psi)	0.0072
#	2

Tee branch

inner diameter (in)	0.36
flow (Gpm)	0.57
friction factor	0.031
K factor	1.86
Pressure Loss (psi)	0.0381
#	2

Tee run

inner diameter (in)	1.61
flow avg (Gpm)	4.53
friction factor	0.021
K factor	0.42
Pressure Loss (psi)	0.000003
#	2

Hose Manifold Pressure Loss Analysis Conclusions

HM set	*min dP*	*Max dP*	*avg dP*

1	0.314	0.328	0.323
2	0.267	0.278	0.274
3	0.252	0.263	0.260
4	0.283	0.294	0.291
5	0.325	0.337	0.333

HM set	*tec flow (Gpm)*	*TEC Flow (mL/s)*	largest TEC Flow diff
1	0.566	35.705	13.42 %
2	0.515	32.492	
3	0.501	31.598	Avg TEC Flow (Gpm)
4	0.534	33.705	0.539
5	0.578	36.496	

Full Route Pressure Loss (psi)		largest Pressure Loss % diff
1	0.956	0.879
2	0.964	
3	0.963	Avg Pressure Loss Total (psi)
4	0.963	0.961
5	0.957	

Heat Transfer Analysis

In/Out Pipe

	English	Metric
Length (ft--m)	10.000	3.048
inner radius (in--m)	1.034	0.026
outer rad/pipe(in--m)	1.188	0.030
insulation out. Rad.	1.563	0.040
#	3.000	3.000
Total Length (ft--m)	30.000	9.144
Ther. cond. Pipe	0.190	0.190
Ther. Cond. insulation	0.020	0.020
Temp air (F--K)	70.000	293.000
Temp water (F--K)	59.000	288.000
Ther. res. Pipe		0.013
Ther. res. Insulation		0.239

Heat Transfer (W)		-19.876

Distribution Manifolds

	English	Metric
Length (ft--m)	8.530	2.600
inner radius (in--m)	1.034	0.026
outer rad/pipe(in--m)	1.188	0.030
insulation out. Rad.	1.563	0.040
#	4.000	4.000
Total Length (ft--m)	34.121	10.400
Ther. cond. Pipe	0.190	0.190
Ther. Cond. insulation	0.020	0.020
Temp air (F--K)	70.000	293.000
Temp water (F--K)	59.000	288.000
Ther. res. Pipe		0.011
Ther. res. Insulation		0.210
Heat Transfer (W)		-22.606

Hose Manifolds

	English	Metric
Length (ft--m)	11.483	3.500
inner radius (in--m)	0.805	0.020
outer rad/pipe(in--m)	0.950	0.024
insulation out.	1.325	0.034

Rad.		
#	10.000	10.000
Total Length (ft--m)	114.829	35.000
Ther. cond. Pipe	0.190	0.190
Ther. Cond. insulation	0.020	0.020
Temp air (F--K)	70.000	293.000
Temp water (F--K)	59.000	288.000
Ther. res. Pipe		0.004
Ther. res. Insulation		0.076
Heat Transfer (W)		-62.807

Hose 1's

	English	Metric
Length (ft--m)	1.000	0.305
inner radius (in--m)	0.182	0.005
outer rad/pipe(in--m)	0.270	0.007
insulation out. Rad.	0.645	0.016
#	156.000	156.000
Total Length (ft--m)	156.000	47.549
Ther. cond. Pipe	0.190	0.190
Ther. Cond. insulation	0.020	0.020
Temp air (F--K)	70.000	293.000
Temp water (F--K)	59.000	288.000
Ther. res. Pipe		0.007
Ther. res. Insulation		0.146
Heat Transfer (W)		-32.746

Hose 2's

	English units	Metric units
Length (ft--m)	0.500	0.152
inner radius (in--m)	0.135	0.003
outer rad/pipe(in--m)	0.203	0.005

insulation out.			
Rad.	0.578		0.015
#	156.000		156.000
Total Length (ft--m)	78.000		23.774
Ther. cond. Pipe	0.190		0.190
Ther. Cond. insulation	0.020		0.020
Temp air (F--K)	70.000		293.000
Temp water (F--K)	59.000		288.000
Ther. res. Pipe			0.014
Ther. res. Insulation			0.351
Heat Transfer (W)			-13.691

TEC's

*Area (in^2--m^2)	1		0.0254
*Heat flux (W/m^2)			-10
#	78		78
Heat Transfer (W)			-19.812

Total

Heat Transfer (W)		-160.56	

over one third of which is coming from the HM's

*assumed values

Equations used

-Pressure drop

(ΔP) Pipes = [0.000216*(f*L*rho*Q^2)]/d^5

(ΔP) Valves/T's/Elbow's = [0.00001799*(K*rho*Q^2)]/d^4

Reynolds # = 50.6*(Q*L/d*u)

(ΔP) → head loss = ΔP*144/rho

Where f = friction factor
L = length (ft)
Rho = density (lb/ft^3)
Q = flow rate (Gpm)
d = inner diameter (inches)
K = resistance coefficient

-Heat Transfer

q = (Tin-Tout)/R-total + (q-TEC's)

R-total = R-insulation + R-pipe (conduction only)

R-insulation = ln(roi/rii)/(2*pi*l*ki)

R-pipe = ln(rop/rip)/(2*pi*l*kp)

Where q = Total heat transfer (W)
q-TEC's = total heat transfer from TEC's (W)
R = thermal resistance
roi = outer radius of insulation (m)
rii = inner radius of insulation (m)
l = length (m)
ki = thermal conductivity of insulation (W/mK)
rop = outer radius of pipe = rii (m)
rip = inner radius of pipe (m)
kp = thermal conductivity of PVC pipe (W/mK)
Tin = temperature of water in pipe (constant, uniform) (K)
Tout = temperature of ambient air (K)