Heat Transfer in Jacketed Vessels

Version 2.0

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by Stephen M. Hall, PE

All cells are locked except user-defined data; unlock sheet from Tools menu (no password required)
VIEW-COMMENTS to see some additional explanations.
Scroll down and to the right to enter data.

Project Data

Prepared by	SMH	Client	XYZ Co.
Date	2001	W.O.	123-54
		Unit	Reactor
		Area	1
		Equip No	R-101

(●) Customary US ( ) SI

To restore a saved calculation, select it from the drop-down box below, then click the "Restore Saved Calculation" button

Temperature Conversion

Enter value to convert:

550	°F	=	287.78 °C
270	°C	=	518.00 °F

Vessel Data

Calc Title or Description	3000 gallon Batch Chemical Reactor		
Orientation		vertical	vol to tangent
Total working volume	gallons	3200	3,258.54
Inside diameter	inches	96	
Tangent-to-tangent	inches	72	
Heads	Hemispherical Dished		
Material of construction	316 SS		
Thickness	inches	0.5	
Lining	None		
Thickness	inches	0	
Internal surface roughness	inches	0.002	
Outside surface roughness	inches	0.007	
Internal fouling factor	ft²-hr-°F/Btu	0	
Outside fouling factor (jacket)	ft²-hr-°F/Btu	0.001	

☑ Tank is Baffled

Side-Wall Jacket

( ) No Jacket ( ) Conventional

(●) Half-Pipe Coil ( ) Dimple

Inlet/Outlet Nozzle Size	inches	3
Number of Zones		3
Percentage of side-wall covered by jacket		1

Jacket Fluid Data

Fluid name	Therminol FS, 40 wt% pg	
Temperature at jacket inlet	°F	40
Properties from data table:		
Thermal Conductivity	Btu/h-ft-°F	0.23
Specific Heat	Btu/lb-°F	0.87
Density	lb/ft³	65.23
Viscosity	cP	9.30
	lb/ft-h	22.50
Prandtl Number	dimensionles	86.87

Flow Rate in Side-Wall Jacket

( ) Specify flow rate per zone

( ) Target velocity in jacket

(●) Target pressure drop

Target pressure drop	psi	25

Vessel Fluid Data

Name		Water
Bulk Temp	°F	160.0
Thermal Conductivity	Btu/h-ft-°F	0.37
Specific Heat	Btu/lb-°F	1.02
Density	lb/ft³	60.25
Viscosity	cP	0.40000
	lb/ft-h	0.97
Viscosity at wall	cP	0.50392
	lb/ft-h	1.22

Agitator Data

Impeller Type	Turbine (Rushton)	
Impeller Diameter	inches	35
Blade Height or Flight Pitch	inches	4
Blade Pitch (90 deg = upright)	degress	45
Number of blades		6
Agitator Rotational Speed	rpm	60

Half-Pipe Coil Jacket Data

Nominal Pipe Diameter	inches	3
Cross section angle (180 or 120 deg)		180
Spacing between Coils	inches	0.75

Conventional Jacket Data

Not Applicable

Annular space dimension	inches	1.5313

○ Standard ◉ Baffled ○ Agit. Nozzles

		2
		0.625
Baffle spacing	inches	2.36

☐ Aiding flow (upflow during cooling/downflow during heating)

Dimple Jacket Data

Not Applicable

Annular space dimension	inches	0.1969
Center-to-center distance between adjacent dimples		
Longitudinal	inches	3.94
Transverse	inches	3.94
Mean dimple diameter	inches	3.54

Dimple pitch ○ Triangular ◉ Square

Bottom Head Jacket

○ No Jacket ○ Conventional

○ Half-Pipe Coil ○ Dimple

◉ Same type as Side-Wall Jacket

☐ Series Flow

1

Internal Coil

◉ No Coil ○ Helical ○ Hairpin

Coil pipe size	inches	2
Length of coil	inches	672.1

Quick Results

Heat Transfer Coefficients	hi	ho	Overall U	
From Vessel to Sidewall Jacket	519	194	79	Btu/ft²-hr-°F
From Vessel to Bottom Jacket	519	231	84	Btu/ft²-hr-°F
From Vessel to Coil	--	--	--	Btu/ft²-hr-°F

Fluid Flow	Flow Rate		Velocity		Pressure Drop	
Sidewall Jacket (each zone)	111.7	gal/min	9.7	ft/sec	24.9	psi
Sidewall Jacket (combined)	335.2	gal/min	9.7	ft/sec	24.9	psi
Bottom Jacket (in parallel with sidewall)	136.8	gal/min	11.9	ft/sec	24.8	psi
Internal Coil	--	gal/min	--	ft/sec	--	psi

Temperature Effects	Inlet	Outlet		Heat Transferred	
Sidewall Jacket	40.0	48.2	°F	-1,259,062	Btu/hr
Bottom Jacket	40.0	47.2	°F	-450,770	Btu/hr
Internal Coil	--	--	°F	--	Btu/hr
Vessel Contents	160.0		°F		Btu/hr

Vessel contents will cool at a rate of 1.1 °F/minute

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JACKETED VESSEL HEAT TRANSFER

REV	PREPARED BY	DATE	APPROVAL
0	SMH	Jun-23-05	
1			
2			

CLIENT	EQUIP. NO	PAGE
XYZ Co.	R-101	
W.O. 123-54	REQUISITION NO.	SPECIFICATION NO.
UNIT Reactor / AREA 1	PROCURED BY	INSTALLED BY

3000 gallon Batch Chemical Reactor

Vessel Data

Orientation	vertical, cylindrical			**Contents**	Water	
Total working volume	3,200	gallons		Bulk Temperature	160	°F
Inside diameter	96	inches		Thermal Conductivity	0.37	Btu/h-ft-°F
Tangent-to-tangent	72	inches		Specific Heat	1.02	Btu/lb-°F
Heads	Hemispherical Dished			Density	60.25	lb/ft³
Material of construction	316 SS			Viscosity	0.40	cP
Thickness	0.5	inches			0.968	lb/ft-h
Lining	None			Viscosity at wall	0.50	cP
Thickness	0	inches			1.219	lb/ft-h
Internal surface roughness	0.0020	inches		**Agitator Type**	Turbine (Rushton)	
Outside surface roughness	0.0070	inches		Impeller Diameter	35	inches
Internal fouling factor	0	ft²-hr-°F/Btu		Speed	60	rpm
Outside fouling factor (jacket)	0.001	ft²-hr-°F/Btu				

Vessel is baffled

Jacket Fluid

Method for determining flow rate in jacket or coil:
Target Pressure Drop
Value 25 psi
Pressure drop in sidewall determines flow in bottom jacket
Therminol FS, 40 wt% pg
Solutia
Propylene Glycol
Estimated vessel wall temp. 127 °F

Fluid Name	Therminol FS, 40 wt% pg		
Temperature at jacket	40	°F	
Thermal Conductivity	0.23	Btu/h-ft-°F	
Specific Heat	0.87	Btu/lb-°F	
Density	65.23	lb/ft³	
Viscosity	9.30	cP	
	22.50	lb/ft-h	
Prandtl Number	86.87	dimensionless	

Jacket and Coil Data

Sidewall Jacket Type	Half-Pipe Coil	Pipe size: 3 inches; 180 deg included angle; 0.75 inches between loops 16 loops divided into 3 zones; 138 ft² total heat transfer area
Bottom Jacket Type	Half-Pipe Coil	Pipe size: 3 inches; 180 deg included angle; 0.75 inches between loops 46 ft² heat transfer area; piped in parallel with sidewall
Internal Coil Type	No Coil	

Calculated Results

Heat Transfer Coefficients	hi	hw	ho	Overall U	
From Vessel to Sidewall Jacket	519	217	194	79	Btu/ft²-hr-°F
From Vessel to Bottom Jacket	519	217	231	84	Btu/ft²-hr-°F
From Vessel to Coil	--	--	--	--	Btu/ft²-hr-°F

Fluid Flow	Flow Rate		Velocity		Pressure Drop	
Sidewall Jacket (each zone)	111.7	gal/min	9.7	ft/sec	24.9	psi
Sidewall Jacket (combined)	335.2	gal/min	9.7	ft/sec	24.9	psi
Bottom Jacket (in parallel with sidewall)	136.8	gal/min	11.9	ft/sec	24.8	psi
Internal Coil	--	gal/min	--	ft/sec	--	psi

Temperature Effects	Inlet	Outlet		Heat Transferred	
Sidewall Jacket	40.0	48.2	°F	-1,259,062	Btu/hr
Bottom Jacket	40.0	47.2	°F	-450,770	Btu/hr
Internal Coil	--	--	°F	--	Btu/hr
Vessel Contents	160.0		°F	-1,709,833	Btu/hr

Vessel contents will cool at a rate of 1.1 °F/minute

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JACKETED VESSEL HEAT TRANSFER

CLIENT	EQUIP. NO	PAGE
XYZ Co.	R-101	

REV	PREPARED BY	DATE	APPROVAL
0	SMH	Jun-23-05	
1			
2			

W.O.	REQUISITION NO.	SPECIFICATION NO.
123-54		

UNIT	AREA	PROCURED BY	INSTALLED BY
Reactor	1		

3000 gallon Batch Chemical Reactor

Vessel Data

Orientation	vertical, cylindrical		**Contents**	Water	
Total working volume	3200	gallons	Initial Temperature	160	°F
Inside diameter	96	inches	Thermal Conductivity	0.37	Btu/h-ft-°F
Tangent-to-tangent	72	inches	Specific Heat	1.02	Btu/lb-°F
Heads	Hemispherical Dished		Density	60.25	lb/ft³
Material of construction	316 SS		Viscosity	0.40	cP
Thickness	0.5	inches		0.968	lb/ft-h
Lining	None		Viscosity at wall	0.50	cP
Thickness	0	inches		1.219	lb/ft-h
Internal surface roughness	0.0020	inches	**Agitator Type**	Turbine (Rushton)	
Outside surface roughness	0.0070	inches	Impeller Diameter	35	inches
Internal fouling factor	0	ft²-hr-°F/Btu	Speed	60	rpm
Outside fouling factor (jacket)	0.001	ft²-hr-°F/Btu			

Vessel is baffled

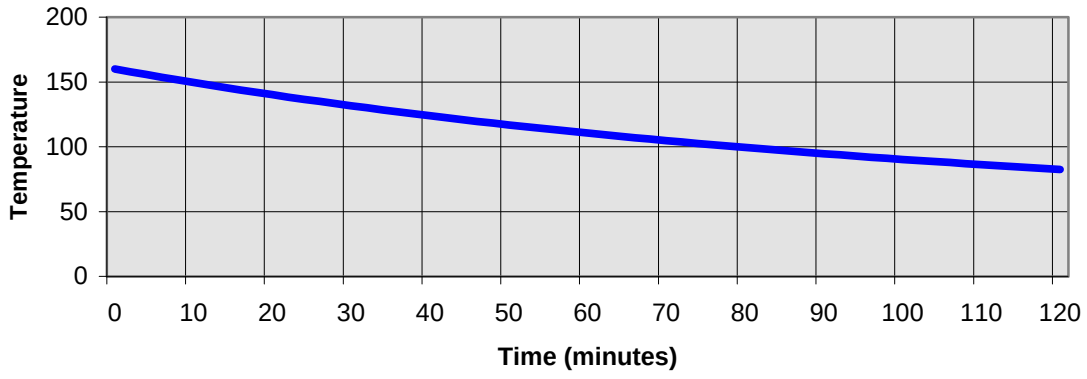
Jacket Fluid

Method for determining flow rate in jacket or coil:			**Fluid Name**	Therminol FS, 40 wt% pg	
Target Pressure Drop			Temperature at jacket	40	°F
Value	25	psi	Thermal Conductivity	0.23	Btu/h-ft-°F
			Specific Heat	0.87	Btu/lb-°F
Pressure drop in sidewall determines flow in bottom jacket			Density	65.23	lb/ft³
			Viscosity	9.30	cP
				22.50	lb/ft-h
Estimated vessel wall temp.	127	°F	Prandtl Number	86.87	dimensionless

Jacket and Coil Data

Sidewall Jacket Type	Half-Pipe Coil	Pipe size: 3 inches; 180 deg included angle; 0.75 inches between loops 16 loops divided into 3 zones; 138 ft² total heat transfer area
Bottom Jacket Type	Half-Pipe Coil	Pipe size: 3 inches; 180 deg included angle; 0.75 inches between loops 46 ft² heat transfer area; piped in parallel with sidewall
Internal Coil Type	No Coil	

Timeline (calculated at 2-minute intervals)



Heat Transfer in Jacketed Vessels
Version 2.0

by Stephen M. Hall, PE

CALCULATIONS

Symbol	Name	Source	US Units		SI Units	
	Jacket Fluid Data					
T_{j0}	Jacket fluid temperature	User input	40.0	°F	4.4	°C
	Jacket pressure (if steam)	User input		psi		kPa
	Properties from data table:					
k	Thermal Conductivity	Calc from properties data	0.23	Btu/h-ft-°F	0.4	W/m-°C
c_j	Specific Heat	Calc from properties data	0.87	Btu/lb-°F	3,656.8	joules/kg-°C
ρ	Density	Calc from properties data	65.23	lb/ft³	1.045	g/cc
	Viscosity	Calc from properties data	9.30	cP	0.00930	Pa-sec
μ		Convert from cP	22.50	lb/ft-h		
Pr	Prandtl Number	$c_{j*\mu/k}$	86.87	dimensionless		
	Estimated wall temperature		128.10	°F	53.4	°C
	Viscosity at wall		1.51	cP	0.00151	Pa-sec
			3.65	lb/ft-h		
	Coefficient of expansion		-1.0927E-05	1/F	-1.9668E-05	1/K
	Method for Determining Flowrate in Jacket or Coil					
	Sidewall Jacket	Pressure Drop	25.00	psi	172.37	kPa
	Bottom Jacket	= Sidewall Jacket Pressure Drop	24.92	psi	171.84	kPa
	Internal Coil	N/A	N/A			
	Vessel Fluid Data					
	Reactor contents temp	User input	160.0	°F	71.1	°C
	Properties from data table:					
k	Thermal Conductivity	User input	0.37	Btu/h-ft-°F	0.6	W/m-°C
cv	Specific Heat	User input	1.02	Btu/lb-°F	4,270.5	joules/kg-°C
ρ	Density	User input	60.25	lb/ft³	0.966	g/cc
	Viscosity	User input	0.40	cP	0.00040	Pa-sec
μ		Convert from cP	0.97	lb/ft-h		
	Viscosity at wall	Estimated from wall temp.	0.50	cP	0.00050	Pa-sec
		Convert from cP	1.22	lb/ft-h	0.00050	kg/m-s
	Vessel Data					
	Volume of liquid in vessel	User input	3,200.0	gallons	12,113.3	liters
d_v	Inside diameter	User input	96.000	inches	2,438.4	millimeters
	Tangent-to-tangent	User input	72.000	inches	1,828.8	millimeters
	Sidewall covered by jacket	User input	72.000	inches	1,828.8	millimeters
	Shell thickness	User input	0.500	inches	12.7	millimeters
	Lining thickness	User input	0.000	inches	0.0	millimeters
	Internal surface roughness	User input	0.002	inches	0.0508	millimeters
	Outside surface roughness	User input	0.00700	inches	0.17780	millimeters
	Internal fouling factor	User input	0.00000	ft²-hr-°F/Btu	0.00000	m²-°C/W
	Outside fouling factor (jacke	User input	0.00100	ft²-hr-°F/Btu	0.00018	m²-°C/W
$O.D.v$	Outside diameter	I.D. + wall & lining	8.08	feet		
	Jacket nozzle size	User input	3	inches	75	DN
	Volume of bottom head	see table "head_types"	1,003	gallons	3,795.4	liters
	Sidewall covered by content	h = vol/(pi r^2)	70.13	inches	1,781.3	millimeters
	Jacket coverage to use	lesser of contents or jacket	70.132	inches	1,781.3	millimeters

Inside Heat Transfer Coefficient		From Inside to Jacket				From Inside to Internal Coil	
Impeller Type		Turbine (Rushton)				Turbine (Rushton)	
Impeller Diameter	User input	35.000 inches	889 millimeters			35.000 inches	889 millimeters
Blade Height	User input	4.000 inches	102 millimeters			4.000 inches	102 millimeters
Blade Pitch (90 deg = uprigl	User input	45 degrees				45 degrees	
Agitator Rotational Speed	User input	60 rpm	60			60 rpm	60
Number of blades	User input	6				6	
Calculations for pumped circulation							
Pumping rate	User input	35.0 gal/min	132.49 liters/min			35.0 gal/min	132.49 liters/min
Vessel diameter	User input	8.0 feet	2,438 millimeters			8.0 feet	2,438 millimeters
Flow area	vessel cross-section	50.3 ft²	4.6698 m²			50.3 ft²	4.6698 m²
Velocity		0.0016 ft/sec	0.00 m/sec			0.0 ft/sec	0.00 m/sec
Reynolds Number		6,730.3				6,730.3	
Nu ignore viscosity Laminar		53.6					
Nu ignore viscosity Turbulent		43.2					
Nu at upper laminar limit	RE=2100	36.4					
Nu at lower Turbulent limi	RE=10000	59.3					
Nu ignore viscosity Transitional		53.5			from Chapter 7-20, Handbook of Chemical Engineering Calculations, by Chopey, 2nd edi		
Nusselt Number ignoring viscosity		53.5	303.87		factor a	0.211	
Inside coefficient ignoring viscosity effect		2.5			factor m	0.349	
Estimated wall temperature		42 °F	5.3 °C		flow area	50.3 ft²	4.6698 m²
Estimated viscosity at wall		1.02			mass velocity	281.92 lb/min	
Nusselt Number		53.9	306.31		h	106.64 Btu/ft²-hr-°F	606 W/m²-°C
Calculations for agitated vessel							
RE Vessel Reynolds Number	impeller_diam^2*impeller_speed*60*	1,906,783 dimensionless					
PR Vessel Prandtl Number	vessel_heat*vessel_viscosity/vessel_	2.67 dimensionless					
GR Grashof Number	gBH^3ro^2deltaT/viscosity^2	776.52 dimensionless					
Viscosity Ratio		0.794					
Refer to "Impellers" table for further calculations							
Impeller formula	[0.740]*[RE^0.67]*[PR^0.33]*[Visc_Ratio^0.14]*[(5Wsin( )/D)^0.20]*[(No.Blades/6)^0.20]*[sin( )^0.50]						
Inside coefficient ignoring viscosity effect		535.6				857	
Estimated wall temperature		128 °F	53.4 °C			65	
Estimated viscosity at wall	viscosity^-.2661 = (known visc)^-.26	0.50 cP				2.3 cP	
Revised estimated wall temperature		127.3 °F	53.0 °C			70.7	
NU Nusselt Number		11,211 dimensionless				359 dimensionless	
hi Inside Heat Transfer Coeffic	NU * k / dv	518.5 Btu/ft²-hr-°F	2,944 W/m²-°C			671 Btu/ft²-hr-°F	3,809 W/m²-°C
Calculations for heat transfer through tank wall							
Vessel wall material	User input	316 SS					
Vessel wall temperature	Revised estimate above	127.3 °F	53.0 °C				
Wall conductivity	Table lookup	9.05 Btu/h-ft-°F	16 W/m-°C				
hw Wall heat transfer coefficient		217 Btu/ft²-hr-°F	1,233 W/m²-°C				
Calculations for heat transfer through tank lining							
Lining material	User input	None					
Lining temperature	average wall & vessel temps	127.3 °F	53.0 °C				
Lining conductivity	Table lookup	N/A Btu/h-ft-°F	N/A W/m-°C				
hl Lining Heat Transfer Coefficient		N/A Btu/ft²-hr-°F	N/A W/m²-°C				
Calculations for heat transfer through internal coil wall							
Coil wall material	User input					316 SS	
Coil wall temperature						70.7 °F	21.5 °C
Coil conductivity						8.81 Btu/h-ft-°F	15 W/m-°C
Coil heat transfer coefficient						687 Btu/ft²-hr-°F	3,899 W/m²-°C

	Jacket Selection and Overall Summary		Sidewall				Bottom Head				Internal Coil			
	Jacket Type	User input	Half-Pipe Coil				Half-Pipe Coil				none			
	Jacket Heat Transfer Coefficient		194	Btu/ft²-hr-°F	1,101	W/m²-°C	231	Btu/ft²-hr-°F	1,309	W/m²-°C	--	Btu/ft²-hr-°F	--	W/m²-°C
	Wall and Lining Heat Transfer Coefficient		217	Btu/ft²-hr-°F	1,233	W/m²-°C	217	Btu/ft²-hr-°F	1,233	W/m²-°C	--	Btu/ft²-hr-°F	--	W/m²-°C
	Inside Heat Transfer Coefficient		519	Btu/ft²-hr-°F	2,944	W/m²-°C	519	Btu/ft²-hr-°F	2,944	W/m²-°C	--	Btu/ft²-hr-°F	--	W/m²-°C
U	**Overall Heat Transfer Coefficient**		79	Btu/ft²-hr-°F	447	W/m²-°C	84	Btu/ft²-hr-°F	478	W/m²-°C	--	Btu/ft²-hr-°F	--	W/m²-°C
	Jacket Flowrate		111.7	gal/min	422.97	liters/min	136.8	gal/min	517.92	liters/min	--	gal/min	--	liters/min
	Jacket Velocity		9.7	ft/sec	2.96	m/sec	11.9	ft/sec	3.62	m/sec	--	ft/sec	--	m/sec
	Jacket Pressure Drop		24.92	psi	172	kPa	24.85	psi	171	kPa	--	psi	--	kPa
	Temperature In		40.0	°F	4.4	°C	40.0	°F	4.4	°C	--	°F	--	°C
	Temperature Out		48.2	°F	9.0	°C	47.2	°F	8.5	°C	--	°F	--	°C
Q	Heat Transferred		-1,259,062	Btu/hr	-368,905	W	-450,770	Btu/hr	-132,076	W	--	Btu/hr	--	W
	Half-Pipe Coil Jacket		**Sidewall**				**Bottom Head**							
	Nominal pipe diameter	User input	3	inches	75	DN	3	inches	75	DN				
	Spacing between coils	User input	0.75	inches	19.1	millimeters	0.75	inches	19.1	millimeters				
d_w	Actual O.D. of Pipe	From data table	3.5	inches	88.90	millimeters	3.5	inches	88.90	millimeters				
	Actual I.D. of Pipe	From data table	3.068	inches	77.93	millimeters	3.068	inches	77.93	millimeters				
	Transfer Area correction factor		93%		93%		93%		93%					
	Included angle of pipe section		180	degrees			180	degrees						
	Pipe diameter at tank wall		0.29	feet	88.90	millimeters	0.29	feet	88.90	millimeters				
	Hydraulic Diameter (heat trans)		0.40	feet	122.41	millimeters	0.40	feet	122.41	millimeters				
	Number of Coils on Straight Side (all zones)		16		16		7		7					
A_j	Flow Area of Coil		0.0257	ft²	0.0024	m²	0.0257	ft²	0.0024	m²				
	Equivalent diameter used by the pressure drop macro		0.1808	feet		millimeters	0.1808	feet		millimeters				
d_e	Hydraulic Diameter (flow)	4 x flow area/flow perimeter	0.1562	feet	47.61	millimeters	0.1562	feet	47.61	millimeters				
A	Effective Heat Transfer Are	total area, all zones	137.94	ft²	12.81	m²	45.99	ft²	4.27	m²				
L	Actual coil length (each zone)		136	feet	41,300	millimeters	89	feet	27,231	millimeters				
	Equivalent length of coil per zone		205	feet	62,393	millimeters	140	feet	42,695	millimeters				
	Target pressure drop	User input	25.00	psi	172	kPa	25	psi	172	kPa				
	Flowrate for target p-drop	VBA calculation	111.7	gal/min	422.97	liters/min	136.8	gal/min	517.92	liters/min				
	Flowrate	Copied from above VBA calc.	111.74	gal/min	422.97	liters/min	136.82	gal/min	517.92	liters/min				
	Maximum theoretical rate for steam			lb/hr		kg/hr		lb/hr		kg/hr				
	Convert to equiv gpm			gal/min		liters/min		gal/min		liters/min				
	Flowrate to use		111.74	gal/min	246	liters/min	136.82	gal/min	301	liters/min				
V	Velocity	=Flow/(Flow Area)	9.70	ft/sec	2.96	m/sec	11.88	ft/sec	3.62	m/sec				
	Flowrate (mass)	converted from above	58,380	lb/hr	128,437	kg/hr	71,487	lb/hr	157,270	kg/hr				
Re	Reynolds Number	VBA calculation	15,815		15,815		19,365		19,365					
f	Fanning Friction Factor	VBA calculation	0.0334		0.0334		0.0324		0.0324					
	Pressure Drop	VBA calculation	24.92	psi	171.84	kPa	24.85	psi	171.31	kPa				
h_i	Heat transfer coefficient	Garvin, equation 8	193.94	Btu/ft²-hr-°F	1,101.22	W/m²-°C	230.60	Btu/ft²-hr-°F	1,309.39	W/m²-°C				

	Dimple Jacket		Sidewall			Bottom Head		
A_i	Flow Area of Coil		0.0526 ft²	0.0049 m²		0.0067 ft²	0.0006 m²	
	Inner Diameter of Jacket		8.12 feet	2,473.80 millimeters				
	Equivalent diameter used by the pressure drop macro		0.2587 feet	78.85 millimeters		0.0921 feet	28.07 millimeters	
d_e	Hydraulic Diameter (flow)	4 x flow area/flow perimeter	0.66 feet	201.17 millimeters		0.66 feet	201.17 millimeters	
A	Effective Heat Transfer Area	total area, all zones	148.41 ft²	13.79 m²		50.27 ft²	4.67 m²	
L	Actual coil length (each zone)		15 feet	4,440 millimeters		4 feet	1,232 millimeters	
	Annular space dimple jkt	User input	0.2 inches	5.0 millimeters		0.2 inches	5.0 millimeters	
dcl	Transverse distance dimple	User input	3.9 inches	100.1 millimeters		3.9 inches	100.1 millimeters	
dct	Longitudinal distance dimple	User input	3.9 inches	100.1 millimeters		3.9 inches	100.1 millimeters	
	Dimple diameter	User input	3.5 inches	89.9 millimeters		3.5 inches	89.9 millimeters	
	Flow area of jacket, minimum		0.053 ft²	0.0049 m²		0.007 ft²	0.0006 m²	
	Flow area of jacket, maximum		0.418 ft²	0.0388 m²		0.066 ft²	0.0061 m²	
	Target pressure drop	User input	25.0 psi	172.4 kPa		24.92 psi	172.4 kPa	
	Flowrate for target p-drop	VBA calculation	106.0 gal/min	401.1 liters/min		18.7 gal/min	70.8 liters/min	
	Flowrate	Copied from above VBA calc.	105.97 gal/min	401.1 liters/min		18.71 gal/min	70.8 liters/min	
	Maximum theoretical rate for steam		lb/hr	kg/hr		lb/hr	kg/hr	
	Convert to equiv gpm		gal/min	liters/min		gal/min	liters/min	
	Flowrate to use		105.97 gal/min	233 liters/min		18.71 gal/min	41 liters/min	
V	Velocity	=Flow/(Flow Area)	4.49 ft/sec	1.37 m/sec		6.26 ft/sec	1.91 m/sec	
	Flowrate (mass)	converted from above	55,369 lb/hr	121,812 kg/hr		9,775 lb/hr	21,504 kg/hr	
Re	Reynolds Number	max velocity*ro*mean dimple diamet	13,831			19,263		
f	Fanning Friction Factor							
	Pressure Drop	Bondy, Figure 9	25.00 psi	172.37 kPa		24.92 psi	171.84 kPa	
h_i	Heat transfer coefficient	Garvin, Equation 9	302.80 Btu/ft²-hr-°F	1,719.37 W/m²-°C		426.73 Btu/ft²-hr-°F	2,423.06 W/m²-°C	

	Conventional Jacket		Sidewall			Bottom Head		
d_c	Curvature diameter	$d_c = d_v/\cos(\text{alpha})$; tan(alpha) = 2H/	98.20	inches	2,494 millimeters	98.20	inches	millimeters
	Curvature factor			de/dc=	0.063		de/dc=	0.063 millimeters
D_i	Inner Diameter of jacket		8.34	feet	2,541.59 millimeters	8.44	feet	2,571.97 millimeters
	Hydraulic Diameter (heat trans)		0.52	feet	158 millimeters	0.52	feet	millimeters
A_j	Flow Area of Jacket		3.2917	ft²	0.3058 m²	0.5104	ft²	0.0474 m²
	Equivalent diameter used by the pressure drop macro		2.0472	feet	623.99 millimeters	0.8062	feet	245.72 millimeters
d_e	Hydraulic Diameter (flow)	4 x flow area/flow perimeter	0.26	feet	77.79 millimeters	0.26	feet	77.79 millimeters
A	Effective Heat Transfer Are	total area, all zones	148.41	ft²	13.79 m²	50.27	ft²	4.67 m²
L	Actual coil length (each zone)		5	feet	1,432.56 millimeters	8	feet	2,463.80 millimeters
	Equivalent length of coil per zone		22	feet	6,577.58 millimeters	23	feet	7,035.80 millimeters
	Annular space jkt	User input	1.53	inches	38.9 millimeters	1.53	inches	38.9 millimeters
	Target pressure drop	User input	25.0	psi	kPa	24.9235539	psi	kPa
	Flowrate for target p-drop	VBA calculation	210,536.9	gal/min	liters/min	18,035.83	gal/min	liters/min
	Flowrate	Copied from above VBA calc.	210,536.93	gal/min	796,969.02 liters/min	18,035.83	gal/min	68,273.05 liters/min
	Maximum theoretical rate for steam			lb/hr	kg/hr		lb/hr	kg/hr
	Convert to equiv gpm			gal/min	liters/min		gal/min	liters/min
	Flowrate to use		210,536.93	gal/min	463,181 liters/min	18,035.83	gal/min	39,679 liters/min
V	Velocity	=Flow/(Flow Area)	142.51	ft/sec	m/sec	78.731	ft/sec	m/sec
	Flowrate (mass)	converted from above	110,002,522	lb/hr	242,005,548 kg/hr	9,423,462	lb/hr	20,731,616 kg/hr
Re	Reynolds Number		379,641			209,732		
f	Fanning Friction Factor		0.0166			0.0200		
	Pressure Drop		24.9376441	psi	171.94 kPa	24.8490561	psi	171.33 kPa
	Conv jacket regime	2000(1+13.2(de/dc)^.6)	7,043			7,043		
			Turbulent			Turbulent		
Forced Convection Component								
Calculations assuming wall temperature = bulk temperature								
	Conv jacket laminar	X = Re^.5 * (de PR / dc)^.25	943.76					
		Gz = (mass flowrate) * (heat capacity	1,326,800.50					
		Ge = .09525{Gz/(1+.0525Gz^.67)}	189.92					
		Nu - Garvin, Equation 2	927.23					
	Conv jacket turbulent	Re(de/dc)^2	2.56					
		viscosity ratio coefficient						
		Ge = 1+5.71(de/L)(1-exp(-.07L/de)	1.22					
		Nu - Garvin Equation 6	4,034.84					
	Conv jacket transitional	For estimating wall temp, just use tur	4,034.84					
	ho without viscosity effect		1,760.26					
Calculations with viscosity correction								
	Conv jacket laminar	X = Re^.5 * (de PR / dc)^.25	943.76			701.44		
		Gz = (mass flowrate) * (heat capacity	1.33E+06			6.61E+04		
		Ge = .09525{Gz/(1+.0525Gz^.67)}Vi	244.97			90.16		
		Nu - Garvin, Equation 2	1,195.96			888.42		
	Conv jacket turbulent	Re(de/dc)^2	2.56			1.42		
		viscosity ratio coefficient	0.18			0.18		
		Ge = 1+5.71(de/L)(1-exp(-.07L/de)	1.22			1.16		
		Nu - Garvin Equation 6	5,596.76			3,263.97		
	Conv jacket transitional	Procedure is to interpolate between upper laminar limit and lower turbulent limit against log of Re						
		Lower turbulent limit Re	15,000			15,000		
		Re(de/dc)^2	0.10			0.10		
		viscosity ratio coefficient	0.18			0.18		
		Ge = 1+5.71(de/L)(1-exp(-.07L/de	1.22			1.16		
		Nu - lower turbulent limit	407.38			386.10		
		Upper laminar limit Re	7,043			7,043		
		X = Re^.5 * (de PR / dc)^.25	128.55			128.53		
		Gz = (mass flowrate) * (heat capa	1.33E+06			6.61E+04		
		Ge = .09525{Gz/(1+.0525Gz^.67)}	244.97			90.16		
		Nusselt number for forced convect	161.49			161.48		
		Interpolated Nu	1,458.34			1,169.75		
	Conv jacket selected Nu-for	Turbulent	5,596.76			3,263.97		
Natural Convection Component								
	Estimated wall temperature	based on the forced convection Nu	61.59					
Gr	Grashof number	$\beta g d_e^3$ T/	1,767					
Rt	ratio of diameter to length	de/L	0.0425					
Gz	Graetz number	(pi/4)*Re*Pr*(d/L)	1,101,783					
	Sign	positive for aiding	-1					
m	exponent		0.25					
	Nu-natural convection		-6.52					
Combined Nusselt Number		Nu = (Nu-fc^3 + Nu-nc^3) ^ (1/3)	5,596.76					
h_j	Heat transfer coefficient		2,441.68	Btu/ft²-hr-°F	13,864.48 W/m²-°C	1,424.23	Btu/ft²-hr-°F	8,087.14 W/m²-°C
	Conventional Jacket with Agitating Nozzles		**Sidewall**			**Bottom Head**		
L	Vessel circumference		25.39	feet	7,740.26 millimeters			
D_e	Hydraulic Diameter (flow)	4 x flow area/flow perimeter	0.26	feet	77.79 millimeters			

a	width of annulus	User input	0.13	feet	38.90	millimeters					
b	straight-side length of jacket	from above	5.84	feet	1,781.34	millimeters					
A_f	Cross-sectional flow area	a x b	0.7458	ft²	0.07	m²					
	Number of nozzles	User input	2				1				
	Throat diameter	User input	0.63	inches	15.88	millimeters	0.63	inches	15.88	millimeters	
	Throat area		0.002131	ft²	0.0001979	m²	0.002131	ft²	0.0001979	m²	
A	Effective Heat Transfer Area	total area, all zones	148.41	ft²	13.79	m²	50.27	ft²	4.67	m²	
	Target pressure drop	User input	25	psi	172	kPa					
	Flowrate for target p-drop	Nozzle correlation with .75 "C" factor	38	gal/min	144.75	liters/min					
	Flowrate	Copied from above VBA calc.	38.24	gal/min	144.75	liters/min					
	Maximum theoretical rate for steam			lb/hr		kg/hr					
	Convert to equiv gpm			gal/min		liters/min					
	Flowrate to use (per nozzle)		38.24	gal/min	84	liters/min	38.24	gal/min	84.13	liters/min	
V	Velocity	=Flow/(Flow Area)	39.99	ft/sec	12.19	m/sec	39.99	ft/sec	12.19	m/sec	
	Flowrate (mass, total)	converted from above	39,959	lb/hr	87,910	kg/hr	19,979	lb/hr	43,955	kg/hr	
	Pressure Drop		25.00	psi	172	kPa	25.00	psi	172.37	kPa	calculates pressure drop through nozzle then multiplies by
	Determine swirl velocity	Ref: Bolliger									
w_p	mass flowrate per nozzle		5.55	lb/sec							
V_n	Velocity leaving nozzle		39.93	ft/sec	12.17	m/sec					
Vj	Swirl velocity	iterative calc using VBA subroutine	0.7853	ft/sec	0.24	m/sec					
	Reynolds number	$D_e V_i$ /	2,092								
	Nusselt number		54.21								
	Heat transfer coefficient		48.05	Btu/ft²-hr-°F	272.84	W/m²-°C	48.05	Btu/ft²-hr-°F	272.84	W/m²-°C	<-- Use same value for bottom jacket with nozzle

	Conventional Jacket with Baffles		Sidewall			Bottom Head		
	Spacing between coils	User input	2.36 inches	59.9 millimeters		2.36 inches	59.9 millimeters	
	Hydraulic Diameter (heat tra	=4w	0.51 feet	13.0 millimeters		0.51 feet	13.0 millimeters	
	Number of Coils on Straight Side (all zones)		30	30		14	14	
A_i	Flow Area of Coil		0.0251 ft²	0.0023 m²		0.025 ft²	0.0023 m²	
	Equivalent diameter used by the pressure drop macro		0.1788 feet	millimeters		0.1788 feet	millimeters	
d_e	Hydraulic Diameter (flow)	4 x flow area/flow perimeter	0.15 feet	47.18 millimeters		0.15 feet	47.18 millimeters	
A	Effective Heat Transfer Are	total area, all zones	148.41 ft²	13.79 m²		50.27 ft²	4.67 m²	
L	Actual coil length (each zone)		254 feet	77,419 millimeters		164.79 feet	50,227 millimeters	
	Equivalent length of coil per zone		371 feet	112,959 millimeters		246 feet	74,890 millimeters	
	Annular space	User input	1.53 inches	38.9 millimeters		1.53 inches	38.9 millimeters	
	Leakage around baffles		0.20			0.20		
	Target pressure drop	User input	25.0 psi	172 kPa		24.92 psi	172 kPa	
	Flowrate for target p-drop	VBA calculation	78.48 gal/min	297.08 liters/min		98.03 gal/min	371.08 liters/min	
	Flowrate	Copied from above VBA calc.	98.10 gal/min	371.35 liters/min		122.54 gal/min	463.85 liters/min	
	Maximum theoretical rate for steam		lb/hr	kg/hr		lb/hr	kg/hr	
	Convert to equiv gpm		gal/min	liters/min		gal/min	liters/min	
	Flowrate to use		98.10 gal/min	216 liters/min		122.54 gal/min	270 liters/min	
V	Effective Velocity	=Flow/(Flow Area) * (1-leakage)	6.97 ft/sec	2.12 m/sec		8.70 ft/sec	2.65 m/sec	
	Flowrate (mass)	converted from "Flowrate to use"	51,257 lb/hr	112,765 kg/hr		64,024 lb/hr	140,853 kg/hr	
Re	Reynolds Number		11,257	11,257		14,062	14,062	
f	Fanning Friction Factor		0.0353	0.0353		0.0340	0.0340	
	Pressure Drop		24.93 psi	171.87 kPa		24.85 psi	171.32 kPa	
	Conv jacket transitional	Procedure is to interpolate between upper laminar limit and lower turbulent limit against log of Re						
		Lower turbulent limit Re	15,000			15,000		
		Nu, turbulent (Garvin, eq. 8)	275.65			275.80		
		Upper laminar limit Re	2,100			2,100		
		Nu, laminar (Bondy, eq. 29)	13.05			15.06		
		Interpolated Nu	237.31			267.24		
h_i	Heat transfer coefficient	Transitional Interpolation	105.17 Btu/ft²-hr-°F	597.16 W/m²-°C		118.43 Btu/ft²-hr-°F	672.46 W/m²-°C	

	Internal Coil					Internal Coil	
	Nominal pipe diameter	User input				2.00 inches	50.00 DN
	Pipe Wall thickness					0.154 inches	3.91 millimeters
d_w	Actual O.D. of Pipe	From data table				2.375 inches	60.33 millimeters
	Actual I.D. of Pipe	From data table				2.067 inches	52.50 millimeters
	Hydraulic Diameter (heat trans)					0.1723 feet	52.50 millimeters
A_i	Flow Area of Coil					0.0233 ft²	0.0022 m²
	Equivalent diameter used by the pressure drop macro					0.1723 feet	52.50 millimeters
d_e	Hydraulic Diameter (flow)	4 x flow area/flow perimeter				0.1723 feet	52.50 millimeters
A	Effective Heat Transfer Are	total area, all zones				30.31 ft²	2.82 m²
L	Actual coil length (each zone)					56 feet	17,070 millimeters
	Equivalent length of coil per zone				--->>>>>	93 feet	28,472 millimeters
	Target pressure drop	User input				N/A psi	N/A kPa
	Flowrate for target p-drop	VBA calculation				N/A gal/min	N/A liters/min
	Flowrate	Copied from above VBA calc.				N/A gal/min	N/A liters/min
	Maximum theoretical rate for steam					N/A lb/hr	N/A kg/hr
	Convert to equiv gpm					N/A gal/min	N/A liters/min
	Flowrate to use					N/A gal/min	N/A liters/min
V	Velocity	=Flow/(Flow Area)				N/A ft/sec	N/A m/sec
	Flowrate (mass)	converted from above				N/A lb/hr	N/A kg/hr
Re	Reynolds Number					N/A	N/A
f	Fanning Friction Factor					N/A	N/A
	Pressure Drop					N/A psi	N/A kPa
h_j	Heat transfer coefficient	Garvin, equation 8, with conversion from inside coil to outside coil				N/A Btu/ft²-hr-°F	N/A W/m²-°C

Nusselt Number Calculations Pitch 45 Impeller Width or Flight Pitch 4.0 Diameter 35.0 No. Blades 6 Ribbon pitch 24

0.041666667

		RE		PR	Visc ratio		GR	e/D		l/D		5Wsin( )/D	blades/6		sin( )						
		1,906,783		2.67	0.794		776.52	0.871428571		0.057142857		0.404061018		1	0.707106781	**Calculated**	**Inside h**	Nusselt Number and hi without viscosity effect		**For internal coil**	
	Coefficient	RE exp		PR exp	Visc exp			(e/D) exp		(l/D) exp		Width exp	Blades exp		theta exp	**Nusselt No.**	Btu/ft²-hr-°F	**Nu**	**h**	**Nu**	**h**
Agitator Type																					
Alloy 3-blade retreating	0.37	0.67		0.33	0.14		0	0		0		0	0		0	7,991	369.57	8,253	381.71	11,862.72	548.6509083
Anchor	0.32	0.67		0.33	0.14		0	0		0		0	0		0	6,911	319.63	7,138	330.13	0.00	0
Glass-steel retreating	0.33	0.67		0.33	0.14		0	0		0		0	0		0	7,127	329.62	7,361	340.45	0.00	0
Helical Ribbon	0.3	0.67		0.33	0.14		0	0		0		0	0		0	6,479	299.65	6,692	309.50	0.00	0
No Agitator		Clam =	0.580060982		Cturb=	0.11266902		Nulam =	5.187991784			Nuturb=	1.432608463			5.2	0.24	2.0	0.09	19.26	36.00054184
Paddle	0.36	0.67		0.33	0.14		0	0		0		0	0		0	7,775	359.58	8,030	371.40	7,371.83	340.9473501
Propeller	0.5	0.67		0.33	0.14		0	0		0		0	0		0	10,798	499.42	11,153	515.83	230.57	431.0364008
Pumped Circulation (no agitator)																	53.94	2.49	53.52	2.48	0.00	106.6370534
Retreating-blade Turbine	0.68	0.67		0.33	0.14		0	0		0		0	0		0	14,686	679.21	15,168	701.53	11,862.72	548.6509083
Turbine (Rushton)	0.74	0.67		0.33	0.14		0	0		0		0.2	0.2		0.5	11,211	518.51	11,579	535.55	358.83	670.8237125

Coil OD = 2.375 inches = 0.197916667 feet

Gr= 1213641.209

Nusselt Number Calculations for internal coils (outside of the coils)

					0.173913043	25dto/dv	15.625dto/dv	3da/dv			d/H			Nusselt Number and hi without viscosity effect		
						0.618489583	0.38655599	1.09375			1.333333333			**Nu**	**h**	
Alloy 3-blade retreating	1.4	0.62	0.33	0.14	0	0	0	0	0	0	0	11,862.72	548.65	15,154.37	700.89	
Anchor																
Glass-steel retreating																
Helical Ribbon																
No Agitator												19.26	36.00	19.88	37.16	Garvin, Equation 17
Paddle	0.87	0.62	0.33	0.14	0	0	0	0	0	0	0	7,371.83	340.95	9,417.36	435.55	Bondy, Equation 27
Propeller	0.016	0.67	0.37	0.14	0.5	0	0.1	0	0	0	0	230.57	431.04	294.54	550.64	Garvin, Equation 20
Pumped Circulation (no agitator)													106.64	19.88	37.16	see body of calculation
Retreating-blade Turbine	1.4	0.62	0.33	0.14	0	0	0	0	0	0	0	11,862.72	548.65	15,154.37	700.89	Bondy, Equation 25
Turbine (Rushton)	0.03	0.67	0.33	0.14	0.5	0	0	0.2	0.5	0.15		358.83	670.82	458.40	856.96	Garvin, Equation 18

33.33dto/dv (da/dv)/3

0.824570313 0.003472222