Components of Flow Processes

Equipment used to extract/provide work and/or heat from a process

- turbines - generate electricity
- compressors and pumps - move fluid, change pressures
- heat exchangers - change temperature of fluid
- throttles - change pressure

OBJECTIVES

- evaluate performance of components of flow processes through appropriate mass, energy, entropy balances

Table 7.1 Pg 256 of SvNA

Table 7.1: Equations of Balance

General Equations of Balance	Balance Equations for Steady-Flow Processes	Balance Equations for Single-Stream Steady-Flow Processes
$\frac{dm_{cv}}{dt} + \Delta(\dot{m})_{fs} = 0$ (2.25)	$\Delta(\dot{m})_{fs} = 0$ (7.1)	$\dot{m}_1 = \dot{m}_2 = \dot{m}$ (7.2)
$\frac{d(mU)_{cv}}{dt} + \Delta\left[\left(H + \frac{1}{2}u^2 + zg\right)\dot{m}\right]_{fs} = \dot{Q} + \dot{W}$ (2.28)	$\Delta\left[\left(H + \frac{1}{2}u^2 + zg\right)\dot{m}\right]_{fs} = \dot{Q} + \dot{W}_s$ (2.30)	$\Delta H + \frac{\Delta u^2}{2} + g\Delta z = Q + W_s$ (2.32a)
$\frac{d(mS)_{cv}}{dt} + \Delta(S\dot{m})_{fs} - \sum_j \frac{\dot{Q}_j}{T_{\sigma,j}} = \dot{S}_G \geq 0$ (5.21)	$\Delta(S\dot{m})_{fs} - \sum_j \frac{\dot{Q}_j}{T_{\sigma,j}} = \dot{S}_G \geq 0$ (5.22)	$\Delta S - \sum_j \frac{Q_j}{T_{\sigma,j}} = S_G \geq 0$ (5.23)

Turbines

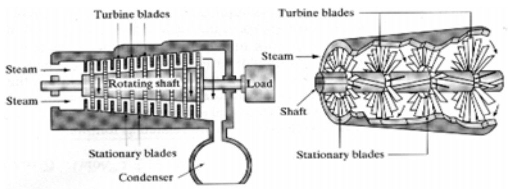
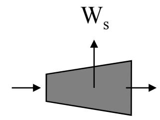


Figure 3.3-3 Sketch of a steam turbine. (Adapted from *The World Book Encyclopedia*, Field Educational Enterprises, New York, 1976.)



convert gas kinetic energy into work, W_s

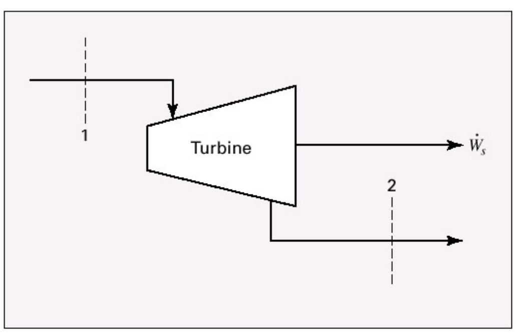
$$\Delta H = T_\sigma(\Delta S_{fs} - S_{gen}) + W_s$$

efficiency

$$\eta_{turbine} = \frac{W_s}{(W_s)_S} = \frac{\Delta H}{(\Delta H)_S}$$

1 MW turboexpander

Figure 7.3: Schematic of Turbine



At steady state an ideal (reversible) turbine converts all the enthalpy change between point 1 and 2 entirely into shaft work.

$$(\Delta H)_S = (W_s)_S$$

Note irritating nomenclature s → shaft
S → isentropic ($\Delta S=0$)

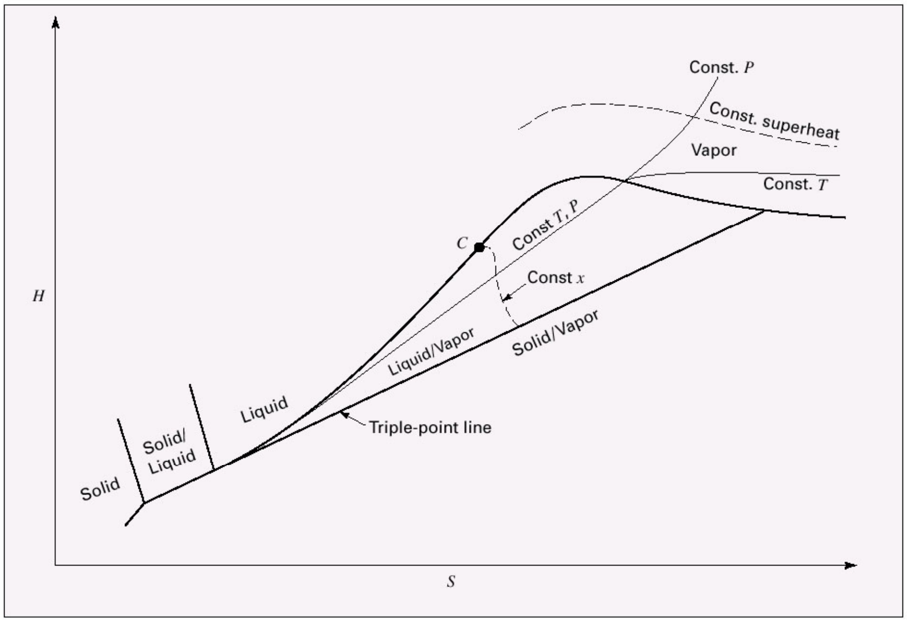


Figure 6.4: Mollier diagram.

Mollier Diagram – Seriously Complicated

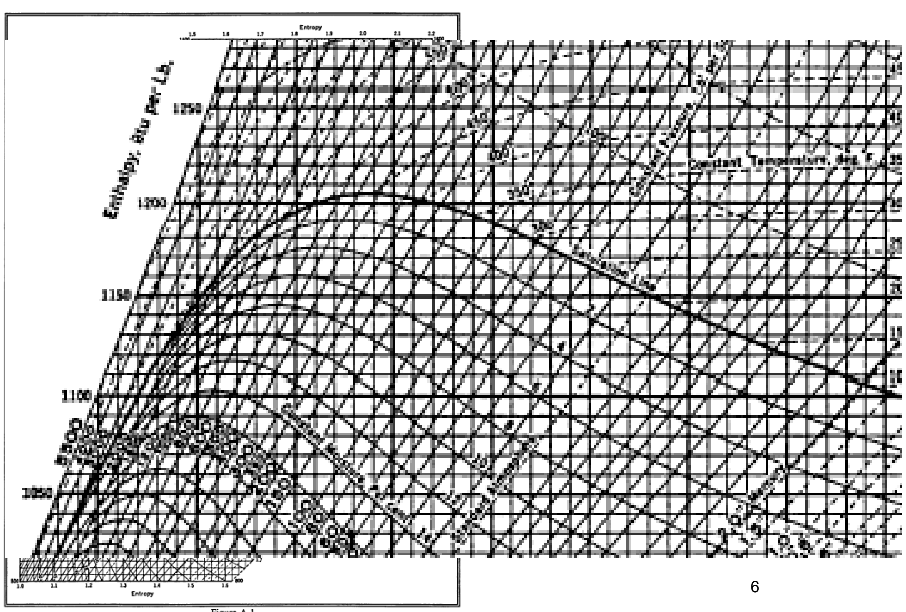


Figure A-1

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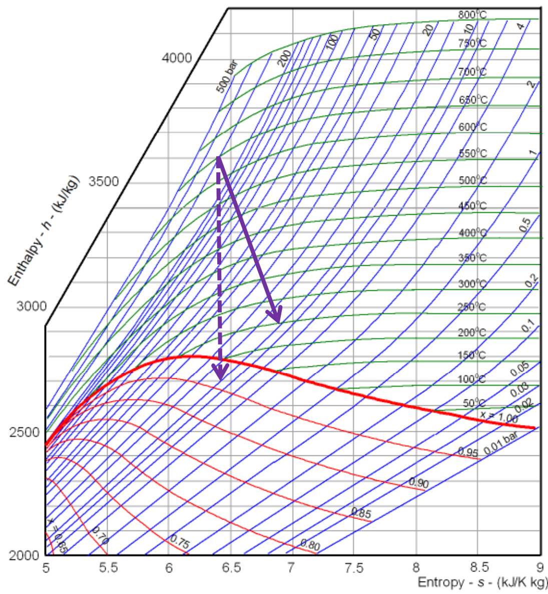
Mollier Diagram (a bit less confusing)



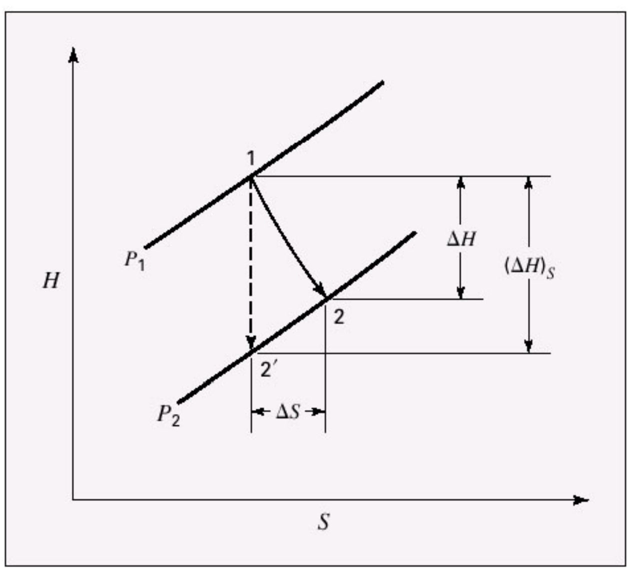
Key points

-Vertical lines are constant entropy (remember that when ΔS=0 we have reversible process → most work possible)

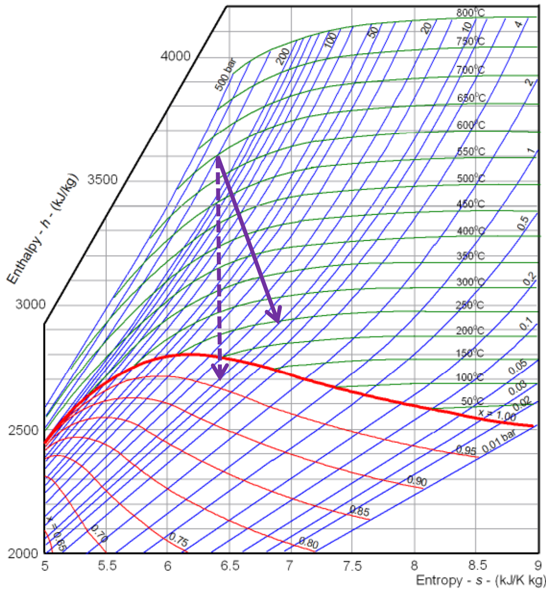
-Turbines turn enthalpy into work

7

Figure 7.4: Efficiency from Mollier Diagram



Mollier Diagram – Turbine Efficiency



$$\eta_{turbine} = \frac{W_s}{(W_s)_S} = \frac{\Delta H}{(\Delta H)_S}$$

Turbine – Efficiency from Steam Tables

A turbine is fed with steam at 475ºC and 100 bar. The steam leaves the turbine saturated at 10 bar. The quality of the exiting steam is 1.0. Calculate the adiabatic efficiency of the turbine using steam tables.

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Table F.2. Superheated Steam, SI Units (Continued)

Pg 730-1 of SVA

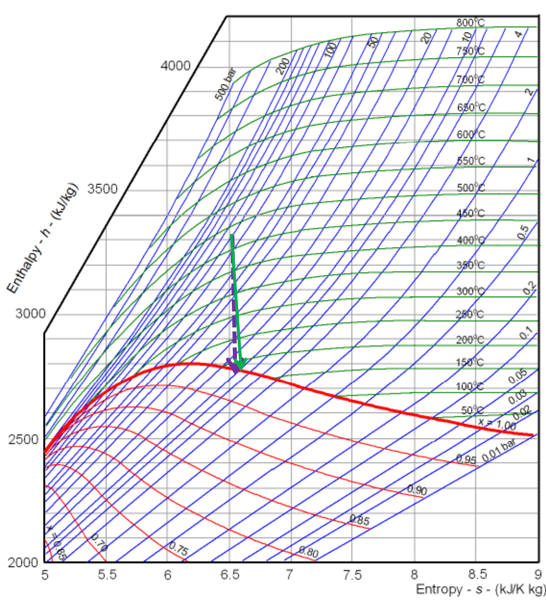
P/kPa (t^{sat}/°C)		sat. liq.	sat. vap.	175 (448.15)	200 (473.15)	220 (493.15)	240 (513.15)	260 (533.15)	280 (553.15)	300 (573.15)	325 (598.15)
				TEMPERATURE: t °C (TEMPERATURE: T kelvins)							
750 (167.76)	V	1.112	255.43	260.88	279.05	293.03	306.65	320.01	333.17	346.19	362.32
	U	708.467	2573.3	2586.9	2632.1	2666.8	2700.6	2733.7	2766.4	2798.9	2839.3
	H	709.301	2764.8	2782.5	2841.4	2886.6	2930.6	2973.7	3016.3	3058.5	3111.0
	S	2.0195	6.6817	6.7215	6.8494	6.9429	7.0303	7.1128	7.1912	7.2662	7.3558
775 (169.10)	V	1.113	247.61	251.93	269.63	283.22	296.45	309.41	322.19	334.81	350.44
	U	714.326	2574.3	2585.4	2631.0	2665.9	2699.8	2733.1	2765.9	2798.4	2838.9
	H	715.189	2766.2	2780.7	2840.0	2885.4	2929.6	2972.9	3015.6	3057.9	3110.5
	S	2.0328	6.6705	6.7031	6.8319	6.9259	7.0137	7.0965	7.1751	7.2502	7.3400
800 (170.41)	V	1.115	240.26	243.53	260.79	274.02	286.88	299.48	311.89	324.14	339.31
	U	720.043	2575.3	2584.0	2629.9	2665.0	2699.1	2732.5	2765.4	2797.9	2838.5
	H	720.935	2767.5	2778.8	2838.6	2884.2	2928.6	2972.1	3014.9	3057.3	3109.9
1000 (179.88)	V	1.127	194.29	....	205.92	216.93	227.55	237.89	248.01	257.98	270.27
	U	761.478	2581.9	....	2620.9	2657.7	2693.0	2727.4	2761.0	2794.2	2835.2
	H	762.605	2776.2	....	2826.8	2874.6	2920.6	2965.2	3009.0	3052.1	3105.5
	S	2.1382	6.5828	....	6.6922	6.7911	6.8825	6.9680	7.0485	7.1251	7.2163
1050 (182.02)	V	1.130	185.45	....	195.45	206.04	216.24	226.15	235.84	245.37	257.12
	U	770.843	2583.3	....	2618.5	2655.8	2691.5	2726.1	2759.9	2793.2	2834.4
	H	772.029	2778.0	....	2823.8	2872.1	2918.5	2963.5	3007.5	3050.8	3104.4
	S	2.1588	6.5659	....	6.6645	6.7647	6.8569	6.9430	7.0240	7.1009	7.1924
1100 (184.07)	V	1.133	177.38	....	185.92	196.14	205.96	215.47	224.77	233.91	245.16
	U	779.878	2584.5	....	2616.2	2653.9	2689.9	2724.7	2758.8	2792.2	2833.6
	H	781.124	2779.7	....	2820.7	2869.6	2916.4	2961.8	3006.0	3049.6	3103.3
	S	2.1786	6.5497	....	6.6379	6.7392	6.8323	6.9190	7.0005	7.0778	7.1695
1150 (186.05)	V	1.136	169.99	....	177.22	187.10	196.56	205.73	214.67	223.44	234.25
	U	788.611	2585.8	....	2613.8	2651.9	2688.3	2723.4	2757.7	2791.3	2832.8
	H	789.917	2781.3	....	2817.6	2867.1	2914.4	2960.0	3004.5	3048.2	3102.2
	S	2.1977	6.5342	....	6.6122	6.7147	6.8086	6.8959	6.9779	7.0556	7.1476
	V	1.139	163.20	....	169.23	178.80	187.95	196.79	205.40	213.85	224.24

Pg 752-3 of SVA

Table F.2. Superheated Steam, SI Units (Continued)

P/kPa (t^{sat}/°C)		sat. liq.	sat. vap.	475 (748.15)	500 (773.15)	525 (798.15)	550 (823.15)	575 (848.15)	600 (873.15)	625 (898.15)	650 (923.15)
				TEMPERATURE: t °C (TEMPERATURE: T kelvins)							
	V	1.391	22.863	38.893	40.614	42.295	43.943	45.566	47.166	48.747	50.313
8200	U	1315.2	2569.5	3015.6	3063.3	3110.5	3157.4	3204.3	3251.1	3298.1	3345.2
(296.70)	H	1326.6	2757.0	3334.5	3396.4	3457.3	3517.8	3577.9	3637.9	3697.8	3757.7
	S	3.2239	5.7338	6.6311	6.7124	6.7900	6.8646	6.9365	7.0062	7.0739	7.1397
	V	1.398	22.231	37.887	39.576	41.224	42.839	44.429	45.996	47.544	49.076
8400	U	1324.3	2567.2	3013.6	3061.6	3108.9	3155.9	3202.9	3249.8	3296.9	3344.1
(298.39)	H	1336.1	2754.0	3331.9	3394.0	3455.2	3515.8	3576.1	3636.2	3696.2	3756.3
	S	3.2399	5.7207	6.6173	6.6990	6.7769	6.8516	6.9238	6.9936	7.0614	7.1274
	V	1.404	21.627	36.928	38.586	40.202	41.787	43.345	44.880	46.397	47.897
	V	1.453	18.041	31.280	32.760	34.196	35.597	36.970	38.320	39.650	40.963
10000	U	1393.5	2547.3	2997.4	3047.0	3095.7	3143.9	3191.7	3239.5	3287.3	3335.1
(310.96)	H	1408.0	2727.7	3310.1	3374.6	3437.7	3499.8	3561.4	3622.7	3683.8	3744.7
	S	3.3605	5.6198	6.5147	6.5994	6.6797	6.7564	6.8302	6.9013	6.9703	7.0373
	V	1.460	17.605	30.599	32.058	33.472	34.851	36.202	37.530	38.837	40.128
10200	U	1401.8	2544.6	2995.3	3045.2	3094.0	3142.3	3190.3	3238.2	3286.1	3334.0
(312.42)	H	1416.7	2724.2	3307.4	3372.1	3435.5	3497.8	3559.6	3621.0	3682.2	3743.3
	S	3.3748	5.6076	6.5027	6.5879	6.6685	6.7454	6.8194	6.8907	6.9598	7.0269
	V	1.467	17.184	29.943	31.382	32.776	34.134	35.464	36.770	38.056	39.325
10400	U	1410.0	2541.8	2993.2	3043.3	3092.4	3140.8	3188.9	3236.9	3284.8	3332.9
(313.86)	H	1425.2	2720.6	3304.6	3369.7	3433.2	3495.8	3557.8	3619.3	3680.6	3741.8
	S	3.3889	5.5955	6.4909	6.5765	6.6574	6.7346	6.8087	6.8803	6.9495	7.0167
	V	1.474	16.778	29.313	30.732	32.106	33.444	34.753	36.039	37.304	38.552
10600	U	1418.1	2539.0	2991.1	3041.4	3090.7	3139.3	3187.5	3235.6	3283.6	3331.7
(315.27)	H	1433.7	2716.9	3301.8	3367.2	3431.0	3493.8	3555.9	3617.6	3679.1	3740.4
	S	3.4029	5.5835	6.4793	6.5652	6.6465	6.7239	6.7983	6.8700	6.9394	7.0067

Mollier Diagram – Turbine Efficiency



$$\eta_{turbine} = \frac{W_s}{(W_s)_S} = \frac{\Delta H}{(\Delta H)_S}$$

The Mollier diagram is much quicker if perhaps not as accurate.

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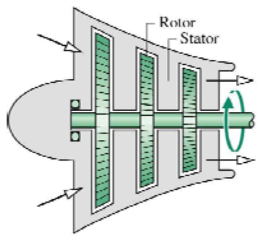
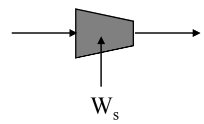
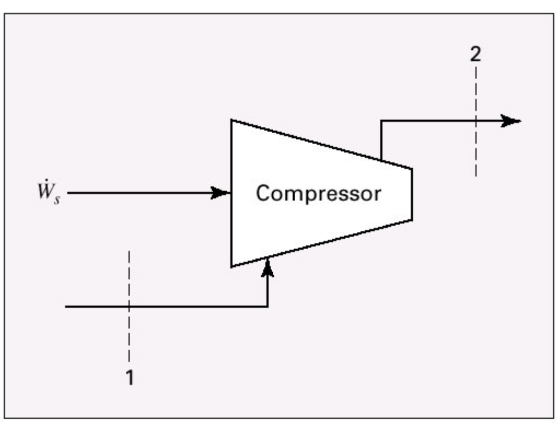
Compressors



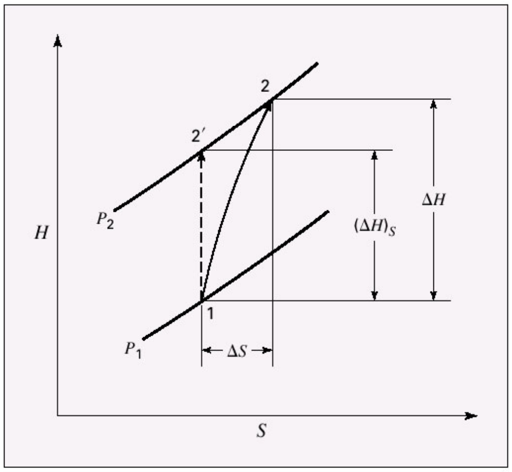


used to transport **gases**

$$\eta_{comp} = \frac{(W_s)_S}{W_s} = \frac{(\Delta H)_S}{\Delta H}$$

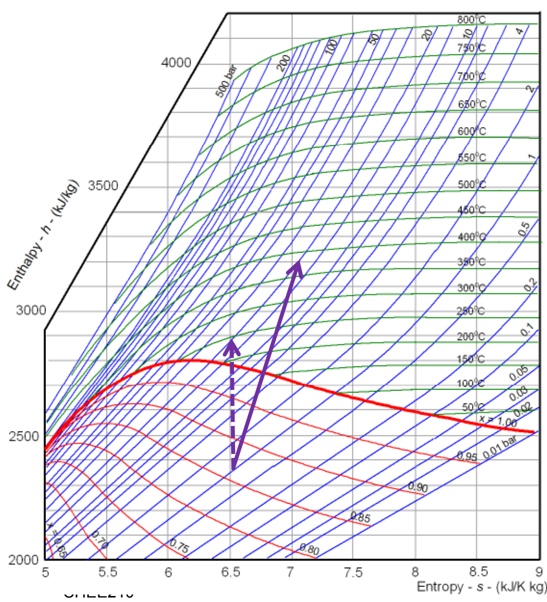


Compressor on the Mollier Diagram



- On the Mollier diagram the change in enthalpy $(\Delta H)_{\Delta S=0} < (\Delta H)_{\Delta S>0}$

Mollier Diagram for Compression

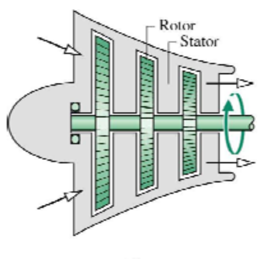


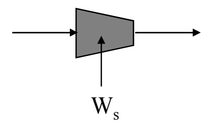
-Vertical lines are constant entropy ($\Delta S=0$ means we have a reversible compressor that requires the least work for compression)

- In a real compressor $\Delta S>0$ and more work is required.

- On the Mollier diagram the change in enthalpy $(\Delta H)_{\Delta S=0} < (\Delta H)_{\Delta S>0}$

Compressors



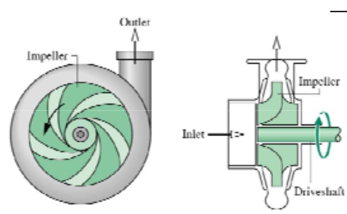


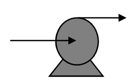
$$\eta_{comp} = \frac{(W_s)_S}{W_s} = \frac{(\Delta H)_S}{\Delta H}$$

From the Mollier diagram for compression of steam from 1bar 100ºC, quality 0.867 to 20 bar and superheated to 375ºC. Reading directly off Mollier Diagram

$$\eta_{comp} = \frac{(W_s)_S}{W_s} = \frac{(\Delta H)_S}{\Delta H} = \frac{(2880 - 2360)_S}{(3200 - 2360)} = \frac{(520)_S}{840} = 0.62$$

Pumps





used to transport **liquids**

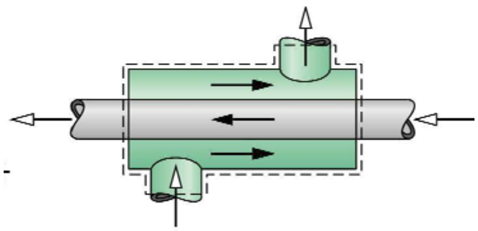
$$\eta_{pump} = \frac{(W_s)_S}{W_s} = \frac{(\Delta H)_S}{\Delta H}$$

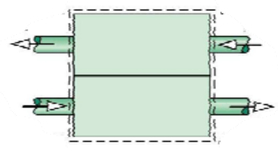
$$(\Delta H)_S = V(P_e - P_i)$$

Heat Exchanger

Fluid flow through a system of pipes with transfer of heat energy from one fluid to another.

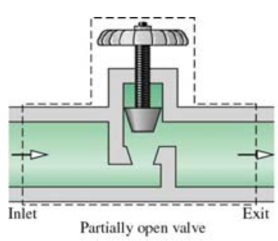
$$\sum \dot{m}_i H_i = \sum \dot{m}_e H_e$$

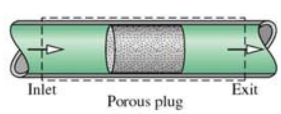




Throttle

Fluid flowing in a pipe suddenly encounters a restriction. Result is a pressure drop at constant enthalpy.





Example

A compressor takes in gas at a lower pressure and discharges it at a higher temperature. The process occurs quickly, therefore it can safely be assumed to be adiabatic. Air (ideal gas, C_P = 29.3 J/(mol K) is the inlet gas at T = 290 K and P = 1 atm. The outlet pressure is 10 atm. Estimate the T of the gas and the rate at which work is done on the gas for a flow rate of 2.5 mol/s.