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THERMODYNAMICS

Doctoral Qualifying Examination, May 2016

Mechanical Engineering Department, Columbia University

Problem 1

In supercritical fluids, the "pseudo-boiling" temperature plays a role similar to the boiling temperature at subcritical conditions. Namely, it has been observed that there exists a peak in the specific heat as the temperature is increased at constant pressure above the critical point – often dubbed the pseudo-boiling temperature. If one were to construct a line on P-T plot of these pseudo-boiling temperatures, it forms the so-called "Widom line." Using a virial equation of state explicit in volume

$$Z = 1 + \sum_{i=1}^{\infty} A_i(T) p^i$$

where $A_i(T)$ are infinitely differentiable functions of temperature; the definition of specific heat at constant pressure:

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p$$

and the thermodynamic relation for h

$$dh = c_p dT + \left[v - T\left(\frac{\partial v}{\partial T}\right)_p\right] dp$$

show that an equation describing the Widom line can be constructed in terms of p, T, R (the gas constant), $c_{p,0}$ (the specific heat at constant pressure in the zero-pressure limit), and $A_i(T)$. Show all steps and explain your reasoning.

(Note that since $A_i(T)$'s are chosen to represent experimental data where there is only one extremum in c_p and it is a maximum, you do not need to show that the extremum found corresponds to a maximum.)

Problem 2

An inventor claims to have built a device that will take 0.001 kg/s of water from the faucet at 25°C and 100 kPa and produce separate streams of hydrogen and oxygen gas each at 400 K and 100 kPa. It is stated that the device operates in a 25°C room on 10 kW electrical power input. Evaluate this claim using the laws of thermodynamics.

You can assume constant specific heats and use the following information: M_{H2O} = 18 kg/kmol, $\bar{h}^o_{f,H2O(l)}$ = -285,830 kJ/kmol, $\bar{s}^o_{H2O(l),298K}$ = 69.950 kJ/kmol/K, $\bar{c}_{p,H2}$ = 29.03 kJ/kmol/K, $\bar{s}^o_{H2,298K}$ = 130.678 kJ/kmol/K, $\bar{c}_{p,O2}$ = 29.68 kJ/kmol/K, and $\bar{s}^o_{O2,298K}$ = 205.148 kJ/kmol/K.

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THERMODYNAMICS

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Problem 3

Suppose a container maintained at a constant temperature of 2500 K and constant pressure of 300 kPa initially contains 1 mole of CO_2 and 1 mole of O_2. Determine the equilibrium composition assuming that only O_2, CO, and CO_2 are present.

The equilibrium constant, $K = \left(\prod X_i^{\nu_i''-\nu_i'}\right)\left(\frac{P}{P_0}\right)^{\sum \nu_i''-\nu_i'}$, for $2CO_2 = 2CO + O_2$ with P_0= 100 kPa is 0.00128 at 2500 K.

Problem 4

Consider an adiabatic rocket engine where H_2 and O_2 at 298 K at 100 kPa in stoichiometrically balanced proportions and with negligible kinetic energy enter a constant-pressure combustor operating at 100 kPa. After the flow passes through the combustor, the flow proceeds through a converging-diverging nozzle. The combustion reaction proceeds to completion before the nozzle exit such that only H_2O exits the engine. If the nozzle exit area is sufficiently large that the exit pressure can be considered to be perfectly matched to a space environment of negligible temperature and pressure, find the maximum velocity of the exiting flow at steady-state. You can assume that the flow behaves as an ideal gas mixture. Would this velocity be achieved at sea level on Earth? Justify your answer using arguments based on both exergy and compressible flow considerations.

TABLE A.9 *(continued)*

Ideal Gas Properties of Various Substances (SI Units), Entropies at 0.1-MPa (1-Bar) Pressure, Mole Basis

	Oxygen, Diatomic (O_2) $\bar{h}^0_{f,298} = 0$ kJ/kmol $M = 31.999$ kg/kmol		Oxygen, Monatomic (O) $\bar{h}^0_{f,298} = 249\,170$ kJ/kmol $M = 16.00$ kg/kmol	
T K	$(\bar{h} - \bar{h}^0_{298})$ kJ/kmol	$\bar{s}^0_T$ kJ/kmol K	$(\bar{h} - \bar{h}^0_{298})$ kJ/kmol	$\bar{s}^0_T$ kJ/kmol K
0	−8683	0	−6725	0
100	−5777	173.308	−4518	135.947
200	−2868	193.483	−2186	152.153
298	0	205.148	0	161.059
300	54	205.329	41	161.194
400	3027	213.873	2207	167.431
500	6086	220.693	4343	172.198
600	9245	226.450	6462	176.060
700	12499	231.465	8570	179.310
800	15836	235.920	10671	182.116
900	19241	239.931	12767	184.585
1000	22703	243.579	14860	186.790
1100	26212	246.923	16950	188.783
1200	29761	250.011	19039	190.600
1300	33345	252.878	21126	192.270
1400	36958	255.556	23212	193.816
1500	40600	258.068	25296	195.254
1600	44267	260.434	27381	196.599
1700	47959	262.673	29464	197.862
1800	51674	264.797	31547	199.053
1900	55414	266.819	33630	200.179
2000	59176	268.748	35713	201.247
2200	66770	272.366	39878	203.232
2400	74453	275.708	44045	205.045
2600	82225	278.818	48216	206.714
2800	90080	281.729	52391	208.262
3000	98013	284.466	56574	209.705
3200	106022	287.050	60767	211.058
3400	114101	289.499	64971	212.332
3600	122245	291.826	69190	213.538
3800	130447	294.043	73424	214.682
4000	138705	296.161	77675	215.773
4400	155374	300.133	86234	217.812
4800	172240	303.801	94873	219.691
5200	189312	307.217	103592	221.435
5600	206618	310.423	112391	223.066
6000	224210	313.457	121264	224.597

TABLE A.9 *(continued)*

Ideal Gas Properties of Various Substances (SI Units), Entropies at 0.1-MPa (1-Bar) Pressure, Mole Basis

	Carbon Dioxide (CO_2) $\bar{h}^0_{f,298} = -393\,522$ **kJ/kmol** $M = 44.01$ **kg/kmol**		**Carbon Monoxide (CO)** $\bar{h}^0_{f,298} = -110\,527$ **kJ/kmol** $M = 28.01$ **kg/kmol**	
T K	$(\bar{h} - \bar{h}^0_{298})$ kJ/kmol	$\bar{s}^0_T$ kJ/kmol K	$(\bar{h} - \bar{h}^0_{298})$ kJ/kmol	$\bar{s}^0_T$ kJ/kmol K
0	−9364	0	−8671	0
100	−6457	179.010	−5772	165.852
200	−3413	199.976	−2860	186.024
298	0	213.794	0	197.651
300	69	214.024	54	197.831
400	4003	225.314	2977	206.240
500	8305	234.902	5932	212.833
600	12906	243.284	8942	218.321
700	17754	250.752	12021	223.067
800	22806	257.496	15174	227.277
900	28030	263.646	18397	231.074
1000	33397	269.299	21686	234.538
1100	38885	274.528	25031	237.726
1200	44473	279.390	28427	240.679
1300	50148	283.931	31867	243.431
1400	55895	288.190	35343	246.006
1500	61705	292.199	38852	248.426
1600	67569	295.984	42388	250.707
1700	73480	299.567	45948	252.866
1800	79432	302.969	49529	254.913
1900	85420	306.207	53128	256.860
2000	91439	309.294	56743	258.716
2200	103562	315.070	64012	262.182
2400	115779	320.384	71326	265.361
2600	128074	325.307	78679	268.302
2800	140435	329.887	86070	271.044
3000	152853	334.170	93504	273.607
3200	165321	338.194	100962	276.012
3400	177836	341.988	108440	278.279
3600	190394	345.576	115938	280.422
3800	202990	348.981	123454	282.454
4000	215624	352.221	130989	284.387
4400	240992	358.266	146108	287.989
4800	266488	363.812	161285	291.290
5200	292112	368.939	176510	294.337
5600	317870	373.711	191782	297.167
6000	343782	378.180	207105	299.809

TABLE A.9 *(continued)*

Ideal Gas Properties of Various Substances (SI Units), Entropies at 0.1-MPa (1-Bar) Pressure, Mole Basis

	Water (H_2O) $\bar{h}^0_{f,298} = -241\,826$ kJ/kmol $M = 18.015$ kg/kmol		Hydroxyl (OH) $\bar{h}^0_{f,298} = 38\,987$ kJ/kmol $M = 17.007$ kg/kmol	
T K	$(\bar{h} - \bar{h}^0_{298})$ kJ/kmol	$\bar{s}^0_T$ kJ/kmol K	$(\bar{h} - \bar{h}^0_{298})$ kJ/kmol	$\bar{s}^0_T$ kJ/kmol K
0	−9904	0	−9172	0
100	−6617	152.386	−6140	149.591
200	−3282	175.488	−2975	171.592
298	**0**	**188.835**	**0**	**183.709**
300	**62**	**189.043**	**55**	**183.894**
400	**3450**	**198.787**	**3034**	**192.466**
500	6922	206.532	5991	199.066
600	10499	213.051	8943	204.448
700	14190	218.739	11902	209.008
800	**18002**	**223.826**	**14881**	**212.984**
900	**21937**	**228.460**	**17889**	**216.526**
1000	**26000**	**232.739**	**20935**	**219.735**
1100	30190	236.732	24024	222.680
1200	34506	240.485	27159	225.408
1300	38941	244.035	30340	227.955
1400	**43491**	**247.406**	**33567**	**230.347**
1500	**48149**	**250.620**	**36838**	**232.604**
1600	**52907**	**253.690**	**40151**	**234.741**
1700	57757	256.631	43502	236.772
1800	62693	259.452	46890	238.707
1900	67706	262.162	50311	240.556
2000	**72788**	**264.769**	**53763**	**242.328**
2200	**83153**	**269.706**	**60751**	**245.659**
2400	**93741**	**274.312**	**67840**	**248.743**
2600	104520	278.625	75018	251.614
2800	115463	282.680	82268	254.301
3000	126548	286.504	89585	256.825
3200	**137756**	**290.120**	**96960**	**259.205**
3400	**149073**	**293.550**	**104388**	**261.456**
3600	**160484**	**296.812**	**111864**	**263.592**
3800	171981	299.919	119382	265.625
4000	183552	302.887	126940	267.563
4400	206892	308.448	142165	271.191
4800	**230456**	**313.573**	**157522**	**274.531**
5200	**254216**	**318.328**	**173002**	**277.629**
5600	**278161**	**322.764**	**188598**	**280.518**
6000	302295	326.926	204309	283.227

TABLE A.9 *(continued)*

Ideal Gas Properties of Various Substances (SI Units), Entropies at 0.1-MPa (1-Bar) Pressure, Mole Basis

	Hydrogen (H_2) $\bar{h}^0_{f,298} = 0$ **kJ/kmol** $M = 2.016$ **kg/kmol**		**Hydrogen, Monatomic (H)** $\bar{h}^0_{f,298} = 217\,999$ **kJ/kmol** $M = 1.008$ **kg/kmol**	
T **K**	$(\bar{h} - \bar{h}^0_{298})$ **kJ/kmol**	$\bar{s}^0_T$ **kJ/kmol K**	$(\bar{h} - \bar{h}^0_{298})$ **kJ/kmol**	$\bar{s}^0_T$ **kJ/kmol K**
0	−8467	0	−6197	0
100	−5467	100.727	−4119	92.009
200	−2774	119.410	−2040	106.417
298	0	130.678	0	114.716
300	53	130.856	38	114.845
400	2961	139.219	2117	120.825
500	5883	145.738	4196	125.463
600	8799	151.078	6274	129.253
700	11730	155.609	8353	132.457
800	14681	159.554	10431	135.233
900	17657	163.060	12510	137.681
1000	20663	166.225	14589	139.871
1100	23704	169.121	16667	141.852
1200	26785	171.798	18746	143.661
1300	29907	174.294	20825	145.324
1400	33073	176.637	22903	146.865
1500	36281	178.849	24982	148.299
1600	39533	180.946	27060	149.640
1700	42826	182.941	29139	150.900
1800	46160	184.846	31218	152.089
1900	49532	186.670	33296	153.212
2000	52942	188.419	35375	154.279
2200	59865	191.719	39532	156.260
2400	66915	194.789	43689	158.069
2600	74082	197.659	47847	159.732
2800	81355	200.355	52004	161.273
3000	88725	202.898	56161	162.707
3200	96187	205.306	60318	164.048
3400	103736	207.593	64475	165.308
3600	111367	209.773	68633	166.497
3800	119077	211.856	72790	167.620
4000	126864	213.851	76947	168.687
4400	142658	217.612	85261	170.668
4800	158730	221.109	93576	172.476
5200	175057	224.379	101890	174.140
5600	191607	227.447	110205	175.681
6000	208332	230.322	118519	177.114

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TABLE A.11

Logarithms to the Base e of the Equilibrium Constant K

For the reaction $\nu_A A + \nu_B B \rightleftharpoons \nu_C C + \nu_D D$, the equilibrium constant K is defined as

$$K = \frac{y_C^{\nu_C} y_D^{\nu_D}}{y_A^{\nu_A} y_B^{\nu_B}} \left(\frac{P}{P^0} \right)^{\nu_C+\nu_D-\nu_A-\nu_B}, \quad P^0 = 0.1 \text{ MPa}$$

Temp K	$H_2 \rightleftharpoons 2H$	$O_2 \rightleftharpoons 2O$	$N_2 \rightleftharpoons 2N$	$2H_2O \rightleftharpoons 2H_2 + O_2$	$2H_2O \rightleftharpoons H_2 + 2OH$	$2CO_2 \rightleftharpoons 2CO + O_2$	$N_2 + O_2 \rightleftharpoons 2NO$	$N_2 + 2O_2 \rightleftharpoons 2NO_2$
298	−164.003	−186.963	−367.528	−184.420	−212.075	−207.529	−69.868	−41.355
500	−92.830	−105.623	−213.405	−105.385	−120.331	−115.234	−40.449	−30.725
1000	−39.810	−45.146	−99.146	−46.321	−51.951	−47.052	−18.709	−23.039
1200	−30.878	−35.003	−80.025	−36.363	−40.467	−35.736	−15.082	−21.752
1400	−24.467	−27.741	−66.345	−29.222	−32.244	−27.679	−12.491	−20.826
1600	−19.638	−22.282	−56.069	−23.849	−26.067	−21.656	−10.547	−20.126
1800	−15.868	−18.028	−48.066	−19.658	−21.258	−16.987	−9.035	−19.577
2000	−12.841	−14.619	−41.655	−16.299	−17.406	−13.266	−7.825	−19.136
2200	−10.356	−11.826	−36.404	−13.546	−14.253	−10.232	−6.836	−18.773
2400	−8.280	−9.495	−32.023	−11.249	−11.625	−7.715	−6.012	−18.470
2600	−6.519	−7.520	−28.313	−9.303	−9.402	−5.594	−5.316	−18.214
2800	−5.005	−5.826	−25.129	−7.633	−7.496	−3.781	−4.720	−17.994
3000	−3.690	−4.356	−22.367	−6.184	−5.845	−2.217	−4.205	−17.805
3200	−2.538	−3.069	−19.947	−4.916	−4.401	−0.853	−3.755	−17.640
3400	−1.519	−1.932	−17.810	−3.795	−3.128	0.346	−3.359	−17.496
3600	−0.611	−0.922	−15.909	−2.799	−1.996	1.408	−3.008	−17.369
3800	0.201	−0.017	−14.205	−1.906	−0.984	2.355	−2.694	−17.257
4000	0.934	0.798	−12.671	−1.101	−0.074	3.204	−2.413	−17.157
4500	2.483	2.520	−9.423	0.602	1.847	4.985	−1.824	−16.953
5000	3.724	3.898	−6.816	1.972	3.383	6.397	−1.358	−16.797
5500	4.739	5.027	−4.672	3.098	4.639	7.542	−0.980	−16.678
6000	5.587	5.969	−2.876	4.040	5.684	8.488	−0.671	−16.588

Source: Consistent with thermodynamic data in *JANAF Thermochemical Tables*, third edition, Thermal Group, Dow Chemical U.S.A., Midland, MI, 1985.

Note that y_i in the equation in the table given above represents the *mole* fraction.

SYS= System CV=Control Volume, scs = simple comp subs, sfs=single fluid stream
Processes: REV=Reversible, IRR=Irreversible

Property Relations for any scs: Tds=du-Pdv and Tds =dh-vdP

Property Relations for an Ideal Gas: Pv=RT or PV=mRT dh=c_pdT and du=c_vdT
s_2-s_1=$c_p$ln(T_2\$T_1$) - R ln ($p_2$\$p_1$); s_2-s_1=$c_v$ln(T_2\$T_1$) + R ln ($v_2$\$v_1$)

Isentropic Relations for an Ideal Gas: $\left(\frac{P_2}{P_1}\right) = \left(\frac{v_1}{v_2}\right)^k, \quad \left(\frac{T_2}{T_1}\right) = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

I Law: SYS: $\delta Q = dE + \delta W$

CV: $\dot{Q}_{cv} + \sum \dot{m}_i (h_i + \frac{1}{2}V_i^2 + gZ_i) = dE_{cv}/dt + \sum \dot{m}_e (h_e + \frac{1}{2}V_e^2 + gZ_e) + \dot{W}_{cv}$

II Law: SYS: $dS = \frac{\delta Q}{T} + \delta S_{gen}$

CV: $dS_{cv}/dt + \sum \dot{m}_e s_e - \sum \dot{m}_i s_i \geq \sum_{cv} \frac{\dot{Q}_{cv}}{T}$

THERMODYNAMICS
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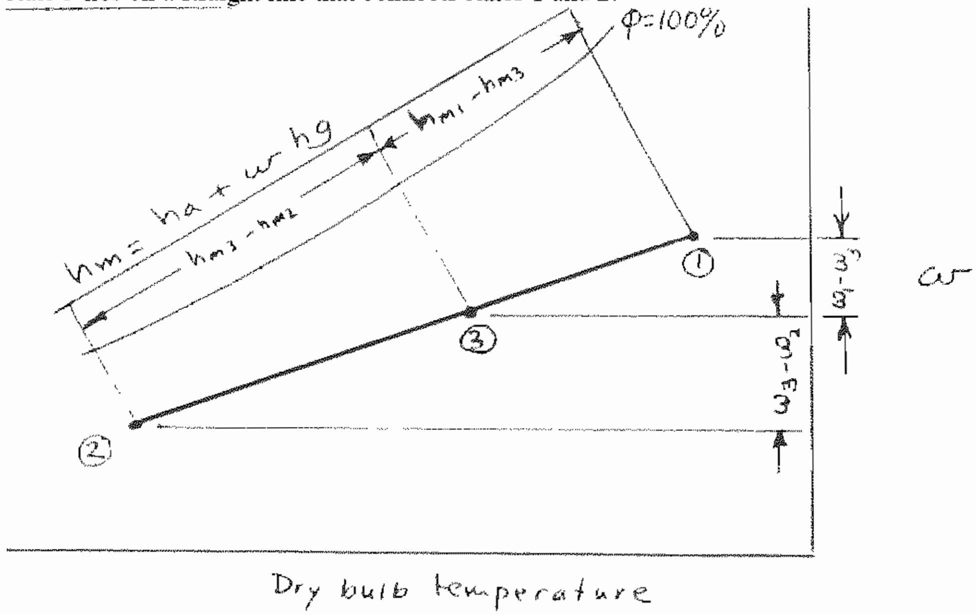
Mechanical Engineering Department, Columbia University

PROBLEM 1.
Two streams of moist air are being mixed adiabatically. Show that on a psychometric chart exit state 3 lies on a straight line that connects states 1 and 2.



PROBLEM 2.
Derive the expression for mass flow rate through a sonic nozzle:

$$\dot{m} = A^* P_o \frac{1}{\sqrt{RT_o}} \left[k \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \right]^{1/2}$$

where A^* is the throat area, P_o and T_0 are upstream stagnation pressure and temperatures and k is the specific heat ratio. Clearly list the assumptions that are made during the derivation. Speed of sound for an ideal gas is $\sqrt{kRT}$.

Isentropic relations for an Ideal Gas: $\left(\frac{P_2}{P_1}\right) = \left(\frac{v_1}{v_2}\right)^k$, $\left(\frac{T_2}{T_1}\right) = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

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PROBLEM 3.

You are given the following data about an actual gasoline engine assumed to operate on an air-standard (use properties of air) cycle. The compression and expansion processes can be idealized as polytropic with n=1.3 and 1.5 respectively. Air enters the engine at absolute temperature T_o degrees K. During compression the temperature rises to $2T_o$. During the constant volume heat addition process, combustion adds enough heat to raise the temperature further to $7T_o$, followed by expansion. After expansion the exhaust gases can be assumed to leave during a constant volume process. We wish to carry out an energy balance of the cycle. Specifically, determine what fraction of the heat supplied

i) ends up as useful work
ii) ends up as heat lost from the walls and
iii) ends up as increase in internal energy of air (and hence goes out the exhaust)

Compare the efficiency of the above cycle to that of an ideal Otto cycle (both the compression and expansion are isentropic) with the compression ratio of the above cycle.

$\eta_{\text{ideal otto}} = 1 - (1/(r^{k-1}))$ where r = compression ratio

PROBLEM 4.

Consider a 10 L piston/cylinder arrangement in a hydraulic press. The cylinder is filled with air initially at 500 kPa, and 200 °C. Removal of the load from the press results in expansion of air in the cylinder, which now occupies 2.5 times larger volume. After the process is finished the air pressure in the cylinder drops to 150 kPa. Calculate the work, assuming that the actual work done is 70 percent of that seen in reversible expansion of the same arrangement. Show whether Clausius inequality is satisfied.

Some useful constants for Air: $R = 0.287$ kJ/kgK; $C_p = 1.004$ kJ/kgK; $C_v = 0.717$ kJ/kgK

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Mechanical Engineering Department, Columbia University
Thermodynamics

Problem 1: Consider the steady operation of three air compressors (assume ideal gas behavior). It is fair to assume that the kinetic and potential energy changes are small. Assume initial state 1 is given by P_1 and v_1 and that the exhaust pressure is P_2 for all three. The type of process for each compressor is different:

i. Reversible polytropic process with polytropic coefficient n
ii. Reversible adiabatic (or isentropic) process with ratio of specific heats, k
iii. Reversible isothermal process

For each case evaluate compressor work per unit mass flow rate, in terms of P_1, v_1, P_2 and n or k where applicable. For a pressure ratio of 10, compare $(w/P_1 v_1)$ for the three cases with n=2 and k=1.4. Which compressor consumes the least work?

Problem 2. A large stationary Brayton cycle gas-turbine power plant delivers a power output of 100 MW to an electric generator. The minimum temperature in the cycle is 300K, and the maximum temperature is 1600K. The minimum pressure in the cycle is 100kPa, with a compressor pressure ratio of 14:1.

a) Calculate the power output of this turbine.
b) In a table, show the temperature (K) and pressure (kPa) for all states within the cycle.
c) What is the mass flow rate entering the compressor?
d) What fraction of the turbine output is used to power the compressor?
e) What is the thermal efficiency of the entire cycle?
f) Under steady-state operation, determine the power in MW for the following separate processes:
    i. Compression
    ii. Combustion
    iii. Expansion

Problem 3

Derive the expression for mass flow rate through a sonic nozzle:

$$\dot{m} = A^{*} P_o \frac{1}{\sqrt{RT_o}} \left[k \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \right]^{1/2}$$

where A^* is the throat area, P_o and T_o are upstream stagnation pressure and temperatures and k is the specific heat ratio. Clearly list the assumptions that are made during the derivation. Speed of sound for an ideal gas is $\sqrt{kRT}$.

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Mechanical Engineering Department, Columbia University
Thermodynamics

Ideal Gas Properties at 300K
Ideal Gas behavior: Either $P< 0.1P_c$ OR ($T > 2T_c$ and $P < 5P_c$)

Gas	Mol Wt	R kJ/kgK	c_p kJ/kgK	c_v kJ/kgK	$c_p/c_v = k$
Air	29	0.287	1.00	0.72	1.4
Steam	18	0.46	1.87	1.41	1.33
Nitrogen	28	0.297	1.04	0.745	1.4

SYS= System CV=Control Volume, scs = simple comp subs, sfs=single fluid stream
Processes: REV=Reversible, IRR=Irreversible

Property Relations for any scs: $Tds=du-Pdv$ and $Tds=dh-vdP$

Property Relations for an Ideal Gas: $Pv=RT$ or $PV=mRT$ $dh=c_pdT$ and $du=c_vdT$
$s_2-s_1=c_p\ln(T_2\backslash T_1) - R\ln(p_2\backslash p_1)$; $s_2-s_1=c_v\ln(T_2\backslash T_1) + R\ln(v_2\backslash v_1)$

Isentropic Relations for an Ideal Gas: $\left(\frac{P_2}{P_1}\right)=\left(\frac{v_1}{v_2}\right)^k$, $\left(\frac{T_2}{T_1}\right)=\left(\frac{v_1}{v_2}\right)^{k-1}=\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

I Law: SYS: $\delta Q = dE + \delta W$

$$\text{CV:}\quad \dot{Q}_{cv} + \sum \dot{m}_i\left(h_i + \frac{1}{2}V_i^2 + gZ_i\right) = dE_{cv}/dt + \sum \dot{m}_e\left(h_e + \frac{1}{2}V_e^2 + gZ_e\right) + \dot{W}_{cv}$$

II Law: SYS: $dS = \frac{\delta Q}{T} + \delta S_{gen}$

$$\text{CV:}\quad dS_{cv}/dt + \sum \dot{m}_e s_e - \sum \dot{m}_i s_i \geq \sum_{cv} \frac{\dot{Q}_{cv}}{T}$$

Work for SSSF REV Process: $w = -\int_i^e vdP + \frac{1}{2}(V_i^2 - V_e^2) + g(Z_i - Z_e)$

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1. One kmol H_2 in a closed vessel, initially at 300K, is heated to a final state of 5 atm and 3500K.
   (a) Determine the mole fraction of atomic hydrogen in the gas.
   (b) If the gas were heated to 5 atm and 5000 K, would the mole fraction of hydrogen atoms increase or decrease compared to your answer in part (a)?
   (c) If the gas were instead pressurized to 10 atm and 3500 K, would the mole fraction of hydrogen atoms increase or decrease compared to your answer in part (a)?

Provide answers for parts (b) and (c) in words – no calculations are necessary.

2. A cold air-standard Brayton cycle has a pressure ratio of 9. Air enters a two-stage compressor at 100 kPa, 300 K. The compressor employs an intercooler at 300 kPa, cooling the air back to 300 K. An 85% effective regenerator preheats the compressed air. The turbine inlet temperature is 1400 K. The net power output from the cycle is 1 MW. Both the turbine and compressor have isentropic efficiencies of 90%. Calculate:
   (a) What is the thermal (first law) efficiency?
   (b) What is the external heat added in MW?
   (c) What is the second law efficiency of the turbine?

Assume specific heats at 298 K in your calculations. Assume an environment at 25°C and 1 atm.

3. Sketch a T-s diagram of an air-standard refrigeration cycle. Clearly mark states at which temperature is the

- ambient-temperature and
- temperature of the refrigerated space.

Assuming that all processes are ideal and working fluid is air,
   (a) derive an expression for Coefficient of Performance (COP) as a function of the ambient temperature and the maximum temperature in the cycle. State all assumptions.
   (b) If in the air-standard refrigeration cycle air enters the compressor at *P=200 KPa* and *T=300K*, and if the compression ratio is 5:1, find the highest cycle temperature.

	Critical Point Data	**Triple Point Data**
Water:	374.14 **C**, 22.09 MPa, 0.00316 m^3/kg	0.01 C, 0.6113 kPa
Nitrogen:	126.2 K, 3.39 MPa, 0.00321 m^3/kg	-210 C, 12.53 kPa

Ideal Gas Properties at 300K. Ideal Gas behavior: Either $P< 0.1P_c$ OR ($T > 2T_c$ and $P < 5P_c$)

Gas	Mol Wt	R kJ/kgK	c_p kJ/kgK	c_v kJ/kgK	$c_p/c_v = k$
Air	29	0.287	1.00	0.72	1.4
Steam	18	0.46	1.87	1.41	1.33
Nitrogen	28	0.297	1.04	0.745	1.4

Properties of Selected **Solids and Liquids**

Substance	Spec Heat kJ/kgK	ρ kg/m^3	v m^3/kg
Liquid Water 25C	4.18	997	0.001003
Ice at 0 C	2.04	917	0.001087
Copper	0.42	8300	

scs = simple comp subs, REV=Reversible IRR=Irreversible, sfs=single fluid stream

SYS, scs, REV: $\delta W = \int PdV$.

For $Pv^n = const$: $\int PdV = \frac{1}{1-n}(P_2V_2 - P_1V_1)$ *for* $n \neq 1$ *and* $P_1V_1 \ln\frac{V_2}{V_1}$ *for* $n = 1$

Property Relations for any scs: $Tds=du+Pdv$ *and* $Tds=dh-vdP$

Property Relations for an Ideal Gas: $Pv=RT$ *or* $PV=mRT$ $dh=c_p dT$ *and* $du=c_v dT$

For constant c_p, c_v : $s_2-s_1=c_p ln(T_2\backslash T_1) - R\ ln\ (p_2\backslash p_1)$; $s_2-s_1=c_v ln(T_2\backslash T_1) + R\ ln\ (v_2\backslash v_1)$

If $Pv^k = const$ for an Ideal Gas: $\left(\frac{P_2}{P_1}\right) = \left(\frac{v_1}{v_2}\right)^k$, $\left(\frac{T_2}{T_1}\right) = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

I Law: SYS: $\delta Q = dE + \delta W$ *where* $E = U + (1/2)mV_i^2 + mgZ_i$

CV: $\dot{Q}_{cv} + \sum \dot{m}_i(h_i + \frac{1}{2}V_i^2 + gZ_i) = dE_{cv}/dt + \sum \dot{m}_e(h_e + \frac{1}{2}V_e^2 + gZ_e) + \dot{W}_{cv}$

SSSF+sfs: $q + h_i + \frac{1}{2}V_i^2 + gZ_i = h_e + \frac{1}{2}V_e^2 + gZ_e + w$

II Law: SYS: $dS = \frac{\delta Q}{T} + \delta S_{gen}$ CV: $dS_{cv}/dt + \sum \dot{m}_e s_e - \sum \dot{m}_i s_i \geq \sum_{cv} \frac{\dot{Q}_{cv}}{T}$

Work for SSSF REV Process: $w = -\int_i^e vdP + \frac{1}{2}(V_i^2 - V_e^2) + g(Z_i - Z_e)$

For $Pv^n = const$: $-\int_i^e vdP = -\frac{n}{n-1}(P_e v_e - P_i v_i)$ *for* $n \neq 1$ *and* $-P_i v_i \ln\frac{P_e}{P_i}$ *for* $n = 1$

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Table A.3 Hydrogen (H_2), *MW* = 2.016, enthalpy of formation @ 298 K (kJ/kmol) = 0

T(K)	$\bar{c}_p$ (kJ/kmol-K)	$(\bar{h}^o(T)-\bar{h}^o_f(298))$ (kJ/kmol)	$\bar{h}^o_f(T)$ (kJ/kmol)	$\bar{s}^o(T)$ (kJ/kmol-K)	$\bar{g}^o_f(T)$ (kJ/kmol)
200	28.522	−2,818	0	119.137	0
298	28.871	0	0	130.595	0
300	28.877	53	0	130.773	0
400	29.120	2,954	0	139.116	0
500	29.275	5,874	0	145.632	0
600	29.375	8,807	0	150.979	0
700	29.461	11,749	0	155.514	0
800	29.581	14,701	0	159.455	0
900	29.792	17,668	0	162.950	0
1000	30.160	20,664	0	166.106	0
1100	30.625	23,704	0	169.003	0
1200	31.077	26,789	0	171.687	0
1300	31.516	29,919	0	174.192	0
1400	31.943	33,092	0	176.543	0
1500	32.356	36,307	0	178.761	0
1600	32.758	39,562	0	180.862	0
1700	33.146	42,858	0	182.860	0
1800	33.522	46,191	0	184.765	0
1900	33.885	49,562	0	186.587	0
2000	34.236	52,968	0	188.334	0
2100	34.575	56,408	0	190.013	0
2200	34.901	59.882	0	191.629	0
2300	35.216	63,388	0	193.187	0
2400	35.519	66,925	0	194.692	0
2500	35.811	70.492	0	196.148	0
2600	36.091	74,087	0	197.558	0
2700	36.361	77,710	0	198.926	0
2800	36.621	81,359	0	200.253	0
2900	36.871	85,033	0	201.542	0
3000	37.112	88.733	0	202.796	0
3100	37.343	92,455	0	204.017	0
3200	37.566	96,201	0	205.206	0
3300	37.781	99,968	0	206.365	0
3400	37.989	103.757	0	207.496	0
3500	38.190	107,566	0	208.600	0
3600	38.385	111,395	0	209.679	0
3700	38.574	115.243	0	210.733	0
3800	38.759	119,109	0	211.764	0
3900	38.939	122,994	0	212.774	0
4000	39.116	126,897	0	213.762	0
4100	39.291	130,817	0	214.730	0
4200	39.464	134,755	0	215.679	0
4300	39.636	138,710	0	216.609	0
4400	39.808	142,682	0	217.522	0
4500	39.981	146,672	0	218.419	0
4600	40.156	150,679	0	219.300	0
4700	40.334	154,703	0	220.165	0
4800	40.516	158,746	0	221.016	0
4900	40.702	162,806	0	221.853	0
5000	40.895	166,886	0	222.678	0

Table A.4 Hydrogen atom (H), $MW = 1.008$, enthalpy of formation @ 298 K (kJ/kmol) = 217,977

T(K)	$\bar{c}_p$ (kJ/kmol-K)	$(\bar{h}^o(T)-\bar{h}^o_f(298))$ (kJ/kmol)	$\bar{h}^o_f(T)$ (kJ/kmol)	$\bar{s}^o(T)$ (kJ/kmol-K)	$\bar{g}^o_f(T)$ (kJ/kmol)
200	20.786	–2,040	217,346	106.305	207,999
298	20.786	0	217,977	114.605	203,276
300	20.786	38	217,989	114.733	203,185
400	20.786	2,117	218,617	120.713	198,155
500	20.786	4,196	219,236	125.351	192,968
600	20.786	6,274	219,848	129.351	187,657
700	20.786	8,353	220,456	132.345	182,244
800	20.786	10,431	221,059	135.121	176,744
900	20.786	12,510	221.653	137.569	171,169
1000	20.786	14,589	222,234	139.759	165,528
1100	20.786	16,667	222,793	141.740	159,830
1200	20.786	18,746	223,329	143.549	154,082
1300	20.786	20,824	223,843	145.213	148,291
1400	20.786	22,903	224,335	146.753	142,461
1500	20.786	24,982	224,806	148.187	136.596
1600	20.786	27,060	225.256	149.528	130,700
1700	20.786	29,139	225,687	150.789	124,777
1800	20.786	31,217	226,099	151.977	118,830
1900	20.786	33,296	226,493	153.101	112,859
2000	20.786	35,375	226,868	154.167	106,869
2100	20.786	37,453	227,226	155.181	100,860
2200	20.786	39,532	227,568	156.148	94,834
2300	20.786	41,610	227,894	157.072	88,794
2400	20.786	43,689	228,204	157.956	82,739
2500	20.786	45,768	228,499	158.805	76,672
2600	20.786	47,846	228,780	159.620	70.593
2700	20.786	49,925	229,047	160.405	64,504
2800	20.786	52,003	229,301	161.161	58,405
2900	20.786	54,082	229,543	161.890	52,298
3000	20.786	56,161	229,772	162.595	46,182
3100	20.786	58,239	229,989	163.276	40,058
3200	20.786	60,318	230,195	163.936	33,928
3300	20.786	62,396	230,390	164.576	27,792
3400	20.786	64,475	230,574	165.196	21,650
3500	20.786	66,554	230,748	165.799	15,502
3600	20.786	68,632	230,912	166.384	9,350
3700	20.786	70,711	231,067	166.954	3,194
3800	20.786	72,789	231,212	167.508	–2,967
3900	20.786	74,868	231,348	168.048	–9,132
4000	20.786	76,947	231,475	168.575	–15,299
4100	20.786	79,025	231,594	169.088	–21,470
4200	20.786	81.104	231,704	169.589	–27,644
4300	20.786	83,182	231,805	170.078	–33,820
4400	20.786	85,261	231,897	170.556	–39,998
4500	20.786	87,340	231,981	171.023	–46,179
4600	20.786	89,418	232,056	171.480	–52,361
4700	20.786	91,497	232,123	171.927	–58,545
4800	20.786	93,575	232,180	172.364	–64,730
4900	20.786	95,654	232,228	172.793	–70,916
5000	20.786	97,733	232.267	173.213	–77,103

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PROBLEM 1

A piston cylinder assembly contains water at 1000 kPa and 250°C. In an isothermal process, the water is slowly brought to saturated vapor.

(a) Show the process in a T-s diagram
(b) Calculate the heat transfer
(c) Find the specific work

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PROBLEM 2

A steady-flow compressor is used to compress air flowing at the rate of 2 kg/s to an exit pressure of 350 kPa. The compressor requires a power input of 800 kW. Heat losses to the environment are estimated to be 10 percent of the magnitude of the power input. The air enters the compressor at room temperature (27°C) and 100 kPa.

(a) Determine the temperature of the air at the exit of the compressor
(b) Calculate the efficiency of the compressor.

Assuming that the inlet and exit conditions are unchanged but that the compressor is well insulated to eliminate the heat transfer losses. Is the magnitude of the power input for the adiabatic compressor higher, lower or the same as for that of the actual compressor?

(c) Would the magnitude of the power input for the adiabatic compressor be higher, lower or the same as that for the actual compressor?
(d) And what about the efficiency? Would it be higher, lower or the same as the efficiency of the actual compressor found in part (b)?

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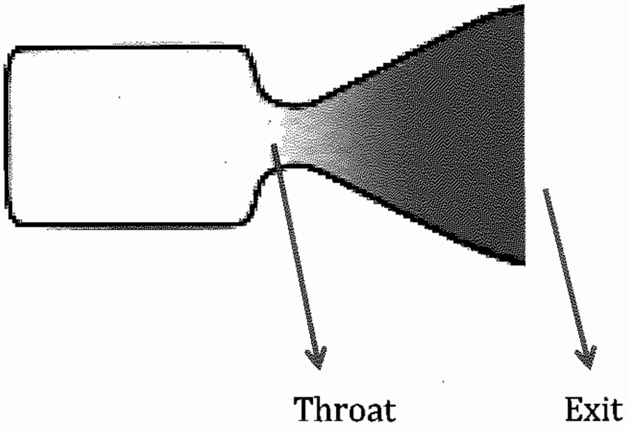
PROBLEM 3

Consider a liquid rocket engine with a convergent-divergent shape nozzle (see figure below). Liquid hydrogen and oxygen are burned in the combustion chamber producing a combustion gas pressure and temperature of 30 atm and 3500 K, respectively. The nozzle throat area is 0.4 m^2. The area of the nozzle exit is designed so that the exit pressure exactly equals the ambient atmospheric pressure which is equal to 5.53 kN/m^2 at an altitude of 20 km. Assuming an isentropic flow through the rocket nozzle with an effective value of the ratio of specific heats $\gamma = 1.22$, and a constant value of the specific gas constant $R = 520$ J/(kg.K), calculate:

(a) The exit Mach number,
(b) The exit velocity,
(c) The area of the nozzle exit,
(d) The thrust of the rocket engine.



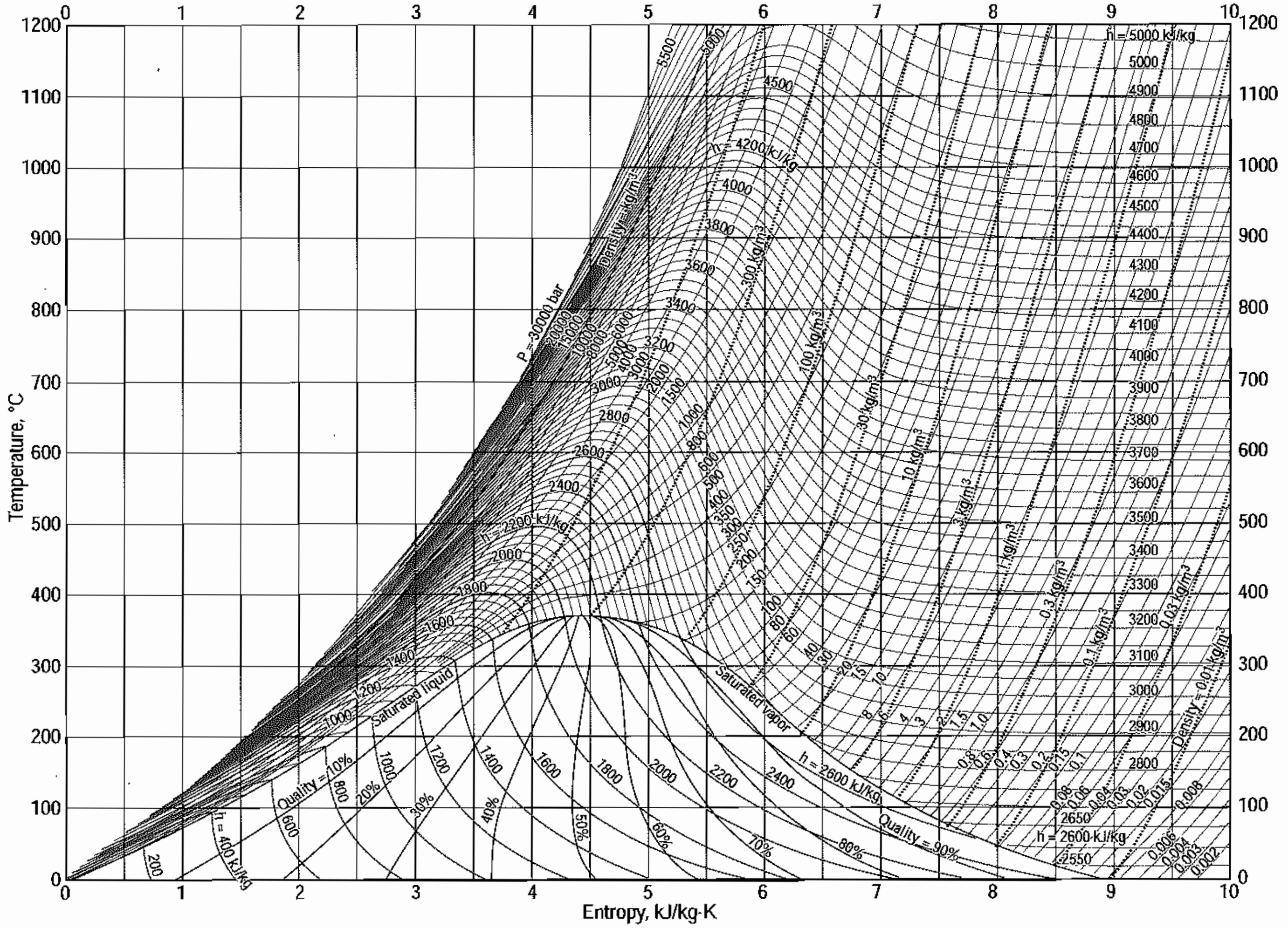


FIGURE A–9

T-s diagram for water.

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TABLE A–4

Saturated water—Temperature table

		Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6720	419.06	2087.0	2506.0	419.17	2256.4	2675.6	1.3072	6.0470	7.3542
105	120.90	0.001047	1.4186	440.15	2071.8	2511.9	440.28	2243.1	2683.4	1.3634	5.9319	7.2952
110	143.38	0.001052	1.2094	461.27	2056.4	2517.7	461.42	2229.7	2691.1	1.4188	5.8193	7.2382
115	169.18	0.001056	1.0360	482.42	2040.9	2523.3	482.59	2216.0	2698.6	1.4737	5.7092	7.1829
120	198.67	0.001060	0.89133	503.60	2025.3	2528.9	503.81	2202.1	2706.0	1.5279	5.6013	7.1292
125	232.23	0.001065	0.77012	524.83	2009.5	2534.3	525.07	2188.1	2713.1	1.5816	5.4956	7.0771
130	270.28	0.001070	0.66808	546.10	1993.4	2539.5	546.38	2173.7	2720.1	1.6346	5.3919	7.0265
135	313.22	0.001075	0.58179	567.41	1977.3	2544.7	567.75	2159.1	2726.9	1.6872	5.2901	6.9773
140	361.53	0.001080	0.50850	588.77	1960.9	2549.6	589.16	2144.3	2733.5	1.7392	5.1901	6.9294
145	415.68	0.001085	0.44600	610.19	1944.2	2554.4	610.64	2129.2	2739.8	1.7908	5.0919	6.8827
150	476.16	0.001091	0.39248	631.66	1927.4	2559.1	632.18	2113.8	2745.9	1.8418	4.9953	6.8371
155	543.49	0.001096	0.34648	653.19	1910.3	2563.5	653.79	2098.0	2751.8	1.8924	4.9002	6.7927
160	618.23	0.001102	0.30680	674.79	1893.0	2567.8	675.47	2082.0	2757.5	1.9426	4.8066	6.7492
165	700.93	0.001108	0.27244	696.46	1875.4	2571.9	697.24	2065.6	2762.8	1.9923	4.7143	6.7067
170	792.18	0.001114	0.24260	718.20	1857.5	2575.7	719.08	2048.8	2767.9	2.0417	4.6233	6.6650
175	892.60	0.001121	0.21659	740.02	1839.4	2579.4	741.02	2031.7	2772.7	2.0906	4.5335	6.6242
180	1002.8	0.001127	0.19384	761.92	1820.9	2582.8	763.05	2014.2	2777.2	2.1392	4.4448	6.5841
185	1123.5	0.001134	0.17390	783.91	1802.1	2586.0	785.19	1996.2	2781.4	2.1875	4.3572	6.5447
190	1255.2	0.001141	0.15636	806.00	1783.0	2589.0	807.43	1977.9	2785.3	2.2355	4.2705	6.5059
195	1398.8	0.001149	0.14089	828.18	1763.6	2591.7	829.78	1959.0	2788.8	2.2831	4.1847	6.4678
200	1554.9	0.001157	0.12721	850.46	1743.7	2594.2	852.26	1939.8	2792.0	2.3305	4.0997	6.4302

TABLE A–4

Saturated water—Temperature table (*Concluded*)

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
205	1724.3	0.001164	0.11508	872.86	1723.5	2596.4	874.87	1920.0	2794.8	2.3776	4.0154	6.3930
210	1907.7	0.001173	0.10429	895.38	1702.9	2598.3	897.61	1899.7	2797.3	2.4245	3.9318	6.3563
215	2105.9	0.001181	0.094680	918.02	1681.9	2599.9	920.50	1878.8	2799.3	2.4712	3.8489	6.3200
220	2319.6	0.001190	0.086094	940.79	1660.5	2601.3	943.55	1857.4	2801.0	2.5176	3.7664	6.2840
225	2549.7	0.001199	0.078405	963.70	1638.6	2602.3	966.76	1835.4	2802.2	2.5639	3.6844	6.2483
230	2797.1	0.001209	0.071505	986.76	1616.1	2602.9	990.14	1812.8	2802.9	2.6100	3.6028	6.2128
235	3062.6	0.001219	0.065300	1010.0	1593.2	2603.2	1013.7	1789.5	2803.2	2.6560	3.5216	6.1775
240	3347.0	0.001229	0.059707	1033.4	1569.8	2603.1	1037.5	1765.5	2803.0	2.7018	3.4405	6.1424
245	3651.2	0.001240	0.054656	1056.9	1545.7	2602.7	1061.5	1740.8	2802.2	2.7476	3.3596	6.1072
250	3976.2	0.001252	0.050085	1080.7	1521.1	2601.8	1085.7	1715.3	2801.0	2.7933	3.2788	6.0721
255	4322.9	0.001263	0.045941	1104.7	1495.8	2600.5	1110.1	1689.0	2799.1	2.8390	3.1979	6.0369
260	4692.3	0.001276	0.042175	1128.8	1469.9	2598.7	1134.8	1661.8	2796.6	2.8847	3.1169	6.0017
265	5085.3	0.001289	0.038748	1153.3	1443.2	2596.5	1159.8	1633.7	2793.5	2.9304	3.0358	5.9662
270	5503.0	0.001303	0.035622	1177.9	1415.7	2593.7	1185.1	1604.6	2789.7	2.9762	2.9542	5.9305
275	5946.4	0.001317	0.032767	1202.9	1387.4	2590.3	1210.7	1574.5	2785.2	3.0221	2.8723	5.8944
280	6416.6	0.001333	0.030153	1228.2	1358.2	2586.4	1236.7	1543.2	2779.9	3.0681	2.7898	5.8579
285	6914.6	0.001349	0.027756	1253.7	1328.1	2581.8	1263.1	1510.7	2773.7	3.1144	2.7066	5.8210
290	7441.8	0.001366	0.025554	1279.7	1296.9	2576.5	1289.8	1476.9	2766.7	3.1608	2.6225	5.7834
295	7999.0	0.001384	0.023528	1306.0	1264.5	2570.5	1317.1	1441.6	2758.7	3.2076	2.5374	5.7450
300	8587.9	0.001404	0.021659	1332.7	1230.9	2563.6	1344.8	1404.8	2749.6	3.2548	2.4511	5.7059
305	9209.4	0.001425	0.019932	1360.0	1195.9	2555.8	1373.1	1366.3	2739.4	3.3024	2.3633	5.6657
310	9865.0	0.001447	0.018333	1387.7	1159.3	2547.1	1402.0	1325.9	2727.9	3.3506	2.2737	5.6243
315	10,556	0.001472	0.016849	1416.1	1121.1	2537.2	1431.6	1283.4	2715.0	3.3994	2.1821	5.5816
320	11,284	0.001499	0.015470	1445.1	1080.9	2526.0	1462.0	1238.5	2700.6	3.4491	2.0881	5.5372
325	12,051	0.001528	0.014183	1475.0	1038.5	2513.4	1493.4	1191.0	2684.3	3.4998	1.9911	5.4908
330	12,858	0.001560	0.012979	1505.7	993.5	2499.2	1525.8	1140.3	2666.0	3.5516	1.8906	5.4422
335	13,707	0.001597	0.011848	1537.5	945.5	2483.0	1559.4	1086.0	2645.4	3.6050	1.7857	5.3907
340	14,601	0.001638	0.010783	1570.7	893.8	2464.5	1594.6	1027.4	2622.0	3.6602	1.6756	5.3358
345	15,541	0.001685	0.009772	1605.5	837.7	2443.2	1631.7	963.4	2595.1	3.7179	1.5585	5.2765
350	16,529	0.001741	0.008806	1642.4	775.9	2418.3	1671.2	892.7	2563.9	3.7788	1.4326	5.2114
355	17,570	0.001808	0.007872	1682.2	706.4	2388.6	1714.0	812.9	2526.9	3.8442	1.2942	5.1384
360	18,666	0.001895	0.006950	1726.2	625.7	2351.9	1761.5	720.1	2481.6	3.9165	1.1373	5.0537
365	19,822	0.002015	0.006009	1777.2	526.4	2303.6	1817.2	605.5	2422.7	4.0004	0.9489	4.9493
370	21,044	0.002217	0.004953	1844.5	385.6	2230.1	1891.2	443.1	2334.3	4.1119	0.6890	4.8009
373.95	22,064	0.003106	0.003106	2015.7	0	2015.7	2084.3	0	2084.3	4.4070	0	4.4070

Source: Tables A–4 through A–8 are generated using the Engineering Equation Solver (EES) software developed by S. A. Klein and F. L. Alvarado. The routine used in calculations is the highly accurate Steam_IAPWS, which incorporates the 1995 Formulation for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use, issued by The International Association for the Properties of Water and Steam (IAPWS). This formulation replaces the 1984 formulation of Haar, Gallagher, and Kell (NBS/NRC Steam Tables, Hemisphere Publishing Co., 1984), which is also available in EES as the routine STEAM. The new formulation is based on the correlations of Saul and Wagner (J. Phys. Chem. Ref. Data, 16, 893, 1987) with modifications to adjust to the International Temperature Scale of 1990. The modifications are described by Wagner and Pruss (J. Phys. Chem. Ref. Data, 22, 783, 1993). The properties of ice are based on Hyland and Wexler, "Formulations for the Thermodynamic Properties of the Saturated Phases of H_2O from 173.15 K to 473.15 K," *ASHRAE Trans.*, Part 2A, Paper 2793, 1983.

TABLE A–5

Saturated water—Pressure table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4	1.2132	6.2426	7.4558
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0	1.3028	6.0562	7.3589
101.325	99.97	0.001043	1.6734	418.95	2087.0	2506.0	419.06	2256.5	2675.6	1.3069	6.0476	7.3545
125	105.97	0.001048	1.3750	444.23	2068.8	2513.0	444.36	2240.6	2684.9	1.3741	5.9100	7.2841
150	111.35	0.001053	1.1594	466.97	2052.3	2519.2	467.13	2226.0	2693.1	1.4337	5.7894	7.2231
175	116.04	0.001057	1.0037	486.82	2037.7	2524.5	487.01	2213.1	2700.2	1.4850	5.6865	7.1716
200	120.21	0.001061	0.88578	504.50	2024.6	2529.1	504.71	2201.6	2706.3	1.5302	5.5968	7.1270
225	123.97	0.001064	0.79329	520.47	2012.7	2533.2	520.71	2191.0	2711.7	1.5706	5.5171	7.0877
250	127.41	0.001067	0.71873	535.08	2001.8	2536.8	535.35	2181.2	2716.5	1.6072	5.4453	7.0525
275	130.58	0.001070	0.65732	548.57	1991.6	2540.1	548.86	2172.0	2720.9	1.6408	5.3800	7.0207
300	133.52	0.001073	0.60582	561.11	1982.1	2543.2	561.43	2163.5	2724.9	1.6717	5.3200	6.9917
325	136.27	0.001076	0.56199	572.84	1973.1	2545.9	573.19	2155.4	2728.6	1.7005	5.2645	6.9650
350	138.86	0.001079	0.52422	583.89	1964.6	2548.5	584.26	2147.7	2732.0	1.7274	5.2128	6.9402
375	141.30	0.001081	0.49133	594.32	1956.6	2550.9	594.73	2140.4	2735.1	1.7526	5.1645	6.9171
400	143.61	0.001084	0.46242	604.22	1948.9	2553.1	604.66	2133.4	2738.1	1.7765	5.1191	6.8955
450	147.90	0.001088	0.41392	622.65	1934.5	2557.1	623.14	2120.3	2743.4	1.8205	5.0356	6.8561
500	151.83	0.001093	0.37483	639.54	1921.2	2560.7	640.09	2108.0	2748.1	1.8604	4.9603	6.8207
550	155.46	0.001097	0.34261	655.16	1908.8	2563.9	655.77	2096.6	2752.4	1.8970	4.8916	6.7886
600	158.83	0.001101	0.31560	669.72	1897.1	2566.8	670.38	2085.8	2756.2	1.9308	4.8285	6.7593
650	161.98	0.001104	0.29260	683.37	1886.1	2569.4	684.08	2075.5	2759.6	1.9623	4.7699	6.7322
700	164.95	0.001108	0.27278	696.23	1875.6	2571.8	697.00	2065.8	2762.8	1.9918	4.7153	6.7071
750	167.75	0.001111	0.25552	708.40	1865.6	2574.0	709.24	2056.4	2765.7	2.0195	4.6642	6.6837

TABLE A–5

Saturated water—Pressure table (*Concluded*)

		Specific volume, m³/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			*Entropy,* kJ/kg·K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
800	170.41	0.001115	0.24035	719.97	1856.1	2576.0	720.87	2047.5	2768.3	2.0457	4.6160	6.6616
850	172.94	0.001118	0.22690	731.00	1846.9	2577.9	731.95	2038.8	2770.8	2.0705	4.5705	6.6409
900	175.35	0.001121	0.21489	741.55	1838.1	2579.6	742.56	2030.5	2773.0	2.0941	4.5273	6.6213
950	177.66	0.001124	0.20411	751.67	1829.6	2581.3	752.74	2022.4	2775.2	2.1166	4.4862	6.6027
1000	179.88	0.001127	0.19436	761.39	1821.4	2582.8	762.51	2014.6	2777.1	2.1381	4.4470	6.5850
1100	184.06	0.001133	0.17745	779.78	1805.7	2585.5	781.03	1999.6	2780.7	2.1785	4.3735	6.5520
1200	187.96	0.001138	0.16326	796.96	1790.9	2587.8	798.33	1985.4	2783.8	2.2159	4.3058	6.5217
1300	191.60	0.001144	0.15119	813.10	1776.8	2589.9	814.59	1971.9	2786.5	2.2508	4.2428	6.4936
1400	195.04	0.001149	0.14078	828.35	1763.4	2591.8	829.96	1958.9	2788.9	2.2835	4.1840	6.4675
1500	198.29	0.001154	0.13171	842.82	1750.6	2593.4	844.55	1946.4	2791.0	2.3143	4.1287	6.4430
1750	205.72	0.001166	0.11344	876.12	1720.6	2596.7	878.16	1917.1	2795.2	2.3844	4.0033	6.3877
2000	212.38	0.001177	0.099587	906.12	1693.0	2599.1	908.47	1889.8	2798.3	2.4467	3.8923	6.3390
2250	218.41	0.001187	0.088717	933.54	1667.3	2600.9	936.21	1864.3	2800.5	2.5029	3.7926	6.2954
2500	223.95	0.001197	0.079952	958.87	1643.2	2602.1	961.87	1840.1	2801.9	2.5542	3.7016	6.2558
3000	233.85	0.001217	0.066667	1004.6	1598.5	2603.2	1008.3	1794.9	2803.2	2.6454	3.5402	6.1856
3500	242.56	0.001235	0.057061	1045.4	1557.6	2603.0	1049.7	1753.0	2802.7	2.7253	3.3991	6.1244
4000	250.35	0.001252	0.049779	1082.4	1519.3	2601.7	1087.4	1713.5	2800.8	2.7966	3.2731	6.0696
5000	263.94	0.001286	0.039448	1148.1	1448.9	2597.0	1154.5	1639.7	2794.2	2.9207	3.0530	5.9737
6000	275.59	0.001319	0.032449	1205.8	1384.1	2589.9	1213.8	1570.9	2784.6	3.0275	2.8627	5.8902
7000	285.83	0.001352	0.027378	1258.0	1323.0	2581.0	1267.5	1505.2	2772.6	3.1220	2.6927	5.8148
8000	295.01	0.001384	0.023525	1306.0	1264.5	2570.5	1317.1	1441.6	2758.7	3.2077	2.5373	5.7450
9000	303.35	0.001418	0.020489	1350.9	1207.6	2558.5	1363.7	1379.3	2742.9	3.2866	2.3925	5.6791
10,000	311.00	0.001452	0.018028	1393.3	1151.8	2545.2	1407.8	1317.6	2725.5	3.3603	2.2556	5.6159
11,000	318.08	0.001488	0.015988	1433.9	1096.6	2530.4	1450.2	1256.1	2706.3	3.4299	2.1245	5.5544
12,000	324.68	0.001526	0.014264	1473.0	1041.3	2514.3	1491.3	1194.1	2685.4	3.4964	1.9975	5.4939
13,000	330.85	0.001566	0.012781	1511.0	985.5	2496.6	1531.4	1131.3	2662.7	3.5606	1.8730	5.4336
14,000	336.67	0.001610	0.011487	1548.4	928.7	2477.1	1571.0	1067.0	2637.9	3.6232	1.7497	5.3728
15,000	342.16	0.001657	0.010341	1585.5	870.3	2455.7	1610.3	1000.5	2610.8	3.6848	1.6261	5.3108
16,000	347.36	0.001710	0.009312	1622.6	809.4	2432.0	1649.9	931.1	2581.0	3.7461	1.5005	5.2466
17,000	352.29	0.001770	0.008374	1660.2	745.1	2405.4	1690.3	857.4	2547.7	3.8082	1.3709	5.1791
18,000	356.99	0.001840	0.007504	1699.1	675.9	2375.0	1732.2	777.8	2510.0	3.8720	1.2343	5.1064
19,000	361.47	0.001926	0.006677	1740.3	598.9	2339.2	1776.8	689.2	2466.0	3.9396	1.0860	5.0256
20,000	365.75	0.002038	0.005862	1785.8	509.0	2294.8	1826.6	585.5	2412.1	4.0146	0.9164	4.9310
21,000	369.83	0.002207	0.004994	1841.6	391.9	2233.5	1888.0	450.4	2338.4	4.1071	0.7005	4.8076
22,000	373.71	0.002703	0.003644	1951.7	140.8	2092.4	2011.1	161.5	2172.6	4.2942	0.2496	4.5439
22,064	373.95	0.003106	0.003106	2015.7	0	2015.7	2084.3	0	2084.3	4.4070	0	4.4070

TABLE A–6

Superheated water

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P 0.01 MPa (45.81°C)*				*P* 0.05 MPa (81.32°C)				*P* 0.10 MPa (99.61°C)			
Sat.†	14.670	2437.2	2583.9	8.1488	3.2403	2483.2	2645.2	7.5931	1.6941	2505.6	2675.0	7.3589
50	14.867	2443.3	2592.0	8.1741								
100	17.196	2515.5	2687.5	8.4489	3.4187	2511.5	2682.4	7.6953	1.6959	2506.2	2675.8	7.3611
150	19.513	2587.9	2783.0	8.6893	3.8897	2585.7	2780.2	7.9413	1.9367	2582.9	2776.6	7.6148
200	21.826	2661.4	2879.6	8.9049	4.3562	2660.0	2877.8	8.1592	2.1724	2658.2	2875.5	7.8356
250	24.136	2736.1	2977.5	9.1015	4.8206	2735.1	2976.2	8.3568	2.4062	2733.9	2974.5	8.0346
300	26.446	2812.3	3076.7	9.2827	5.2841	2811.6	3075.8	8.5387	2.6389	2810.7	3074.5	8.2172
400	31.063	2969.3	3280.0	9.6094	6.2094	2968.9	3279.3	8.8659	3.1027	2968.3	3278.6	8.5452
500	35.680	3132.9	3489.7	9.8998	7.1338	3132.6	3489.3	9.1566	3.5655	3132.2	3488.7	8.8362
600	40.296	3303.3	3706.3	10.1631	8.0577	3303.1	3706.0	9.4201	4.0279	3302.8	3705.6	9.0999
700	44.911	3480.8	3929.9	10.4056	8.9813	3480.6	3929.7	9.6626	4.4900	3480.4	3929.4	9.3424
800	49.527	3665.4	4160.6	10.6312	9.9047	3665.2	4160.4	9.8883	4.9519	3665.0	4160.2	9.5682
900	54.143	3856.9	4398.3	10.8429	10.8280	3856.8	4398.2	10.1000	5.4137	3856.7	4398.0	9.7800
1000	58.758	4055.3	4642.8	11.0429	11.7513	4055.2	4642.7	10.3000	5.8755	4055.0	4642.6	9.9800
1100	63.373	4260.0	4893.8	11.2326	12.6745	4259.9	4893.7	10.4897	6.3372	4259.8	4893.6	10.1698
1200	67.989	4470.9	5150.8	11.4132	13.5977	4470.8	5150.7	10.6704	6.7988	4470.7	5150.6	10.3504
1300	72.604	4687.4	5413.4	11.5857	14.5209	4687.3	5413.3	10.8429	7.2605	4687.2	5413.3	10.5229
	P 0.20 MPa (120.21°C)				*P* 0.30 MPa (133.52°C)				*P* 0.40 MPa (143.61°C)			
Sat.	0.88578	2529.1	2706.3	7.1270	0.60582	2543.2	2724.9	6.9917	0.46242	2553.1	2738.1	6.8955
150	0.95986	2577.1	2769.1	7.2810	0.63402	2571.0	2761.2	7.0792	0.47088	2564.4	2752.8	6.9306
200	1.08049	2654.6	2870.7	7.5081	0.71643	2651.0	2865.9	7.3132	0.53434	2647.2	2860.9	7.1723
250	1.19890	2731.4	2971.2	7.7100	0.79645	2728.9	2967.9	7.5180	0.59520	2726.4	2964.5	7.3804
300	1.31623	2808.8	3072.1	7.8941	0.87535	2807.0	3069.6	7.7037	0.65489	2805.1	3067.1	7.5677
400	1.54934	2967.2	3277.0	8.2236	1.03155	2966.0	3275.5	8.0347	0.77265	2964.9	3273.9	7.9003
500	1.78142	3131.4	3487.7	8.5153	1.18672	3130.6	3486.6	8.3271	0.88936	3129.8	3485.5	8.1933
600	2.01302	3302.2	3704.8	8.7793	1.34139	3301.6	3704.0	8.5915	1.00558	3301.0	3703.3	8.4580
700	2.24434	3479.9	3928.8	9.0221	1.49580	3479.5	3928.2	8.8345	1.12152	3479.0	3927.6	8.7012
800	2.47550	3664.7	4159.8	9.2479	1.65004	3664.3	4159.3	9.0605	1.23730	3663.9	4158.9	8.9274
900	2.70656	3856.3	4397.7	9.4598	1.80417	3856.0	4397.3	9.2725	1.35298	3855.7	4396.9	9.1394
1000	2.93755	4054.8	4642.3	9.6599	1.95824	4054.5	4642.0	9.4726	1.46859	4054.3	4641.7	9.3396
1100	3.16848	4259.6	4893.3	9.8497	2.11226	4259.4	4893.1	9.6624	1.58414	4259.2	4892.9	9.5295
1200	3.39938	4470.5	5150.4	10.0304	2.26624	4470.3	5150.2	9.8431	1.69966	4470.2	5150.0	9.7102
1300	3.63026	4687.1	5413.1	10.2029	2.42019	4686.9	5413.0	10.0157	1.81516	4686.7	5412.8	9.8828
	P 0.50 MPa (151.83°C)				*P* 0.60 MPa (158.83°C)				*P* 0.80 MPa (170.41°C)			
Sat.	0.37483	2560.7	2748.1	6.8207	0.31560	2566.8	2756.2	6.7593	0.24035	2576.0	2768.3	6.6616
200	0.42503	2643.3	2855.8	7.0610	0.35212	2639.4	2850.6	6.9683	0.26088	2631.1	2839.8	6.8177
250	0.47443	2723.8	2961.0	7.2725	0.39390	2721.2	2957.6	7.1833	0.29321	2715.9	2950.4	7.0402
300	0.52261	2803.3	3064.6	7.4614	0.43442	2801.4	3062.0	7.3740	0.32416	2797.5	3056.9	7.2345
350	0.57015	2883.0	3168.1	7.6346	0.47428	2881.6	3166.1	7.5481	0.35442	2878.6	3162.2	7.4107
400	0.61731	2963.7	3272.4	7.7956	0.51374	2962.5	3270.8	7.7097	0.38429	2960.2	3267.7	7.5735
500	0.71095	3129.0	3484.5	8.0893	0.59200	3128.2	3483.4	8.0041	0.44332	3126.6	3481.3	7.8692
600	0.80409	3300.4	3702.5	8.3544	0.66976	3299.8	3701.7	8.2695	0.50186	3298.7	3700.1	8.1354
700	0.89696	3478.6	3927.0	8.5978	0.74725	3478.1	3926.4	8.5132	0.56011	3477.2	3925.3	8.3794
800	0.98966	3663.6	4158.4	8.8240	0.82457	3663.2	4157.9	8.7395	0.61820	3662.5	4157.0	8.6061
900	1.08227	3855.4	4396.6	9.0362	0.90179	3855.1	4396.2	8.9518	0.67619	3854.5	4395.5	8.8185
1000	1.17480	4054.0	4641.4	9.2364	0.97893	4053.8	4641.1	9.1521	0.73411	4053.3	4640.5	9.0189
1100	1.26728	4259.0	4892.6	9.4263	1.05603	4258.8	4892.4	9.3420	0.79197	4258.3	4891.9	9.2090
1200	1.35972	4470.0	5149.8	9.6071	1.13309	4469.8	5149.6	9.5229	0.84980	4469.4	5149.3	9.3898
1300	1.45214	4686.6	5412.6	9.7797	1.21012	4686.4	5412.5	9.6955	0.90761	4686.1	5412.2	9.5625

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*The temperature in parentheses is the saturation temperature at the specified pressure.

† Properties of saturated vapor at the specified pressure.

TABLE A–6

Superheated water (*Concluded*)

T °C	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg K	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K
	P 1.00 MPa (179.88 C)				*P* 1.20 MPa (187.96 C)				*P* 1.40 MPa (195.04 C)			
Sat.	0.19437	2582.8	2777.1	6.5850	0.16326	2587.8	2783.8	6.5217	0.14078	2591.8	2788.9	6.4675
200	0.20602	2622.3	2828.3	6.6956	0.16934	2612.9	2816.1	6.5909	0.14303	2602.7	2803.0	6.4975
250	0.23275	2710.4	2943.1	6.9265	0.19241	2704.7	2935.6	6.8313	0.16356	2698.9	2927.9	6.7488
300	0.25799	2793.7	3051.6	7.1246	0.21386	2789.7	3046.3	7.0335	0.18233	2785.7	3040.9	6.9553
350	0.28250	2875.7	3158.2	7.3029	0.23455	2872.7	3154.2	7.2139	0.20029	2869.7	3150.1	7.1379
400	0.30661	2957.9	3264.5	7.4670	0.25482	2955.5	3261.3	7.3793	0.21782	2953.1	3258.1	7.3046
500	0.35411	3125.0	3479.1	7.7642	0.29464	3123.4	3477.0	7.6779	0.25216	3121.8	3474.8	7.6047
600	0.40111	3297.5	3698.6	8.0311	0.33395	3296.3	3697.0	7.9456	0.28597	3295.1	3695.5	7.8730
700	0.44783	3476.3	3924.1	8.2755	0.37297	3475.3	3922.9	8.1904	0.31951	3474.4	3921.7	8.1183
800	0.49438	3661.7	4156.1	8.5024	0.41184	3661.0	4155.2	8.4176	0.35288	3660.3	4154.3	8.3458
900	0.54083	3853.9	4394.8	8.7150	0.45059	3853.3	4394.0	8.6303	0.38614	3852.7	4393.3	8.5587
1000	0.58721	4052.7	4640.0	8.9155	0.48928	4052.2	4639.4	8.8310	0.41933	4051.7	4638.8	8.7595
1100	0.63354	4257.9	4891.4	9.1057	0.52792	4257.5	4891.0	9.0212	0.45247	4257.0	4890.5	8.9497
1200	0.67983	4469.0	5148.9	9.2866	0.56652	4468.7	5148.5	9.2022	0.48558	4468.3	5148.1	9.1308
1300	0.72610	4685.8	5411.9	9.4593	0.60509	4685.5	5411.6	9.3750	0.51866	4685.1	5411.3	9.3036
	P 1.60 MPa (201.37 C)				*P* 1.80 MPa (207.11 C)				*P* 2.00 MPa (212.38 C)			
Sat.	0.12374	2594.8	2792.8	6.4200	0.11037	2597.3	2795.9	6.3775	0.09959	2599.1	2798.3	6.3390
225	0.13293	2645.1	2857.8	6.5537	0.11678	2637.0	2847.2	6.4825	0.10381	2628.5	2836.1	6.4160
250	0.14190	2692.9	2919.9	6.6753	0.12502	2686.7	2911.7	6.6088	0.11150	2680.3	2903.3	6.5475
300	0.15866	2781.6	3035.4	6.8864	0.14025	2777.4	3029.9	6.8246	0.12551	2773.2	3024.2	6.7684
350	0.17459	2866.6	3146.0	7.0713	0.15460	2863.6	3141.9	7.0120	0.13860	2860.5	3137.7	6.9583
400	0.19007	2950.8	3254.9	7.2394	0.16849	2948.3	3251.6	7.1814	0.15122	2945.9	3248.4	7.1292
500	0.22029	3120.1	3472.6	7.5410	0.19551	3118.5	3470.4	7.4845	0.17568	3116.9	3468.3	7.4337
600	0.24999	3293.9	3693.9	7.8101	0.22200	3292.7	3692.3	7.7543	0.19962	3291.5	3690.7	7.7043
700	0.27941	3473.5	3920.5	8.0558	0.24822	3472.6	3919.4	8.0005	0.22326	3471.7	3918.2	7.9509
800	0.30865	3659.5	4153.4	8.2834	0.27426	3658.8	4152.4	8.2284	0.24674	3658.0	4151.5	8.1791
900	0.33780	3852.1	4392.6	8.4965	0.30020	3851.5	4391.9	8.4417	0.27012	3850.9	4391.1	8.3925
1000	0.36687	4051.2	4638.2	8.6974	0.32606	4050.7	4637.6	8.6427	0.29342	4050.2	4637.1	8.5936
1100	0.39589	4256.6	4890.0	8.8878	0.35188	4256.2	4889.6	8.8331	0.31667	4255.7	4889.1	8.7842
1200	0.42488	4467.9	5147.7	9.0689	0.37766	4467.6	5147.3	9.0143	0.33989	4467.2	5147.0	8.9654
1300	0.45383	4684.8	5410.9	9.2418	0.40341	4684.5	5410.6	9.1872	0.36308	4684.2	5410.3	9.1384
	P 2.50 MPa (223.95 C)				*P* 3.00 MPa (233.85 C)				*P* 3.50 MPa (242.56 C)			
Sat.	0.07995	2602.1	2801.9	6.2558	0.06667	2603.2	2803.2	6.1856	0.05706	2603.0	2802.7	6.1244
225	0.08026	2604.8	2805.5	6.2629								
250	0.08705	2663.3	2880.9	6.4107	0.07063	2644.7	2856.5	6.2893	0.05876	2624.0	2829.7	6.1764
300	0.09894	2762.2	3009.6	6.6459	0.08118	2750.8	2994.3	6.5412	0.06845	2738.8	2978.4	6.4484
350	0.10979	2852.5	3127.0	6.8424	0.09056	2844.4	3116.1	6.7450	0.07680	2836.0	3104.9	6.6601
400	0.12012	2939.8	3240.1	7.0170	0.09938	2933.6	3231.7	6.9235	0.08456	2927.2	3223.2	6.8428
450	0.13015	3026.2	3351.6	7.1768	0.10789	3021.2	3344.9	7.0856	0.09198	3016.1	3338.1	7.0074
500	0.13999	3112.8	3462.8	7.3254	0.11620	3108.6	3457.2	7.2359	0.09919	3104.5	3451.7	7.1593
600	0.15931	3288.5	3686.8	7.5979	0.13245	3285.5	3682.8	7.5103	0.11325	3282.5	3678.9	7.4357
700	0.17835	3469.3	3915.2	7.8455	0.14841	3467.0	3912.2	7.7590	0.12702	3464.7	3909.3	7.6855
800	0.19722	3656.2	4149.2	8.0744	0.16420	3654.3	4146.9	7.9885	0.14061	3652.5	4144.6	7.9156
900	0.21597	3849.4	4389.3	8.2882	0.17988	3847.9	4387.5	8.2028	0.15410	3846.4	4385.7	8.1304
1000	0.23466	4049.0	4635.6	8.4897	0.19549	4047.7	4634.2	8.4045	0.16751	4046.4	4632.7	8.3324
1100	0.25330	4254.7	4887.9	8.6804	0.21105	4253.6	4886.7	8.5955	0.18087	4252.5	4885.6	8.5236
1200	0.27190	4466.3	5146.0	8.8618	0.22658	4465.3	5145.1	8.7771	0.19420	4464.4	5144.1	8.7053
1300	0.29048	4683.4	5409.5	9.0349	0.24207	4682.6	5408.8	8.9502	0.20750	4681.8	5408.0	8.8786

TABLE A–6

Superheated water (*Continued*)

T °C	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K
	P 4.0 MPa (250.35 C)				*P* 4.5 MPa (257.44 C)				*P* 5.0 MPa (263.94 C)			
Sat.	0.04978	2601.7	2800.8	6.0696	0.04406	2599.7	2798.0	6.0198	0.03945	2597.0	2794.2	5.9737
275	0.05461	2668.9	2887.3	6.2312	0.04733	2651.4	2864.4	6.1429	0.04144	2632.3	2839.5	6.0571
300	0.05887	2726.2	2961.7	6.3639	0.05138	2713.0	2944.2	6.2854	0.04535	2699.0	2925.7	6.2111
350	0.06647	2827.4	3093.3	6.5843	0.05842	2818.6	3081.5	6.5153	0.05197	2809.5	3069.3	6.4516
400	0.07343	2920.8	3214.5	6.7714	0.06477	2914.2	3205.7	6.7071	0.05784	2907.5	3196.7	6.6483
450	0.08004	3011.0	3331.2	6.9386	0.07076	3005.8	3324.2	6.8770	0.06332	3000.6	3317.2	6.8210
500	0.08644	3100.3	3446.0	7.0922	0.07652	3096.0	3440.4	7.0323	0.06858	3091.8	3434.7	6.9781
600	0.09886	3279.4	3674.9	7.3706	0.08766	3276.4	3670.9	7.3127	0.07870	3273.3	3666.9	7.2605
700	0.11098	3462.4	3906.3	7.6214	0.09850	3460.0	3903.3	7.5647	0.08852	3457.7	3900.3	7.5136
800	0.12292	3650.6	4142.3	7.8523	0.10916	3648.8	4140.0	7.7962	0.09816	3646.9	4137.7	7.7458
900	0.13476	3844.8	4383.9	8.0675	0.11972	3843.3	4382.1	8.0118	0.10769	3841.8	4380.2	7.9619
1000	0.14653	4045.1	4631.2	8.2698	0.13020	4043.9	4629.8	8.2144	0.11715	4042.6	4628.3	8.1648
1100	0.15824	4251.4	4884.4	8.4612	0.14064	4250.4	4883.2	8.4060	0.12655	4249.3	4882.1	8.3566
1200	0.16992	4463.5	5143.2	8.6430	0.15103	4462.6	5142.2	8.5880	0.13592	4461.6	5141.3	8.5388
1300	0.18157	4680.9	5407.2	8.8164	0.16140	4680.1	5406.5	8.7616	0.14527	4679.3	5405.7	8.7124
	P 6.0 MPa (275.59 C)				*P* 7.0 MPa (285.83 C)				*P* 8.0 MPa (295.01 C)			
Sat.	0.03245	2589.9	2784.6	5.8902	0.027378	2581.0	2772.6	5.8148	0.023525	2570.5	2758.7	5.7450
300	0.03619	2668.4	2885.6	6.0703	0.029492	2633.5	2839.9	5.9337	0.024279	2592.3	2786.5	5.7937
350	0.04225	2790.4	3043.9	6.3357	0.035262	2770.1	3016.9	6.2305	0.029975	2748.3	2988.1	6.1321
400	0.04742	2893.7	3178.3	6.5432	0.039958	2879.5	3159.2	6.4502	0.034344	2864.6	3139.4	6.3658
450	0.05217	2989.9	3302.9	6.7219	0.044187	2979.0	3288.3	6.6353	0.038194	2967.8	3273.3	6.5579
500	0.05667	3083.1	3423.1	6.8826	0.048157	3074.3	3411.4	6.8000	0.041767	3065.4	3399.5	6.7266
550	0.06102	3175.2	3541.3	7.0308	0.051966	3167.9	3531.6	6.9507	0.045172	3160.5	3521.8	6.8800
600	0.06527	3267.2	3658.8	7.1693	0.055665	3261.0	3650.6	7.0910	0.048463	3254.7	3642.4	7.0221
700	0.07355	3453.0	3894.3	7.4247	0.062850	3448.3	3888.3	7.3487	0.054829	3443.6	3882.2	7.2822
800	0.08165	3643.2	4133.1	7.6582	0.069856	3639.5	4128.5	7.5836	0.061011	3635.7	4123.8	7.5185
900	0.08964	3838.8	4376.6	7.8751	0.076750	3835.7	4373.0	7.8014	0.067082	3832.7	4369.3	7.7372
1000	0.09756	4040.1	4625.4	8.0786	0.083571	4037.5	4622.5	8.0055	0.073079	4035.0	4619.6	7.9419
1100	0.10543	4247.1	4879.7	8.2709	0.090341	4245.0	4877.4	8.1982	0.079025	4242.8	4875.0	8.1350
1200	0.11326	4459.8	5139.4	8.4534	0.097075	4457.9	5137.4	8.3810	0.084934	4456.1	5135.5	8.3181
1300	0.12107	4677.7	5404.1	8.6273	0.103781	4676.1	5402.6	8.5551	0.090817	4674.5	5401.0	8.4925
	P 9.0 MPa (303.35 C)				*P* 10.0 MPa (311.00 C)				*P* 12.5 MPa (327.81 C)			
Sat.	0.020489	2558.5	2742.9	5.6791	0.018028	2545.2	2725.5	5.6159	0.013496	2505.6	2674.3	5.4638
325	0.023284	2647.6	2857.1	5.8738	0.019877	2611.6	2810.3	5.7596				
350	0.025816	2725.0	2957.3	6.0380	0.022440	2699.6	2924.0	5.9460	0.016138	2624.9	2826.6	5.7130
400	0.029960	2849.2	3118.8	6.2876	0.026436	2833.1	3097.5	6.2141	0.020030	2789.6	3040.0	6.0433
450	0.033524	2956.3	3258.0	6.4872	0.029782	2944.5	3242.4	6.4219	0.023019	2913.7	3201.5	6.2749
500	0.036793	3056.3	3387.4	6.6603	0.032811	3047.0	3375.1	6.5995	0.025630	3023.2	3343.6	6.4651
550	0.039885	3153.0	3512.0	6.8164	0.035655	3145.4	3502.0	6.7585	0.028033	3126.1	3476.5	6.6317
600	0.042861	3248.4	3634.1	6.9605	0.038378	3242.0	3625.8	6.9045	0.030306	3225.8	3604.6	6.7828
650	0.045755	3343.4	3755.2	7.0954	0.041018	3338.0	3748.1	7.0408	0.032491	3324.1	3730.2	6.9227
700	0.048589	3438.8	3876.1	7.2229	0.043597	3434.0	3870.0	7.1693	0.034612	3422.0	3854.6	7.0540
800	0.054132	3632.0	4119.2	7.4606	0.048629	3628.2	4114.5	7.4085	0.038724	3618.8	4102.8	7.2967
900	0.059562	3829.6	4365.7	7.6802	0.053547	3826.5	4362.0	7.6290	0.042720	3818.9	4352.9	7.5195
1000	0.064919	4032.4	4616.7	7.8855	0.058391	4029.9	4613.8	7.8349	0.046641	4023.5	4606.5	7.7269
1100	0.070224	4240.7	4872.7	8.0791	0.063183	4238.5	4870.3	8.0289	0.050510	4233.1	4864.5	7.9220
1200	0.075492	4454.2	5133.6	8.2625	0.067938	4452.4	5131.7	8.2126	0.054342	4447.7	5127.0	8.1065
1300	0.080733	4672.9	5399.5	8.4371	0.072667	4671.3	5398.0	8.3874	0.058147	4667.3	5394.1	8.2819

TABLE A–6

Superheated water (*Concluded*)

T °C	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K
	P 15.0 MPa (342.16 C)				*P* 17.5 MPa (354.67 C)				*P* 20.0 MPa (365.75 C)			
Sat.	0.010341	2455.7	2610.8	5.3108	0.007932	2390.7	2529.5	5.1435	0.005862	2294.8	2412.1	4.9310
350	0.011481	2520.9	2693.1	5.4438								
400	0.015671	2740.6	2975.7	5.8819	0.012463	2684.3	2902.4	5.7211	0.009950	2617.9	2816.9	5.5526
450	0.018477	2880.8	3157.9	6.1434	0.015204	2845.4	3111.4	6.0212	0.012721	2807.3	3061.7	5.9043
500	0.020828	2998.4	3310.8	6.3480	0.017385	2972.4	3276.7	6.2424	0.014793	2945.3	3241.2	6.1446
550	0.022945	3106.2	3450.4	6.5230	0.019305	3085.8	3423.6	6.4266	0.016571	3064.7	3396.2	6.3390
600	0.024921	3209.3	3583.1	6.6796	0.021073	3192.5	3561.3	6.5890	0.018185	3175.3	3539.0	6.5075
650	0.026804	3310.1	3712.1	6.8233	0.022742	3295.8	3693.8	6.7366	0.019695	3281.4	3675.3	6.6593
700	0.028621	3409.8	3839.1	6.9573	0.024342	3397.5	3823.5	6.8735	0.021134	3385.1	3807.8	6.7991
800	0.032121	3609.3	4091.1	7.2037	0.027405	3599.7	4079.3	7.1237	0.023870	3590.1	4067.5	7.0531
900	0.035503	3811.2	4343.7	7.4288	0.030348	3803.5	4334.6	7.3511	0.026484	3795.7	4325.4	7.2829
1000	0.038808	4017.1	4599.2	7.6378	0.033215	4010.7	4592.0	7.5616	0.029020	4004.3	4584.7	7.4950
1100	0.042062	4227.7	4858.6	7.8339	0.036029	4222.3	4852.8	7.7588	0.031504	4216.9	4847.0	7.6933
1200	0.045279	4443.1	5122.3	8.0192	0.038806	4438.5	5117.6	7.9449	0.033952	4433.8	5112.9	7.8802
1300	0.048469	4663.3	5390.3	8.1952	0.041556	4659.2	5386.5	8.1215	0.036371	4655.2	5382.7	8.0574
	P 25.0 MPa				*P* 30.0 MPa				*P* 35.0 MPa			
375	0.001978	1799.9	1849.4	4.0345	0.001792	1738.1	1791.9	3.9313	0.001701	1702.8	1762.4	3.8724
400	0.006005	2428.5	2578.7	5.1400	0.002798	2068.9	2152.8	4.4758	0.002105	1914.9	1988.6	4.2144
425	0.007886	2607.8	2805.0	5.4708	0.005299	2452.9	2611.8	5.1473	0.003434	2253.3	2373.5	4.7751
450	0.009176	2721.2	2950.6	5.6759	0.006737	2618.9	2821.0	5.4422	0.004957	2497.5	2671.0	5.1946
500	0.011143	2887.3	3165.9	5.9643	0.008691	2824.0	3084.8	5.7956	0.006933	2755.3	2997.9	5.6331
550	0.012736	3020.8	3339.2	6.1816	0.010175	2974.5	3279.7	6.0403	0.008348	2925.8	3218.0	5.9093
600	0.014140	3140.0	3493.5	6.3637	0.011445	3103.4	3446.8	6.2373	0.009523	3065.6	3399.0	6.1229
650	0.015430	3251.9	3637.7	6.5243	0.012590	3221.7	3599.4	6.4074	0.010565	3190.9	3560.7	6.3030
700	0.016643	3359.9	3776.0	6.6702	0.013654	3334.3	3743.9	6.5599	0.011523	3308.3	3711.6	6.4623
800	0.018922	3570.7	4043.8	6.9322	0.015628	3551.2	4020.0	6.8301	0.013278	3531.6	3996.3	6.7409
900	0.021075	3780.2	4307.1	7.1668	0.017473	3764.6	4288.8	7.0695	0.014904	3749.0	4270.6	6.9853
1000	0.023150	3991.5	4570.2	7.3821	0.019240	3978.6	4555.8	7.2880	0.016450	3965.8	4541.5	7.2069
1100	0.025172	4206.1	4835.4	7.5825	0.020954	4195.2	4823.9	7.4906	0.017942	4184.4	4812.4	7.4118
1200	0.027157	4424.6	5103.5	7.7710	0.022630	4415.3	5094.2	7.6807	0.019398	4406.1	5085.0	7.6034
1300	0.029115	4647.2	5375.1	7.9494	0.024279	4639.2	5367.6	7.8602	0.020827	4631.2	5360.2	7.7841
	P 40.0 MPa				*P* 50.0 MPa				*P* 60.0 MPa			
375	0.001641	1677.0	1742.6	3.8290	0.001560	1638.6	1716.6	3.7642	0.001503	1609.7	1699.9	3.7149
400	0.001911	1855.0	1931.4	4.1145	0.001731	1787.8	1874.4	4.0029	0.001633	1745.2	1843.2	3.9317
425	0.002538	2097.5	2199.0	4.5044	0.002009	1960.3	2060.7	4.2746	0.001816	1892.9	2001.8	4.1630
450	0.003692	2364.2	2511.8	4.9449	0.002487	2160.3	2284.7	4.5896	0.002086	2055.1	2180.2	4.4140
500	0.005623	2681.6	2906.5	5.4744	0.003890	2528.1	2722.6	5.1762	0.002952	2393.2	2570.3	4.9356
550	0.006985	2875.1	3154.4	5.7857	0.005118	2769.5	3025.4	5.5563	0.003955	2664.6	2901.9	5.3517
600	0.008089	3026.8	3350.4	6.0170	0.006108	2947.1	3252.6	5.8245	0.004833	2866.8	3156.8	5.6527
650	0.009053	3159.5	3521.6	6.2078	0.006957	3095.6	3443.5	6.0373	0.005591	3031.3	3366.8	5.8867
700	0.009930	3282.0	3679.2	6.3740	0.007717	3228.7	3614.6	6.2179	0.006265	3175.4	3551.3	6.0814
800	0.011521	3511.8	3972.6	6.6613	0.009073	3472.2	3925.8	6.5225	0.007456	3432.6	3880.0	6.4033
900	0.012980	3733.3	4252.5	6.9107	0.010296	3702.0	4216.8	6.7819	0.008519	3670.9	4182.1	6.6725
1000	0.014360	3952.9	4527.3	7.1355	0.011441	3927.4	4499.4	7.0131	0.009504	3902.0	4472.2	6.9099
1100	0.015686	4173.7	4801.1	7.3425	0.012534	4152.2	4778.9	7.2244	0.010439	4130.9	4757.3	7.1255
1200	0.016976	4396.9	5075.9	7.5357	0.013590	4378.6	5058.1	7.4207	0.011339	4360.5	5040.8	7.3248
1300	0.018239	4623.3	5352.8	7.7175	0.014620	4607.5	5338.5	7.6048	0.012213	4591.8	5324.5	7.5111

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Thermodynamics-

	Critical Point Data	**Triple Point Data**
Water:	374.14 C, 22.09 MPa, 0.00316 m^3/kg	0.01 C, 0.6113 kPa
Nitrogen:	126.2 K, 3.39 MPa, 0.00321 m^3/kg	-210 C, 12.53 kPa

Ideal Gas Properties at 300K. Ideal Gas behavior: Either $P < 0.1P_c$ OR ($T > 2T_c$ and $P < 5P_c$)

Gas	Mol Wt	R kJ/kgK	c_p kJ/kgK	c_v kJ/kgK	$c_p/c_v = k$
Air	29	0.287	1.00	0.72	1.4
Steam	18	0.46	1.87	1.41	1.33
Nitrogen	28	0.297	1.04	0.745	1.4

Properties of Selected **Solids and Liquids**

Substance	Spec Heat kJ/kgK	ρ kg/m^3	v m^3/kg
Liquid Water 25C	4.18	997	0.001003
Ice at 0 C	2.04	917	0.001087
Copper	0.42	8300	

scs = simple comp subs, REV=Reversible IRR=Irreversible, sfs=single fluid stream

SYS, scs, REV: $\delta W = \int P dV$.

For $Pv^n = const$: $\int P dV = \frac{1}{1-n}(P_2V_2 - P_1V_1)$ for $n \neq 1$ and $P_1V_1 \ln\frac{V_2}{V_1}$ for $n = 1$

Property Relations for any scs: *Tds=du+Pdv and Tds =dh-vdP*

Property Relations for an Ideal Gas: *Pv=RT or PV=mRT* $dh=c_p dT$ and $du=c_v dT$

For constant c_p, c_v : $s_2-s_1=c_p \ln(T_2\backslash T_1) - R\ln(p_2\backslash p_1)$; $s_2-s_1=c_v \ln(T_2\backslash T_1) + R\ln(v_2\backslash v_1)$

If $Pv^k = const$ for an Ideal Gas: $\left(\frac{P_2}{P_1}\right) = \left(\frac{v_1}{v_2}\right)^k, \left(\frac{T_2}{T_1}\right) = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

I Law: SYS: $\delta Q = dE + \delta W$ where $E = U + (1/2)mV_i^2 + mgZ_i$

CV: $\dot{Q}_{cv} + \sum \dot{m}_i (h_i + \frac{1}{2}V_i^2 + gZ_i) = dE_{cv}/dt + \sum \dot{m}_e (h_e + \frac{1}{2}V_e^2 + gZ_e) + \dot{W}_{cv}$

SSSF+sfs: $q + h_i + \frac{1}{2}V_i^2 + gZ_i = h_e + \frac{1}{2}V_e^2 + gZ_e + w$

II Law: SYS: $dS = \frac{\delta Q}{T} + \delta S_{gen}$ CV: $dS_{cv}/dt + \sum \dot{m}_e s_e - \sum \dot{m}_i s_i \geq \sum_{cv} \frac{\dot{Q}_{cv}}{T}$

Work for SSSF REV Process: $w = -\int_i^e v dP + \frac{1}{2}(V_i^2 - V_e^2) + g(Z_i - Z_e)$

For $Pv^n = const$: $-\int_i^e v dP = -\frac{n}{n-1}(P_e v_e - P_i v_i)$ for $n \neq 1$ and $-P_i v_i \ln\frac{P_e}{P_i}$ for $n = 1$

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Thermodynamics-

Relevant Equations for Thermodynamics Problems:

Isentropic relations for an Ideal Gas: $\left(\frac{P_2}{P_1}\right)=\left(\frac{v_1}{v_2}\right)^k$, $\left(\frac{T_2}{T_1}\right)=\left(\frac{v_1}{v_2}\right)^{k-1}=\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

Availability Rate Balance Equation

$$\frac{dA_{CV}}{dt}=\sum_j\left(1-\frac{T_o}{T_j}\right)\dot{Q}_j-\left(\dot{W}_{CV}-p_o\frac{dV_{CV}}{dt}\right)+\sum_i\dot{m}_i a_{fi}-\sum_e\dot{m}_e a_{fe}-\dot{I}_{CV}$$

A_{CV} : the availability of the control volume.

$\dot{Q}_j$: the time rate of heat transfer at the location on the boundary where the instantaneous temperature is T_j.

$\dot{W}_{CV}$: the time rate of energy transfer by work other than flow work.

V_{CV} : volume.

$\dot{m}_i a_{fi}$: the time rate of availability transfer accompanying mass flow and flow work at inlet 'i'.

$\dot{m}_e a_{fe}$: the time rate of availability transfer accompanying mass flow and flow work at exit 'e'.

$\dot{I}_{CV}$: the time rate of availability destruction due to irreversibilities within the control volume.

Specific Flow Availability

$$a_f=h-h_o-T_o(s-s_o)+\frac{V^2}{2}+gz$$

NOTE: The subscript 'o' denotes the dead state.

2^{nd} Law of Thermodynamics

$$S_2-S_1=\sum_e\dot{m}_e s_e-\sum_i\dot{m}_i s_i=\sum\frac{\dot{Q}}{T}+\dot{S}_{gen}$$

Mixture Formulas:

$$\Delta\bar{s}=\bar{s}_2-\bar{s}_1=\sum_{i=1}^{j}y_i\left[\bar{s}_{i,2}(T_2,P_{i,2})-\bar{s}_{i,1}(T_1,P_{i,1})\right]$$

$$\bar{s}_X(T_2,P_{X,2})-\bar{s}_{X,1}(T_1,P_{X,1})=\bar{s}_X^0(T_2)-\bar{s}_X^0(T_1)-\bar{R}\ln\frac{P_2}{P_1}$$

Where 'X' in the above equation represents a constituent in the mixture.

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Thermodynamics-

Problem 1. At a consumer products laboratory, a test engineer is assigned to determine the efficiency of a new model hair dryer. Temperature, pressure and mass flow rate measurements are made during operation of the hair dryer. Measurements obtained at steady-state operation indicate that warm air exits the hand-held dryer at a temperature of 83C with a velocity of 9.1 m/s through an area of 18.7 cm^2. Air enters the dryer at a temperature of 22C and a pressure of 1 bar (= 100 kPa=10^5 N/m^2), with a velocity of 3.7 m/s. No significant change in pressure between the inlet and the exit is observed. Also, no significant heat transfer between the dryer and its surroundings occurs. Assume T_o (surroundings temperature) to be 22 C. **NOTE:** Universal gas constant = 8.314 kJ/kmolK; molecular weight of air = 28.97); specific enthalpy (state 1) = 295.2 kJ/kg, specific enthalpy (state 2) = 356.5 kJ/kg. $s_2 - s_1 = s_2^o - s_1^o$ where $s_1^o = 1.685 kJ/kgK$, $s_2^o = 1.874 kJ/kgK$.

Assist the test engineer to:

(a). Evaluate the power, $\dot{W}_{cv}$, in kW required to operate the hair dryer. Draw a control volume, list governing equations, state/justify any assumptions.

(b). Using the availability rate balance equation devise and evaluate a second law efficiency for the hair dryer. Comment on the efficiency of the hair dryer.

Problem 2. A gas mixture consisting of CO_2 and O_2 with mole fractions 0.8 and 0.2, respectively, expands isentropically and at steady state through a rocket nozzle from 700K, 5 atm and 3 m/s (state '1') to an exit pressure of 1 atm (state '2').

(a) Draw a control volume and list all assumptions.

(b) Determine the temperature at the nozzle exit, T_2 in degrees Kelvin. First obtain the equation for $\Delta\bar{s}$ in terms of T_2 and mixture component mole fractions and pressure and then solve iteratively for T_2. NOTE: At T_1=700 K, $\bar{s}_{O2}^0$= 231.465 kJ/kmol K and $\bar{s}_{CO2}^0$ = 250.752 kJ/kmol K, $\bar{R}$ = 8.314 kJ/kmol K.

(c) Determine the entropy changes of the CO_2, $\Delta\bar{s}_{CO2}$ and O_2, $\Delta\bar{s}_{O2}$ from the nozzle inlet (state '1') to the nozzle exit (state '2'), in kJ/kmol K.

Problem 3: Sketch the air-standard ideal Diesel cycle on T-s and P-v diagrams. Define the compression ratio and the cutoff ratios for this cycle. Now obtain an expression for the cycle efficiency in terms of these and the ratio of specific heats.

THERMODYNAMICS
Doctoral Qualifying Examination, January 2011
Mechanical Engineering, Columbia University

Problem 1

An ideal mixture at T, P is made from ideal gases at T, P by flow into a mixing chamber with no external heat transfer and an exit at P. How do the properties (P, v, and h) for each component increase, decrease or remain constant?

Problem 2

Derive the expression for mass flow rate through a sonic nozzle:

$$\dot{m} = A^{*} P_o \frac{1}{\sqrt{RT_o}} \left[k \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \right]^{1/2}$$

where A^{*} is the throat area, P_o and T_0 are upstream stagnation pressure and temperatures and k is the specific heat ratio. Clearly list the assumptions that are made during the derivation. Speed of sound for an ideal gas is $\sqrt{kRT}$.

Isentropic relations for an Ideal Gas: $\left(\frac{P_2}{P_1}\right) = \left(\frac{v_1}{v_2}\right)^{k}, \quad \left(\frac{T_2}{T_1}\right) = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

Problem 3

A steam power plant operates with a high pressure of 4 MPa and has a boiler exit temperature of 600°C receiving heat from a 700°C source. The ambient air at 20°C provides cooling to maintain the condenser at 60°C. All components are ideal except for the turbine, which has an isentropic efficiency of 92%.

Find the ideal and the actual turbine exit qualities.

Find the actual specific work of the turbine and the specific heat transfer in boiler.

TABLE A-2 Properties of Saturated Water (Liquid–Vapor): Temperature Table

H_2O

		Specific Volume m³/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Temp. °C	Press. bar	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	.01
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7	0.0610	9.0514	4
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6	0.0761	9.0257	5
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4	0.0912	9.0003	6
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1	0.1212	8.9501	8
10	0.01228	1.0004	106.379	42.00	2389.2	42.01	2477.7	2519.8	0.1510	8.9008	10
11	0.01312	1.0004	99.857	46.20	2390.5	46.20	2475.4	2521.6	0.1658	8.8765	11
12	0.01402	1.0005	93.784	50.41	2391.9	50.41	2473.0	2523.4	0.1806	8.8524	12
13	0.01497	1.0007	88.124	54.60	2393.3	54.60	2470.7	2525.3	0.1953	8.8285	13
14	0.01598	1.0008	82.848	58.79	2394.7	58.80	2468.3	2527.1	0.2099	8.8048	14
15	0.01705	1.0009	77.926	62.99	2396.1	62.99	2465.9	2528.9	0.2245	8.7814	15
16	0.01818	1.0011	73.333	67.18	2397.4	67.19	2463.6	2530.8	0.2390	8.7582	16
17	0.01938	1.0012	69.044	71.38	2398.8	71.38	2461.2	2532.6	0.2535	8.7351	17
18	0.02064	1.0014	65.038	75.57	2400.2	75.58	2458.8	2534.4	0.2679	8.7123	18
19	0.02198	1.0016	61.293	79.76	2401.6	79.77	2456.5	2536.2	0.2823	8.6897	19
20	0.02339	1.0018	57.791	83.95	2402.9	83.96	2454.1	2538.1	0.2966	8.6672	20
21	0.02487	1.0020	54.514	88.14	2404.3	88.14	2451.8	2539.9	0.3109	8.6450	21
22	0.02645	1.0022	51.447	92.32	2405.7	92.33	2449.4	2541.7	0.3251	8.6229	22
23	0.02810	1.0024	48.574	96.51	2407.0	96.52	2447.0	2543.5	0.3393	8.6011	23
24	0.02985	1.0027	45.883	100.70	2408.4	100.70	2444.7	2545.4	0.3534	8.5794	24
25	0.03169	1.0029	43.360	104.88	2409.8	104.89	2442.3	2547.2	0.3674	8.5580	25
26	0.03363	1.0032	40.994	109.06	2411.1	109.07	2439.9	2549.0	0.3814	8.5367	26
27	0.03567	1.0035	38.774	113.25	2412.5	113.25	2437.6	2550.8	0.3954	8.5156	27
28	0.03782	1.0037	36.690	117.42	2413.9	117.43	2435.2	2552.6	0.4093	8.4946	28
29	0.04008	1.0040	34.733	121.60	2415.2	121.61	2432.8	2554.5	0.4231	8.4739	29
30	0.04246	1.0043	32.894	125.78	2416.6	125.79	2430.5	2556.3	0.4369	8.4533	30
31	0.04496	1.0046	31.165	129.96	2418.0	129.97	2428.1	2558.1	0.4507	8.4329	31
32	0.04759	1.0050	29.540	134.14	2419.3	134.15	2425.7	2559.9	0.4644	8.4127	32
33	0.05034	1.0053	28.011	138.32	2420.7	138.33	2423.4	2561.7	0.4781	8.3927	33
34	0.05324	1.0056	26.571	142.50	2422.0	142.50	2421.0	2563.5	0.4917	8.3728	34
35	0.05628	1.0060	25.216	146.67	2423.4	146.68	2418.6	2565.3	0.5053	8.3531	35
36	0.05947	1.0063	23.940	150.85	2424.7	150.86	2416.2	2567.1	0.5188	8.3336	36
38	0.06632	1.0071	21.602	159.20	2427.4	159.21	2411.5	2570.7	0.5458	8.2950	38
40	0.07384	1.0078	19.523	167.56	2430.1	167.57	2406.7	2574.3	0.5725	8.2570	40
45	0.09593	1.0099	15.258	188.44	2436.8	188.45	2394.8	2583.2	0.6387	8.1648	45

TABLE A-2 *(Continued)*

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Temp. °C	Press. bar	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
50	.1235	1.0121	12.032	209.32	2443.5	209.33	2382.7	2592.1	.7038	8.0763	50
55	.1576	1.0146	9.568	230.21	2450.1	230.23	2370.7	2600.9	.7679	7.9913	55
60	.1994	1.0172	7.671	251.11	2456.6	251.13	2358.5	2609.6	.8312	7.9096	60
65	.2503	1.0199	6.197	272.02	2463.1	272.06	2346.2	2618.3	.8935	7.8310	65
70	.3119	1.0228	5.042	292.95	2469.6	292.98	2333.8	2626.8	.9549	7.7553	70
75	.3858	1.0259	4.131	313.90	2475.9	313.93	2321.4	2635.3	1.0155	7.6824	75
80	.4739	1.0291	3.407	334.86	2482.2	334.91	2308.8	2643.7	1.0753	7.6122	80
85	.5783	1.0325	2.828	355.84	2488.4	355.90	2296.0	2651.9	1.1343	7.5445	85
90	.7014	1.0360	2.361	376.85	2494.5	376.92	2283.2	2660.1	1.1925	7.4791	90
95	.8455	1.0397	1.982	397.88	2500.6	397.96	2270.2	2668.1	1.2500	7.4159	95
100	1.014	1.0435	1.673	418.94	2506.5	419.04	2257.0	2676.1	1.3069	7.3549	100
110	1.433	1.0516	1.210	461.14	2518.1	461.30	2230.2	2691.5	1.4185	7.2387	110
120	1.985	1.0603	0.8919	503.50	2529.3	503.71	2202.6	2706.3	1.5276	7.1296	120
130	2.701	1.0697	0.6685	546.02	2539.9	546.31	2174.2	2720.5	1.6344	7.0269	130
140	3.613	1.0797	0.5089	588.74	2550.0	589.13	2144.7	2733.9	1.7391	6.9299	140
150	4.758	1.0905	0.3928	631.68	2559.5	632.20	2114.3	2746.5	1.8418	6.8379	150
160	6.178	1.1020	0.3071	674.86	2568.4	675.55	2082.6	2758.1	1.9427	6.7502	160
170	7.917	1.1143	0.2428	718.33	2576.5	719.21	2049.5	2768.7	2.0419	6.6663	170
180	10.02	1.1274	0.1941	762.09	2583.7	763.22	2015.0	2778.2	2.1396	6.5857	180
190	12.54	1.1414	0.1565	806.19	2590.0	807.62	1978.8	2786.4	2.2359	6.5079	190
200	15.54	1.1565	0.1274	850.65	2595.3	852.45	1940.7	2793.2	2.3309	6.4323	200
210	19.06	1.1726	0.1044	895.53	2599.5	897.76	1900.7	2798.5	2.4248	6.3585	210
220	23.18	1.1900	0.08619	940.87	2602.4	943.62	1858.5	2802.1	2.5178	6.2861	220
230	27.95	1.2088	0.07158	986.74	2603.9	990.12	1813.8	2804.0	2.6099	6.2146	230
240	33.44	1.2291	0.05976	1033.2	2604.0	1037.3	1766.5	2803.8	2.7015	6.1437	240
250	39.73	1.2512	0.05013	1080.4	2602.4	1085.4	1716.2	2801.5	2.7927	6.0730	250
260	46.88	1.2755	0.04221	1128.4	2599.0	1134.4	1662.5	2796.6	2.8838	6.0019	260
270	54.99	1.3023	0.03564	1177.4	2593.7	1184.5	1605.2	2789.7	2.9751	5.9301	270
280	64.12	1.3321	0.03017	1227.5	2586.1	1236.0	1543.6	2779.6	3.0668	5.8571	280
290	74.36	1.3656	0.02557	1278.9	2576.0	1289.1	1477.1	2766.2	3.1594	5.7821	290
300	85.81	1.4036	0.02167	1332.0	2563.0	1344.0	1404.9	2749.0	3.2534	5.7045	300
320	112.7	1.4988	0.01549	1444.6	2525.5	1461.5	1238.6	2700.1	3.4480	5.5362	320
340	145.9	1.6379	0.01080	1570.3	2464.6	1594.2	1027.9	2622.0	3.6594	5.3357	340
360	186.5	1.8925	0.006945	1725.2	2351.5	1760.5	720.5	2481.0	3.9147	5.0526	360
374.14	220.9	3.155	0.003155	2029.6	2029.6	2099.3	0	2099.3	4.4298	4.4298	374.14

Source: Tables A-2 through A-5 are extracted from J. H. Keenan, F. G. Keyes, P. G. Hill, and J. G. Moore, *Steam Tables*, Wiley, New York, 1969.

TABLE A-3 Properties of Saturated Water (Liquid–Vapor): Pressure Table

		Specific Volume m³/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Press. bar	Temp. °C	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Press. bar
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4	0.4226	8.4746	0.04
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4	0.5210	8.3304	0.06
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0	0.5926	8.2287	0.08
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7	0.6493	8.1502	0.10
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.9085	0.20
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	7.7686	0.30
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8	1.0259	7.6700	0.40
0.50	81.33	1.0300	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	7.5939	0.50
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5	1.1453	7.5320	0.60
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0	1.1919	7.4797	0.70
0.80	93.50	1.0380	2.087	391.58	2498.8	391.66	2274.1	2665.8	1.2329	7.4346	0.80
0.90	96.71	1.0410	1.869	405.06	2502.6	405.15	2265.7	2670.9	1.2695	7.3949	0.90
1.00	99.63	1.0432	1.694	417.36	2506.1	417.46	2258.0	2675.5	1.3026	7.3594	1.00
1.50	111.4	1.0528	1.159	466.94	2519.7	467.11	2226.5	2693.6	1.4336	7.2233	1.50
2.00	120.2	1.0605	0.8857	504.49	2529.5	504.70	2201.9	2706.7	1.5301	7.1271	2.00
2.50	127.4	1.0672	0.7187	535.10	2537.2	535.37	2181.5	2716.9	1.6072	7.0527	2.50
3.00	133.6	1.0732	0.6058	561.15	2543.6	561.47	2163.8	2725.3	1.6718	6.9919	3.00
3.50	138.9	1.0786	0.5243	583.95	2546.9	584.33	2148.1	2732.4	1.7275	6.9405	3.50
4.00	143.6	1.0836	0.4625	604.31	2553.6	604.74	2133.8	2738.6	1.7766	6.8959	4.00
4.50	147.9	1.0882	0.4140	622.25	2557.6	623.25	2120.7	2743.9	1.8207	6.8565	4.50
5.00	151.9	1.0926	0.3749	639.68	2561.2	640.23	2108.5	2748.7	1.8607	6.8212	5.00
6.00	158.9	1.1006	0.3157	669.90	2567.4	670.56	2086.3	2756.8	1.9312	6.7600	6.00
7.00	165.0	1.1080	0.2729	696.44	2572.5	697.22	2066.3	2763.5	1.9922	6.7080	7.00
8.00	170.4	1.1148	0.2404	720.22	2576.8	721.11	2048.0	2769.1	2.0462	6.6628	8.00
9.00	175.4	1.1212	0.2150	741.83	2580.5	742.83	2031.1	2773.9	2.0946	6.6226	9.00
10.0	179.9	1.1273	0.1944	761.68	2583.6	762.81	2015.3	2778.1	2.1387	6.5863	10.0
15.0	198.3	1.1539	0.1318	843.16	2594.5	844.84	1947.3	2792.2	2.3150	6.4448	15.0
20.0	212.4	1.1767	0.09963	906.44	2600.3	908.79	1890.7	2799.5	2.4474	6.3409	20.0
25.0	224.0	1.1973	0.07998	959.11	2603.1	962.11	1841.0	2803.1	2.5547	6.2575	25.0
30.0	233.9	1.2165	0.06668	1004.8	2604.1	1008.4	1795.7	2804.2	2.6457	6.1869	30.0
35.0	242.6	1.2347	0.05707	1045.4	2603.7	1049.8	1753.7	2803.4	2.7253	6.1253	35.0
40.0	250.4	1.2522	0.04978	1082.3	2602.3	1087.3	1714.1	2801.4	2.7964	6.0701	40.0
45.0	257.5	1.2692	0.04406	1116.2	2600.1	1121.9	1676.4	2798.3	2.8610	6.0199	45.0
50.0	264.0	1.2859	0.03944	1147.8	2597.1	1154.2	1640.1	2794.3	2.9202	5.9734	50.0
60.0	275.6	1.3187	0.03244	1205.4	2589.7	1213.4	1571.0	2784.3	3.0267	5.8892	60.0
70.0	285.9	1.3513	0.02737	1257.6	2580.5	1267.0	1505.1	2772.1	3.1211	5.8133	70.0
80.0	295.1	1.3842	0.02352	1305.6	2569.8	1316.6	1441.3	2758.0	3.2068	5.7432	80.0
90.0	303.4	1.4178	0.02048	1350.5	2557.8	1363.3	1378.9	2742.1	3.2858	5.6772	90.0
100.	311.1	1.4524	0.01803	1393.0	2544.4	1407.6	1317.1	2724.7	3.3596	5.6141	100.
110.	318.2	1.4886	0.01599	1433.7	2529.8	1450.1	1255.5	2705.6	3.4295	5.5527	110.

TABLE A-3 *(Continued)*

		Specific Volume m³/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Press. bar	Temp. °C	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Press. bar
120.	324.8	1.5267	0.01426	1473.0	2513.7	1491.3	1193.6	2684.9	3.4962	5.4924	120.
130.	330.9	1.5671	0.01278	1511.1	2496.1	1531.5	1130.7	2662.2	3.5606	5.4323	130.
140.	336.8	1.6107	0.01149	1548.6	2476.8	1571.1	1066.5	2637.6	3.6232	5.3717	140.
150.	342.2	1.6581	0.01034	1585.6	2455.5	1610.5	1000.0	2610.5	3.6848	5.3098	150.
160.	347.4	1.7107	0.009306	1622.7	2431.7	1650.1	930.6	2580.6	3.7461	5.2455	160.
170.	352.4	1.7702	0.008364	1660.2	2405.0	1690.3	856.9	2547.2	3.8079	5.1777	170.
180.	357.1	1.8397	0.007489	1698.9	2374.3	1732.0	777.1	2509.1	3.8715	5.1044	180.
190.	361.5	1.9243	0.006657	1739.9	2338.1	1776.5	688.0	2464.5	3.9388	5.0228	190.
200.	365.8	2.036	0.005834	1785.6	2293.0	1826.3	583.4	2409.7	4.0139	4.9269	200.
220.9	374.1	3.155	0.003155	2029.6	2029.6	2099.3	0	2099.3	4.4298	4.4298	220.9

TABLE A-4 Properties of Superheated Water Vapor

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 0.06 bar = 0.006 MPa (T_{sat} = 36.16°C)				p = 0.35 bar = 0.035 MPa (T_{sat} = 72.69°C)			
Sat.	23.739	2425.0	2567.4	8.3304	4.526	2473.0	2631.4	7.7158
80	27.132	2487.3	2650.1	8.5804	4.625	2483.7	2645.6	7.7564
120	30.219	2544.7	2726.0	8.7840	5.163	2542.4	2723.1	7.9644
160	33.302	2602.7	2802.5	8.9693	5.696	2601.2	2800.6	8.1519
200	36.383	2661.4	2879.7	9.1398	6.228	2660.4	2878.4	8.3237
240	39.462	2721.0	2957.8	9.2982	6.758	2720.3	2956.8	8.4828
280	42.540	2781.5	3036.8	9.4464	7.287	2780.9	3036.0	8.6314
320	45.618	2843.0	3116.7	9.5859	7.815	2842.5	3116.1	8.7712
360	48.696	2905.5	3197.7	9.7180	8.344	2905.1	3197.1	8.9034
400	51.774	2969.0	3279.6	9.8435	8.872	2968.6	3279.2	9.0291
440	54.851	3033.5	3362.6	9.9633	9.400	3033.2	3362.2	9.1490
500	59.467	3132.3	3489.1	10.1336	10.192	3132.1	3488.8	9.3194
	p = 0.70 bar = 0.07 MPa (T_{sat} = 89.95°C)				p = 1.0 bar = 0.10 MPa (T_{sat} = 99.63°C)			
Sat.	2.365	2494.5	2660.0	7.4797	1.694	2506.1	2675.5	7.3594
100	2.434	2509.7	2680.0	7.5341	1.696	2506.7	2676.2	7.3614
120	2.571	2539.7	2719.6	7.6375	1.793	2537.3	2716.6	7.4668
160	2.841	2599.4	2798.2	7.8279	1.984	2597.8	2796.2	7.6597
200	3.108	2659.1	2876.7	8.0012	2.172	2658.1	2875.3	7.8343
240	3.374	2719.3	2955.5	8.1611	2.359	2718.5	2954.5	7.9949
280	3.640	2780.2	3035.0	8.3162	2.546	2779.6	3034.2	8.1445
320	3.905	2842.0	3115.3	8.4504	2.732	2841.5	3114.6	8.2849
360	4.170	2904.6	3196.5	8.5828	2.917	2904.2	3195.9	8.4175
400	4.434	2968.2	3278.6	8.7086	3.103	2967.9	3278.2	8.5435
440	4.698	3032.9	3361.8	8.8286	3.288	3032.6	3361.4	8.6636
500	5.095	3131.8	3488.5	8.9991	3.565	3131.6	3488.1	8.8342
	p = 1.5 bar = 0.15 MPa (T_{sat} = 111.37°C)				p = 3.0 bar = 0.30 MPa (T_{sat} = 133.55°C)			
Sat.	1.159	2519.7	2693.6	7.2233	0.606	2543.6	2725.3	6.9919
120	1.188	2533.3	2711.4	7.2693				
160	1.317	2595.2	2792.8	7.4665	0.651	2587.1	2782.3	7.1276
200	1.444	2656.2	2872.9	7.6433	0.716	2650.7	2865.5	7.3115
240	1.570	2717.2	2952.7	7.8052	0.781	2713.1	2947.3	7.4774
280	1.695	2778.6	3032.8	7.9555	0.844	2775.4	3028.6	7.6299
320	1.819	2840.6	3113.5	8.0964	0.907	2838.1	3110.1	7.7722
360	1.943	2903.5	3195.0	8.2293	0.969	2901.4	3192.2	7.9061
400	2.067	2967.3	3277.4	8.3555	1.032	2965.6	3275.0	8.0330
440	2.191	3032.1	3360.7	8.4757	1.094	3030.6	3358.7	8.1538
500	2.376	3131.2	3487.6	8.6466	1.187	3130.0	3486.0	8.3251
600	2.685	3301.7	3704.3	8.9101	1.341	3300.8	3703.2	8.5892

(Continued)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 5.0 bar = 0.50 MPa (T_{sat} = 151.86°C)				p = 7.0 bar = 0.70 MPa (T_{sat} = 164.97°C)			
Sat.	0.3749	2561.2	2748.7	6.8213	0.2729	2572.5	2763.5	6.7080
180	0.4045	2609.7	2812.0	6.9656	0.2847	2599.8	2799.1	6.7880
200	0.4249	2642.9	2855.4	7.0592	0.2999	2634.8	2844.8	6.8865
240	0.4646	2707.6	2939.9	7.2307	0.3292	2701.8	2932.2	7.0641
280	0.5034	2771.2	3022.9	7.3865	0.3574	2766.9	3017.1	7.2233
320	0.5416	2834.7	3105.6	7.5308	0.3852	2831.3	3100.9	7.3697
360	0.5796	2898.7	3188.4	7.6660	0.4126	2895.8	3184.7	7.5063
400	0.6173	2963.2	3271.9	7.7938	0.4397	2960.9	3268.7	7.6350
440	0.6548	3028.6	3356.0	7.9152	0.4667	3026.6	3353.3	7.7571
500	0.7109	3128.4	3483.9	8.0873	0.5070	3126.8	3481.7	7.9299
600	0.8041	3299.6	3701.7	8.3522	0.5738	3298.5	3700.2	8.1956
700	0.8969	3477.5	3925.9	8.5952	0.6403	3476.6	3924.8	8.4391
	p = 10.0 bar = 1.0 MPa (T_{sat} = 179.91°C)				p = 15.0 bar = 1.5 MPa (T_{sat} = 198.32°C)			
Sat.	0.1944	2583.6	2778.1	6.5865	0.1318	2594.5	2792.2	6.4448
200	0.2060	2621.9	2827.9	6.6940	0.1325	2598.1	2796.8	6.4546
240	0.2275	2692.9	2920.4	6.8817	0.1483	2676.9	2899.3	6.6628
280	0.2480	2760.2	3008.2	7.0465	0.1627	2748.6	2992.7	6.8381
320	0.2678	2826.1	3093.9	7.1962	0.1765	2817.1	3081.9	6.9938
360	0.2873	2891.6	3178.9	7.3349	0.1899	2884.4	3169.2	7.1363
400	0.3066	2957.3	3263.9	7.4651	0.2030	2951.3	3255.8	7.2690
440	0.3257	3023.6	3349.3	7.5883	0.2160	3018.5	3342.5	7.3940
500	0.3541	3124.4	3478.5	7.7622	0.2352	3120.3	3473.1	7.5698
540	0.3729	3192.6	3565.6	7.8720	0.2478	3189.1	3560.9	7.6805
600	0.4011	3296.8	3697.9	8.0290	0.2668	3293.9	3694.0	7.8385
640	0.4198	3367.4	3787.2	8.1290	0.2793	3364.8	3783.8	7.9391
	p = 20.0 bar = 2.0 MPa (T_{sat} = 212.42°C)				p = 30.0 bar = 3.0 MPa (T_{sat} = 233.90°C)			
Sat.	0.0996	2600.3	2799.5	6.3409	0.0667	2604.1	2804.2	6.1869
240	0.1085	2659.6	2876.5	6.4952	0.0682	2619.7	2824.3	6.2265
280	0.1200	2736.4	2976.4	6.6828	0.0771	2709.9	2941.3	6.4462
320	0.1308	2807.9	3069.5	6.8452	0.0850	2788.4	3043.4	6.6245
360	0.1411	2877.0	3159.3	6.9917	0.0923	2861.7	3138.7	6.7801
400	0.1512	2945.2	3247.6	7.1271	0.0994	2932.8	3230.9	6.9212
440	0.1611	3013.4	3335.5	7.2540	0.1062	3002.9	3321.5	7.0520
500	0.1757	3116.2	3467.6	7.4317	0.1162	3108.0	3456.5	7.2338
540	0.1853	3185.6	3556.1	7.5434	0.1227	3178.4	3546.6	7.3474
600	0.1996	3290.9	3690.1	7.7024	0.1324	3285.0	3682.3	7.5085
640	0.2091	3362.2	3780.4	7.8035	0.1388	3357.0	3773.5	7.6106
700	0.2232	3470.9	3917.4	7.9487	0.1484	3466.5	3911.7	7.7571

TABLE A-4 *(Continued)*

p = 40 bar = 4.0 MPa
(T_{sat} = 250.4°C)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	0.04978	2602.3	2801.4	6.0701
280	0.05546	2680.0	2901.8	6.2568
320	0.06199	2767.4	3015.4	6.4553
360	0.06788	2845.7	3117.2	6.6215
400	0.07341	2919.9	3213.6	6.7690
440	0.07872	2992.2	3307.1	6.9041
500	0.08643	3099.5	3445.3	7.0901
540	0.09145	3171.1	3536.9	7.2056
600	0.09885	3279.1	3674.4	7.3688
640	0.1037	3351.8	3766.6	7.4720
700	0.1110	3462.1	3905.9	7.6198
740	0.1157	3536.6	3999.6	7.7141

p = 60 bar = 6.0 MPa
(T_{sat} = 275.64°C)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	0.03244	2589.7	2784.3	5.8892
280	0.03317	2605.2	2804.2	5.9252
320	0.03876	2720.0	2952.6	6.1846
360	0.04331	2811.2	3071.1	6.3782
400	0.04739	2892.9	3177.2	6.5408
440	0.05122	2970.0	3277.3	6.6853
500	0.05665	3082.2	3422.2	6.8803
540	0.06015	3156.1	3517.0	6.9999
600	0.06525	3266.9	3658.4	7.1677
640	0.06859	3341.0	3752.6	7.2731
700	0.07352	3453.1	3894.1	7.4234
740	0.07677	3528.3	3989.2	7.5190

p = 80 bar = 8.0 MPa
(T_{sat} = 295.06°C)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	0.02352	2569.8	2758.0	5.7432
320	0.02682	2662.7	2877.2	5.9489
360	0.03089	2772.7	3019.8	6.1819
400	0.03432	2863.8	3138.3	6.3634
440	0.03742	2946.7	3246.1	6.5190
480	0.04034	3025.7	3348.4	6.6586
520	0.04313	3102.7	3447.7	6.7871
560	0.04582	3178.7	3545.3	6.9072
600	0.04845	3254.4	3642.0	7.0206
640	0.05102	3330.1	3738.3	7.1283
700	0.05481	3443.9	3882.4	7.2812
740	0.05729	3520.4	3978.7	7.3782

p = 100 bar = 10.0 MPa
(T_{sat} = 311.06°C)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	0.01803	2544.4	2724.7	5.6141
320	0.01925	2588.8	2781.3	5.7103
360	0.02331	2729.1	2962.1	6.0060
400	0.02641	2832.4	3096.5	6.2120
440	0.02911	2922.1	3213.2	6.3805
480	0.03160	3005.4	3321.4	6.5282
520	0.03394	3085.6	3425.1	6.6622
560	0.03619	3164.1	3526.0	6.7864
600	0.03837	3241.7	3625.3	6.9029
640	0.04048	3318.9	3723.7	7.0131
700	0.04358	3434.7	3870.5	7.1687
740	0.04560	3512.1	3968.1	7.2670

p = 120 bar = 12.0 MPa
(T_{sat} = 324.75°C)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	0.01426	2513.7	2684.9	5.4924
360	0.01811	2678.4	2895.7	5.8361
400	0.02108	2798.3	3051.3	6.0747
440	0.02355	2896.1	3178.7	6.2586
480	0.02576	2984.4	3293.5	6.4154
520	0.02781	3068.0	3401.8	6.5555
560	0.02977	3149.0	3506.2	6.6840
600	0.03164	3228.7	3608.3	6.8037
640	0.03345	3307.5	3709.0	6.9164
700	0.03610	3425.2	3858.4	7.0749
740	0.03781	3503.7	3957.4	7.1746

p = 140 bar = 14.0 MPa
(T_{sat} = 336.75°C)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
Sat.	0.01149	2476.8	2637.6	5.3717
360	0.01422	2617.4	2816.5	5.6602
400	0.01722	2760.9	3001.9	5.9448
440	0.01954	2868.6	3142.2	6.1474
480	0.02157	2962.5	3264.5	6.3143
520	0.02343	3049.8	3377.8	6.4610
560	0.02517	3133.6	3486.0	6.5941
600	0.02683	3215.4	3591.1	6.7172
640	0.02843	3296.0	3694.1	6.8326
700	0.03075	3415.7	3846.2	6.9939
740	0.03225	3495.2	3946.7	7.0952

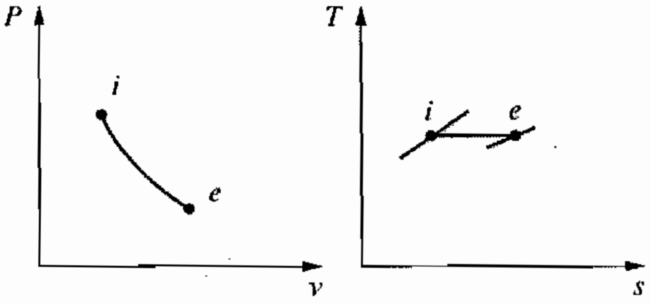
[illegible] *(Continued)*

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 160 bar = 16.0 MPa (T_{sat} = 347.44°C)				p = 180 bar = 18.0 MPa (T_{sat} = 357.06°C)			
Sat.	0.00931	2431.7	2580.6	5.2455	0.00749	2374.3	2509.1	5.1044
360	0.01105	2539.0	2715.8	5.4614	0.00809	2418.9	2564.5	5.1922
400	0.01426	2719.4	2947.6	5.8175	0.01190	2672.8	2887.0	5.6887
440	0.01652	2839.4	3103.7	6.0429	0.01414	2808.2	3062.8	5.9428
480	0.01842	2939.7	3234.4	6.2215	0.01596	2915.9	3203.2	6.1345
520	0.02013	3031.1	3353.3	6.3752	0.01757	3011.8	3378.0	6.2960
560	0.02172	3117.8	3465.4	6.5132	0.01904	3101.7	3444.4	6.4392
600	0.02323	3201.8	3573.5	6.6399	0.02042	3188.0	3555.6	6.5696
640	0.02467	3284.2	3678.9	6.7580	0.02174	3272.3	3663.6	6.6905
700	0.02674	3406.0	3833.9	6.9224	0.02362	3396.3	3821.5	6.8580
740	0.02808	3486.7	3935.9	7.0251	0.02483	3478.0	3925.0	6.9623
	p = 200 bar = 20.0 MPa (T_{sat} = 365.81°C)				p = 240 bar = 24.0 MPa			
Sat.	0.00583	2293.0	2409.7	4.9269				
400	0.00994	2619.3	2818.1	5.5540	0.00673	2477.8	2639.4	5.2393
440	0.01222	2774.9	3019.4	5.8450	0.00929	2700.6	2923.4	5.6506
480	0.01399	2891.2	3170.8	6.0518	0.01100	2838.3	3102.3	5.8950
520	0.01551	2992.0	3302.2	6.2218	0.01241	2950.5	3248.5	6.0842
560	0.01689	3085.2	3423.0	6.3705	0.01366	3051.1	3379.0	6.2448
600	0.01818	3174.0	3537.6	6.5048	0.01481	3145.2	3500.7	6.3875
640	0.01940	3260.2	3648.1	6.6286	0.01588	3235.5	3616.7	6.5174
700	0.02113	3386.4	3809.0	6.7993	0.01739	3366.4	3783.8	6.6947
740	0.02224	3469.3	3914.1	6.9052	0.01835	3451.7	3892.1	6.8038
800	0.02385	3592.7	4069.7	7.0544	0.01974	3578.0	4051.6	6.9567
	p = 280 bar = 28.0 MPa				p = 320 bar = 32.0 MPa			
400	0.00383	2223.5	2330.7	4.7494	0.00236	1980.4	2055.9	4.3239
440	0.00712	2613.2	2812.6	5.4494	0.00544	2509.0	2683.0	5.2327
480	0.00885	2780.8	3028.5	5.7446	0.00722	2718.1	2949.2	5.5968
520	0.01020	2906.8	3192.3	5.9566	0.00853	2860.7	3133.7	5.8357
560	0.01136	3015.7	3333.7	6.1307	0.00963	2979.0	3287.2	6.0246
600	0.01241	3115.6	3463.0	6.2823	0.01061	3085.3	3424.6	6.1858
640	0.01338	3210.3	3584.8	6.4187	0.01150	3184.5	3552.5	6.3290
700	0.01473	3346.1	3758.4	6.6029	0.01273	3325.4	3732.8	6.5203
740	0.01558	3433.9	3870.0	6.7153	0.01350	3415.9	3847.8	6.6361
800	0.01680	3563.1	4033.4	6.8720	0.01460	3548.0	4015.1	6.7966
900	0.01873	3774.3	4298.8	7.1084	0.01633	3762.7	4285.1	7.0372

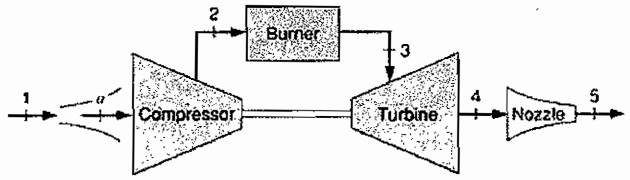
THERMODYNAMICS

Doctoral Qualifying Examination, January 2010
Mechanical Engineering, Columbia University

1. A reversible process in a steady flow of air with negligible kinetic and potential energy changes is shown in Figure below. Indicate the change in enthalpy, and the transfer of work and heat as positive, zero, or negative, explain reasons.



2. A turbojet engine operates in an ideal air-standard cycle as shown below. The pressure and temperature at the compressor inlet are 90 kPa and 290 K. The pressure ratio of the compressor is 14, and the turbine inlet temperature is 1500 K. The gas leaves the nozzle and expands to 90 kPa.
   a. Determine the pressure and temperature at the nozzle inlet, and the velocity and Mach number at the nozzle exit.
   b. If the same cycle is to be used for a turboprop engine, where the turbine is used to power both the compressor and the propeller. Assume the turbine exit temperature is 900 K. Find the specific work of the propeller and the nozzle exit velocity.



THERMODYNAMICS

Doctoral Qualifying Examination, January 2010
Mechanical Engineering, Columbia University

Problem 3 Derive the expression for mass flow rate through a sonic nozzle:

$$\dot{m} = A^* P_o \frac{1}{\sqrt{RT_o}} \left[k \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \right]^{1/2}$$

where A^* is the throat area, P_o and T_0 are upstream stagnation pressure and temperatures and k is the specific heat ratio. Clearly list the assumptions that are made during the derivation. Speed of sound for an ideal gas is $\sqrt{kRT}$.

Relevant Equations for Thermodynamics Problems:

Isentropic relations for an Ideal Gas: $\left(\frac{P_2}{P_1}\right) = \left(\frac{v_1}{v_2}\right)^k$, $\left(\frac{T_2}{T_1}\right) = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

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THERMODYNAMICS

Problem 1:

Consider a jet engine using liquid methane (CH_4) as fuel with 300% theoretical *dry* air. The methane enters the engine as saturated liquid at 1.4 MPa, while the air enters at 0.1 MPa and 298 K. Both have negligible entrance velocities. The products of combustion exit the engine at 0.1 MPa and 1000K, at an unknown velocity v_P. Assume the engine is adiabatic. Determine the following:

a) the balanced combustion equation for methane and 300% theoretical *dry* air.

b) the exit velocity of the combustion products in ***meters/sec***, v_P.

NOTE:

- $\Delta\bar{h}_{H2O(v)} = 25{,}978$ kJ/kgmole
- $\Delta\bar{h}_{CO2} = 33{,}405$ kJ/kgmole
- $\Delta\bar{h}_{O2,reactant} = 22{,}707$ kJ/kgmole
- $\Delta\bar{h}_{N2,reactant} = 21{,}460$ kJ/kgmole
- Enthalpy of formation for liquid CH4 = $\bar{h}_f^0{}_{CH4(l)} = -83{,}545$ kJ/kgmole

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THERMODYNAMICS

Problem 2:

You are given the following data about an actual gasoline engine assumed to operate on an air-standard (use properties of air) cycle. The compression and expansion processes can be idealized as polytropic with n=1.3 and 1.5 respectively. Air enters the engine at absolute temperature T_o degrees K. During compression the temperature rises to $2T_o$. During the constant volume heat addition process, combustion adds enough heat to raise the temperature further to $7T_o$, followed by expansion. After expansion the exhaust gases can be assumed to leave during a constant volume process. We wish to carry out an energy balance of the cycle. Specifically, determine what fraction of the heat supplied

a) ends up as useful work
b) ends up as heat lost from the walls and
c) ends up as increase in internal energy of air (and hence goes out the exhaust)

Compare the efficiency of the above cycle to that of an ideal Otto cycle (both the compression and expansion are isentropic) with the compression ratio of the above cycle.

$\eta_{\text{ideal otto}} = 1 - (1/(r^{k-1}))$ where r = compression ratio

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THERMODYNAMICS

Problem 3:

a) Clearly identifying the assumptions involved, obtain the Tds relations
$du=Tds-Pdv$ and $dh=Tds+vdP$.

b) Define the Gibbs function g and the Helmoltz function, a. Hence obtain the Maxwell relations for a simple compressible substance

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USEFUL EQUATIONS FOR THERMODYNAMICS QUESTIONS

Continuity:

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

1st Law of Thermodynamics

$$\frac{dE_{cv}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_i \dot{m}_i h_{total,i} - \sum_e \dot{m}_e h_{total,e}$$

$$Q_{CV} + \sum_R n_i\left(\bar{h}_f^0 + \Delta\bar{h}\right)_i = W_{CV} + \sum_P n_e\left(\bar{h}_f^0 + \Delta\bar{h}\right)_e$$

2nd Law of Thermodynamics

$$S_2 - S_1 = \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = \sum \frac{\dot{Q}}{T} + \dot{S}_{gen}$$

Flow Availability (Exergy) Equation

$$\psi_i - \psi_e = \left(h_{total,i} - h_{total,e}\right) - T_o\left(s_i - s_{ei}\right)$$

where $h_{total} = h + \frac{1}{2}v^2 + gz$

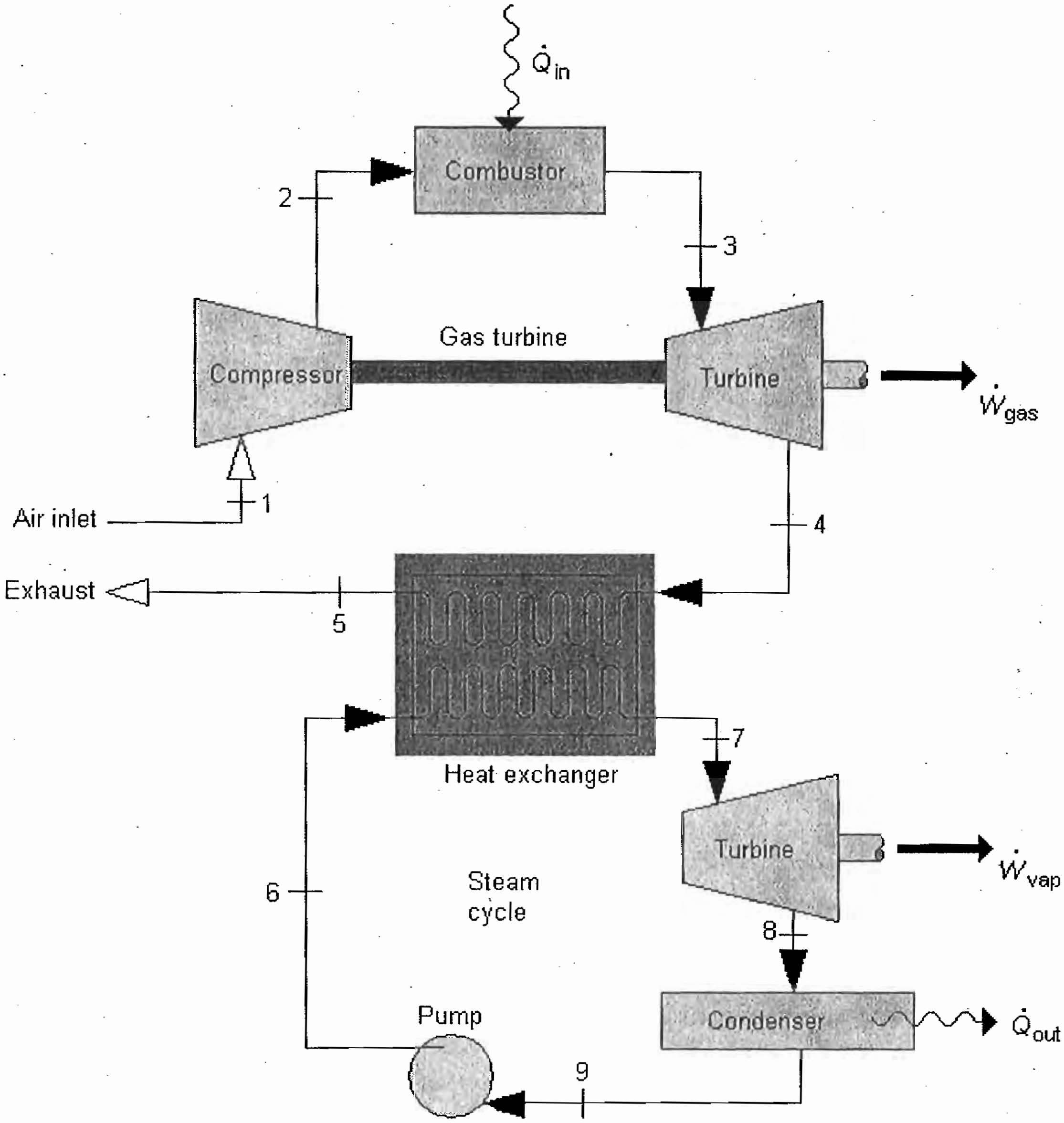
THERMODYNAMICS

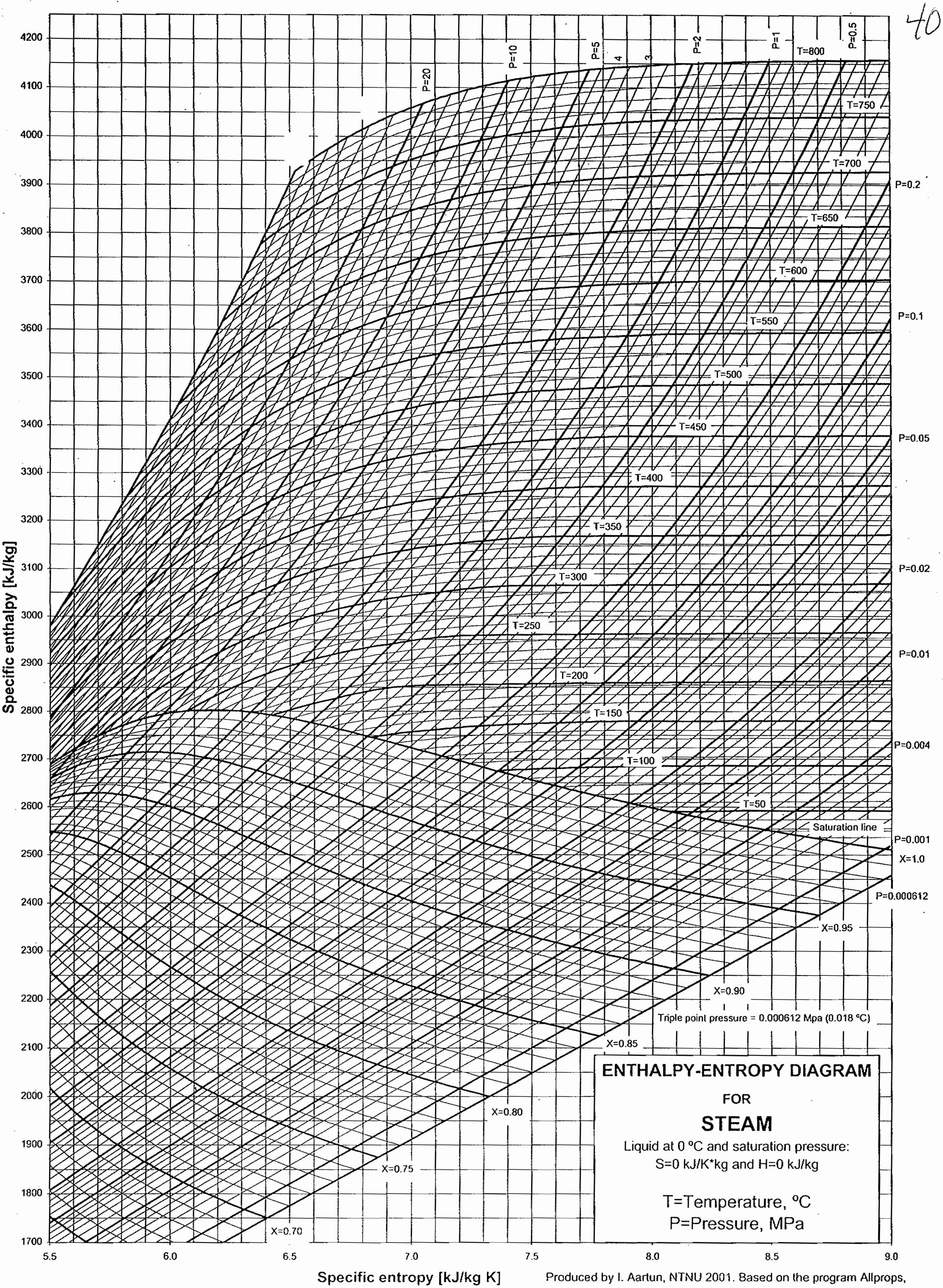
Doctoral Qualifying Examination, January 2008
Mechanical Engineering, Columbia University,

Problem 1 A combined power cycle couples two power cycles such that the energy discharged by one cycle is used as energy input to the second cycle. A sketch of one such combined gas turbine–vapor compression power plant is shown in Fig. 1. Air enters a compressor at 0.1 MPa, 300 K (T_1), where it is compressed isentropically, and exits at a pressure of 1.3 MPa. The air passing through the combustor receives energy by heat transfer at the rate of 50 MW with no significant drop in pressure. The temperature at the exit of the combustor is 1580 K (T_3). Air expands isentropically in the turbine and exits the turbine at 0.1 MPa. **Only part of the work output of the turbine is used to run the compressor**. The air then passes through the heat exchanger where it transfers heat at constant pressure to water from the exit of the pump. Air exhausts from the heat exchanger at 0.1 MPa, 400 K (T_5). The steam cycle operates between pressures of 0.1 MPa and 0.01 MPa. The heat transfer in the heat exchanger and the condenser occur at constant pressures. Steam enters the turbine at 0.1 MPa and 500 °C (T_7). The exit from the condenser is saturated liquid at 0.01 MPa. The isentropic efficiency of the turbine is 90 %. The pump in the steam cycle is isentropic. Answer the following questions:

1. Find T_2, the temperature at the exit of the compressor in the air cycle.
2. Determine the mass flow rate in the air cycle, $\dot{m}_a$.
3. Determine T_4, the temperature at the exit of the turbine in the air cycle.
4. Determine the power generated by the turbine and the power required to run the compressor in the air cycle, $\dot{W}_{Ca}$.
5. Draw a T–s diagram of the vapor compression cycle and mark the points corresponding to the points 6, 7, 8, and 9. Indicate the direction of the cycle. Determine the enthalpies at 9 (exit from condenser), 6 (exit from pump), and 8 (exit from turbine).
6. Determine the mass flow rate in the vapor compression cycle, $\dot{m}_v$.
7. Determine the power generated by the turbine, $\dot{W}_{vap}$, and the power required to run the pump in the steam cycle, $\dot{W}_{Pv}$
8. Determine the overall efficiency of the combined cycle.

Properties of air: $C_p = 1.004\ \text{kJkg}^{-1}\text{K}^{-1}$; $R = 0.287\ \text{kJkg}^{-1}\text{K}^{-1}$.
Properties of water: @ 0.01 MPa, $h_f = 191.81\ \text{kJkg}^{-1}$. For rest of the properties of water or steam, use the h-s diagram provided. Make sure you mark the points legibly on the h-s diagram and return it with your answer sheet. Make reasonable assumptions for any other values not provided. Air can be treated as an ideal gas with the above value of specific heat.


$\dot{Q}_{in}$
Combustor
2
3
Gas turbine
Compressor
Turbine
$\dot{W}_{gas}$
Air inlet
1
4
Exhaust
5
Heat exchanger
7
Turbine
$\dot{W}_{vap}$
6
Steam
cycle
8
Pump
Condenser
$\dot{Q}_{out}$
9



ENTHALPY-ENTROPY DIAGRAM
FOR
STEAM

Liquid at 0 °C and saturation pressure:
S=0 kJ/K*kg and H=0 kJ/kg

T=Temperature, °C
P=Pressure, MPa

Produced by I. Aartun, NTNU 2001. Based on the program Allprops, Center for Applied Thermodynamic Studies, University of Idaho.

THERMODYNAMICS

Doctoral Qualifying Examination, January 2008
Mechanical Engineering, Columbia University,

Problem 2. Consider a jet engine using liquid methane (CH_4) as fuel with 300% theoretical *dry* air. The methane enters the engine as saturated liquid at 1.4 MPa, while the air enters at 0.1 MPa and 298 K. Both have negligible entrance velocities. The products of combustion exit the engine at 0.1 MPa and 1000K, at an unknown velocity v_P. Assume the engine is adiabatic. Determine the following:

(a).The balanced combustion equation for methane and 300% theoretical *dry* air.
(b).The exit velocity of the combustion products in ***meters/sec***, v_P.

NOTE:

- $\Delta\bar{h}_{H2O(v)} = 25{,}978$ kJ/kgmole
- $\Delta\bar{h}_{CO2} = 33{,}405$ kJ/kgmole
- $\Delta\bar{h}_{O2,reactant} = 22{,}707$ kJ/kgmole
- $\Delta\bar{h}_{N2,reactant} = 21{,}460$ kJ/kgmole
- Enthalpy of formation for liquid CH4 = $\bar{h}^0_{f\ CH4(l)} = -83{,}545$ kJ/kgmole

Problem 3. A steam turbine receives superheated steam at 350 °C and 2 MPa and exhausts to a pressure of 8 kPa. The isentropic efficiency of the turbine is 75%.

(a). Draw a control volume and list assumptions
(b). What fraction of the flow exergy (availability) is produced as work by the turbine?
(c). What is the second law efficiency of the turbine?

Property Data for Problem #2

$T_0 = 25°C$; $P_0 = 101.3$ kPa

State	T (°C)	P (kPa)	h (kJ/kg)	s (kJ/kg K)	x (Quality)
Turbine In	350	2000	3136.6	6.9556	---
Turbine Out (Isentropic)	41.5	8	2176.2	6.9556	0.8335
Turbine Out (Actual)	41.5	8	TBD	TBD	0.9335

Some Thermodynamics Equations:

Continuity:

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

1st Law of Thermodynamics

$$\frac{dE_{cv}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_i \dot{m}_i h_{total,i} - \sum_e \dot{m}_e h_{total,e}$$

$$Q_{CV} + \sum_R n_i \left(\bar{h}_f^0 + \Delta \bar{h}\right)_i = W_{CV} + \sum_P n_e \left(\bar{h}_f^0 + \Delta \bar{h}\right)_e$$

2nd Law of Thermodynamics

$$S_2 - S_1 = \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = \sum \frac{\dot{Q}}{T} + \dot{S}_{gen}$$

Flow Availability (Exergy) Equation

$$\psi_i - \psi_e = \left(h_{total,i} - h_{total,e}\right) - T_o\left(s_i - s_{ei}\right)$$

Where $h_{total} = h + \frac{1}{2}v^2 + gz$

THERMODYNAMICS

Doctoral Qualifying Examination, January 2007
Mechanical Engineering, Columbia University

Problem 1:

Liquid propane (C_3H_8) enters a combustion chamber at 25 deg C at a rate of 1.2 kg/min where it is mixed and burned with 150 percent excess air that enters the combustion chamber at 12 deg C. Assume the combustion is complete and the exit temperature of the combustion gases is 1200 K (927 deg C).

a. [2 points] Write the complete and balanced chemical equation for this reaction. Note that dry air is assumed.
b. [3 points] Determine the mass flow rate of air in kg air/min. Show all relevant equations and clearly state assumptions.
c. [5 points] Determine the ***rate*** of heat transfer from the combustion chamber in kJ/min. Show all relevant equations and clearly state assumptions.

You are given the following information for this problem:

- Molar mass of liquid propane is 44 kg/kmol
- Molar mass of air is 29 kg/kmol

Substance	$\bar{h}_f^o$ (kJ/kmol)	$\bar{h}_{285K}$ (kJ/kmol)	$\bar{h}_{298K}$ (kJ/kmol)	$\bar{h}_{1200K}$ (kJ/kmol)
C_3H_8 (l)	-118,910	---	---	---
O_2	0	8296.5	8682	38,447
N_2	0	8286.5	8669	36,777
H_2O (g)	-241,820	---	9904	44,380
CO_2	-393,520	---	9364	53,848

Some Thermodynamic Equations:

Continuity:

$$\frac{dm_{CV}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

1st Law of Thermodynamics

$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_i \dot{m}_i h_{total,i} - \sum_e \dot{m}_e h_{total,e}$$

$$Q_{CV} + \sum_R N_R \left(\bar{h}_f^o + \Delta\bar{h}\right)_R = W_{CV} + \sum_P N_P \left(\bar{h}_f^o + \Delta\bar{h}\right)_P$$

2nd Law of Thermodynamics

$$S_2 - S_1 = \sum_P \dot{m}_P s_P - \sum_R \dot{m}_R s_R = \sum \frac{\dot{Q}}{T} + \dot{S}_{gen}$$

$$\sum_P N_P \bar{s}_P - \sum_R N_R \bar{s}_R = \sum \frac{\dot{Q}}{T} + \dot{S}_{gen}$$

THERMODYNAMICS

Doctoral Qualifying Examination, January 2007
Mechanical Engineering, Columbia University

Problem 2: Sketch the air-standard ideal Diesel cycle on T-s and P-v diagrams. Define the compression ratio and the cutoff ratios for this cycle. Now obtain an expression for the cycle efficiency in terms of these and the ratio of specific heats.

Problem 3 Derive the expression for mass flow rate through a sonic nozzle:

$$\dot{m} = A^* P_o \frac{1}{\sqrt{RT_o}} \left[k \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \right]^{1/2}$$

where A^* is the throat area, P_o and T_0 are upstream stagnation pressure and temperatures and k is the specific heat ratio. Clearly list the assumptions that are made during the derivation. Speed of sound for an ideal gas is $\sqrt{kRT}$.

Relevant Equations for Thermodynamics Problems:

Isentropic relations for an Ideal Gas: $\left(\frac{P_2}{P_1}\right) = \left(\frac{v_1}{v_2}\right)^k$, $\left(\frac{T_2}{T_1}\right) = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

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THERMODYNAMICS

Doctoral Qualifying Examination, January 2006
Mechanical Engineering, Columbia University

Problem 1:

Consider a jet engine using liquid methane (CH_4) as fuel with 300% theoretical *dry* air. The methane enters the engine as saturated liquid at 1.4 MPa, while the air enters at 0.1 MPa and 298 K. Both have negligible entrance velocities. The products of combustion exit the engine at 0.1 MPa and 1000K, at an unknown velocity v_P. Assume the engine is adiabatic. Determine the following:

a. **[3 points]** the balanced combustion equation for methane and 300% theoretical *dry* air.

b. **[7 points]** the exit velocity of the combustion products in ***meters/sec***, v_P.

NOTE:

- $\Delta\bar{h}_{H2O(v)} = 25{,}978$ kJ/kgmole
- $\Delta\bar{h}_{CO2} = 33{,}405$ kJ/kgmole $\Big) \; \Delta h_f = ?$
- $\Delta\bar{h}_{O2,reactant} = 22{,}707$ kJ/kgmole
- $\Delta\bar{h}_{N2,reactant} = 21{,}460$ kJ/kgmole
- Enthalpy of formation for liquid CH4 = $\bar{h}^0_{f\,CH4(l)} = -83{,}545$ kJ/kgmole

$$\bar{h}^{o}_{f}\,(CO_2) = -393500 \text{ kJ/kmol}$$

$$\bar{h}^{o}_{f}\,(CO_2) = -241826 \text{ kJ/kmol}$$

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THERMODYNAMICS

Doctoral Qualifying Examination, January 2006
Mechanical Engineering, Columbia University

Problem 2:

A steam turbine receives superheated steam at 350 °C and 2 MPa and exhausts to a pressure of 8 kPa. The isentropic efficiency of the turbine is 75%.

a. **[2 points]** Draw a control volume and list assumptions

b. **[4 points]** What fraction of the flow exergy (availability) is produced as work by the turbine?

c. **[4 points]** What is the second law efficiency of the turbine?

Property Data for Problem #2
$T_0 = 25°C$; $P_0 = 101.3$ kPa

State	T (°C)	P (kPa)	h (kJ/kg)	s (kJ/kg K)	x (Quality)
Turbine In	350	2000	3136.6	6.9556	---
Turbine Out (Isentropic)	41.5	8	2176.2	6.9556	0.8335
Turbine Out (Actual)	41.5	8	TBD	TBD	0.9335

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THERMODYNAMICS

Doctoral Qualifying Examination, January 2006
Mechanical Engineering, Columbia University

Problem 3:

A device works in a steady thermodynamic cycle: it receives heat $\dot{Q}_0$ from the atmosphere at a temperature T_0, and receives heat $\dot{Q}_S$ at a temperature T_S. Simultaneously, the system rejects heat $\dot{Q}_U$ at a temperature T_U. There are no other exchanges between the device and the surroundings.

a. [**4 points**] Express the first and second law of thermodynamics for a control volume surrounding the device.

b. [**6 points**]Assuming $T_S>T_U>T_0$, express the maximum theoretical value of $\dot{Q}_U$ as a function of $\dot{Q}_S$ and the temperatures T_S, T_U, T_0.

Some Thermodynamics Equations:

Continuity:

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

1st Law of Thermodynamics

$$\frac{dE_{cv}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_i \dot{m}_i h_{total,i} - \sum_e \dot{m}_e h_{total,e}$$

$$Q_{CV} + \sum_R n_i \left(\bar{h}_f^0 + \Delta\bar{h}\right)_i = W_{CV} + \sum_P n_e \left(\bar{h}_f^0 + \Delta\bar{h}\right)_e$$

2nd Law of Thermodynamics

$$S_2 - S_1 = \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = \sum \frac{\dot{Q}}{T} + \dot{S}_{gen}$$

Flow Availability (Exergy) Equation

$$\psi_i - \psi_e = \left(h_{total,i} - h_{total,e}\right) - T_o\left(s_i - s_{ei}\right)$$

Where $h_{total} = h + \frac{1}{2}v^2 + gz$

THERMODYAMICS

Doctoral Qualifying Examination, January 2005
Mechanical Engineering, Columbia University

(some useful relations are provided on the next page)

Problem 1. An insulated rigid tank is divided into two compartments by a partition. One compartment contains 3 kmol of O2, and the other compartment contains 5 kmol of CO2. Both gases are initially at 25 °C and 200 kPa. Now the partition is removed, and the two gases are allowed to mix. Assuming the surroundings are at 25 °C and both gases behave as ideal gases, determine:

(a). the entropy change, ΔS.
(b). the irreversibility, I, associated with this process.
(c). is this process actually possible? Why?

Problem 2. A gas-turbine cycle (Brayton cycle) shown below in Figure 1.0 is used the basis for an automotive engine. In the first turbine, the gas expands to pressure P_5, just low enough for this turbine to drive the compressor. The gas is then expanded through the second turbine connected to the drive wheels. The data for the engine are shown in the figure. Assume that all processes are ideal. NOTE: $C_{p,\,air} = 1.004$ kJ/kg K; isentropic coefficient, k =1.4 for air.

(a). Draw T-s and P-v diagram; label processes 1-7 on diagram.
(b). Determine the intermediate pressure P_5.
(c). Determine the net specific work output of the engine.
(d). Find the air temperature, T_3, entering the burner.
(e). Calculate the thermal efficiency of the engine.

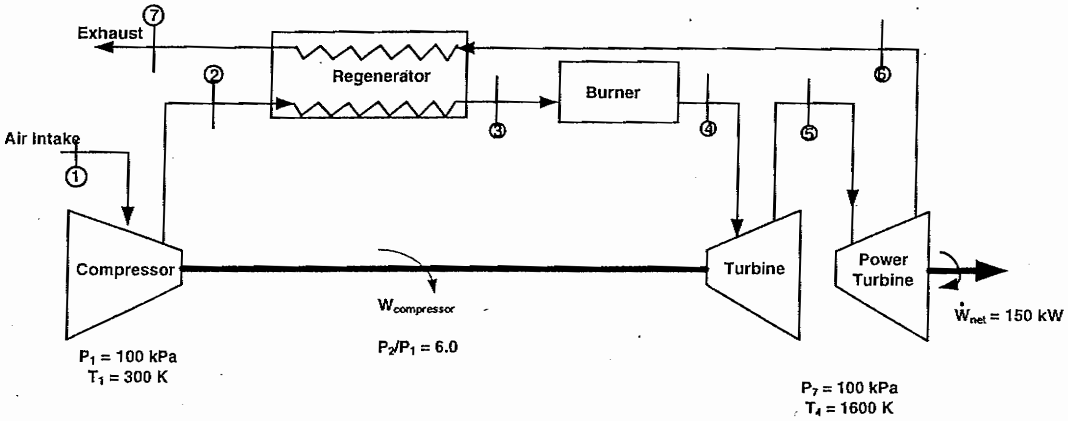


Figure 1.0 Gas Turbine Cycle for Problem # 2

Problem 3 Clearly identifying the assumptions involved, obtain the Tds relations:
$du=Tds-Pdv$ *and* $dh=Tds+vdP$.

Define the Gibbs function *g* and the Helmoltz function, *a*. Hence obtain the Maxwell relations for a simple compressible substance.

Some Thermodynamics Equations:

Continuity:

$$\frac{dm_{cv}}{dt}=\sum_i \dot{m}_i-\sum_e \dot{m}_e$$

1st Law of Thermodynamics

$$\frac{dE_{cv}}{dt}=\dot{Q}_{CV}-\dot{W}_{CV}+\sum_i \dot{m}_i h_{total,i}-\sum_e \dot{m}_e h_{total,e}$$

2nd Law of Thermodynamics

$$S_2-S_1=\sum_e \dot{m}_e s_e-\sum_i \dot{m}_i s_i=\sum\frac{\dot{Q}}{T}+\dot{S}_{gen}$$

Mixture Formulas

$$\Delta S_{mixture}=\sum \Delta S_i=\sum n_i\left(C_{p,i}\ln {}^{T_{i,2}}\!/_{T_{i,1}}-R_u\,{}^{P_{i,2}}\!/_{P_{i,1}}\right)=C_{p,i}\ln {}^{T_{i,2}}\!/_{T_{i,1}}-R_u\sum n_i\ln y_i$$

Where R_u= 8.314 kJ/kmolK and 'i' is the "i-th" component of the mixture.

$$y_i=\frac{n_i}{n_{mixture}}$$

Isentropic Relations

$$\frac{P_x}{P_y}=\left(\frac{T_x}{T_y}\right)^{k/(k-1)}$$

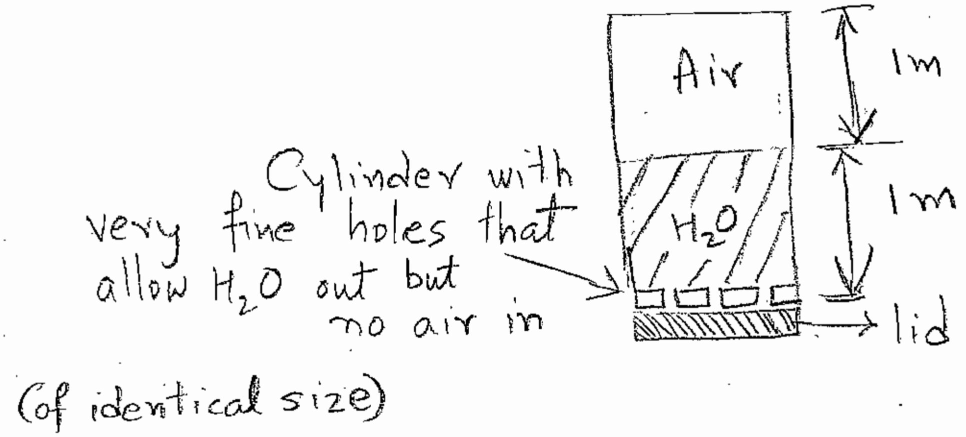
Thermodynamics Qualifying Exam (January 2004)

	Critical Point Data	**Triple Point Data**
Water:	374.14 C, 22.09 MPa, 0.00316 m^3/kg	0.01 C, 0.6113 kPa
Nitrogen:	126.2 K, 3.39 MPa, 0.00321 m^3/kg	-210 C, 12.53 kPa

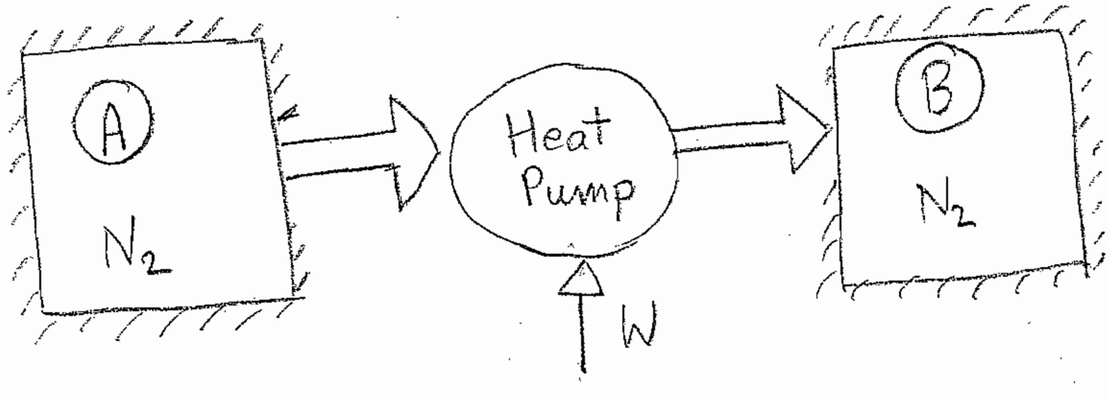
Ideal Gas Properties at 25C.

Gas	Mol Wt	R kJ/kgK	c_p kJ/kgK	c_v kJ/kgK	$c_p/c_v = k$
Air	29	0.287	1.004	0.717	1.400
Steam	18	0.4615	1.872	1.410	1.327
Nitrogen	28	0.297	1.042	0.745	1.400

Problem 1: A 2 m tall cylinder has very fine holes in the bottom as shown in the Figure below. The holes are covered with a water-tight lid. The cylinder is initially filled with liquid water 1 m high, on top of which is 1 m high air column. The air column is initially at atmospheric pressure of 100 kPa. When the lid is suddenly removed liquid water begins to emerge out of the holes as the water pressure near the holes is higher than the ambient pressure of 100 kPa. The holes are so fine that they do not allow air bubbles from the outside to rise through the water column. At what water column height do you expect the flow of water to stop? If you think the entire water column will flow out, you need to prove this result. Assume a slow process with constant T at 27 C. Assume density of water=1000 kg/m3 and g=10 m/sec2.



Problem 2: Two rigid tanks, shown below, each contain 10 kg of N2 gas at 1000 K, 500 kPa. They are now thermally connected to a reversible heat pump, which heats one and cools the other with no heat transfer from either tank to the surroundings. When one tank is heated to 1500 K the process stops. Find the final (P, T) in both tanks and the work input to the heat pump, assuming constant heat capacities.



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Ph.D Qualification Examination/Spring 2004
Mechanical Engineering Department, Columbia University

Thermodynamics-

Problem 3. Two alternative systems are under consideration for bringing a stream of air from 17 to 52°C at an essentially constant pressure of 1 bar (1 atm):

System 1: The air temperature is increased as a consequence of the stirring of a liquid surrounding the line carrying the air. (see Figure 1 below)

System 2: The air temperature is increased by passing it through one side of a counterflow heat exchanger. On the other side, steam condenses at a pressure of 1 bar from saturated vapor to saturated liquid. (see Figure 2 below)

Assume: both systems operate at steady state; all kinetic and potential energy effects can be ignored and no significant heat transfer with the surroundings occurs.

For each of the two systems:

(a) Calculate the rate of entropy production, in kJ/K per kg of air passing through System 1 and System 2. LIST ALL ASSUMPTIONS and JUSTIFY where necessary.
(b) Based on your answers to part (a) is the process possible for System 1? System 2? Justify your answers. (Brief statements are accepted)
(c) Based on your answers to part (a) which system is better ***thermodynamically***. *Why?*

Relevant Data:

$s^o(T_2 = 325K) = 1.78249$ kJ/kgK; $s^o(T_1 = 290K) = 1.66802$ kJ/kgK
At 1 bar: $s_4 = 1.3026$ kJ/kgK; $s_3 = 7.3594$ kJ/kgK
$h_1 = 290.16$ kJ/kg; $h_2 = 325.31$ kJ/kg; $h_3 = 2675.5$ kJ/kg; $h_4 = 417.46$ kJ/kg

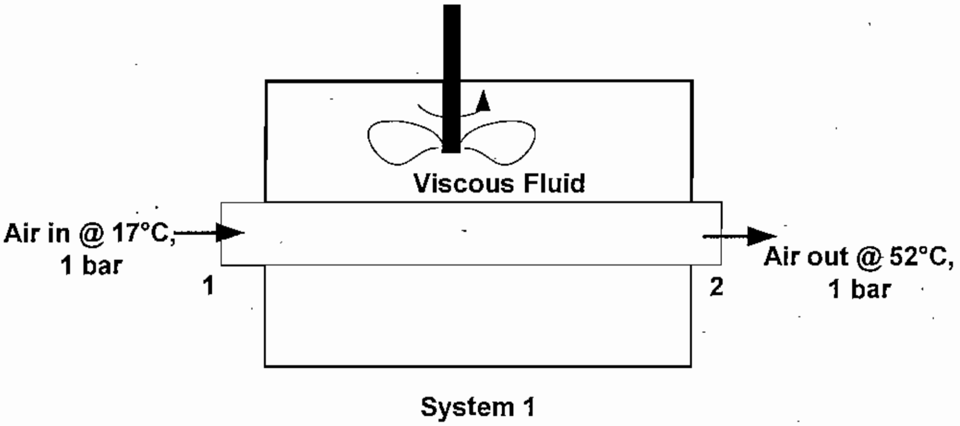

Figure 1 System 1 Schematic

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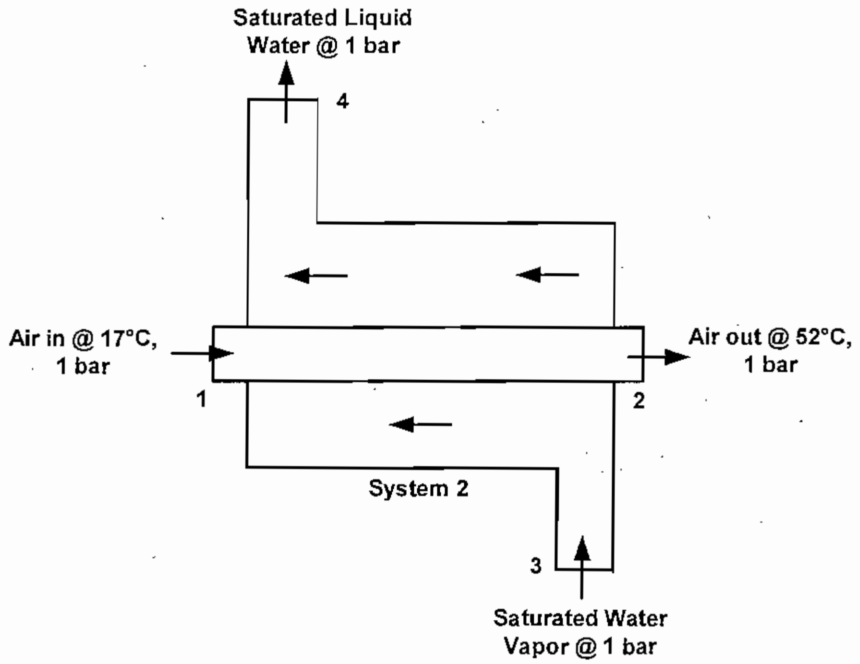

Figure 2 System 2 Schematic

Problem 4 Three SSSF (Steady State Steady Flow) flows are mixed in an adiabatic chamber at 150 kPa. The characteristics of each flow are given as:

Flow 1: O_2; mdot = 2 kg/sec; $T_1(O_2) = 340$ K at 150 kPa; $C_p = 0.922$ kJ/kgK;
mass fraction $= y_{O2} = 0.2285$; O_2 gas constant: $R_{O2} = 0.2598$ kJ/kgK

Flow 2: N_2; mdot = 4 kg/sec; $T_1(N_2) = 280$ K at 150 kPa; $C_p = 1.042$ kJ/kgK
mass fraction $= y_{N2} = 0.5223$; N_2 gas constant: $R_{N2} = 0.2969$ kJ/kgK

Flow 3: CO_2; mdot = 3 kg/sec; $T_1(CO_2) = 310$ K at 150 kPa; $C_p = 0.842$ kJ/kgK
mass fraction $= y_{CO2} = 0.2493$; CO_2 gas constant: $R_{CO2} = 0.1889$ kJ/kgK

NOTE: State '1' represents the inlet to the adiabatic chamber and state '2' represents the outlet.

For this set-up:

(a) Draw a control volume. List your assumptions and JUSTIFY (briefly)
(b) Find the exit temperature T_2 (K)
(c) Find the rate of entropy generation $\dot{S}_{gen}$ (kW/K) in the process.
(d) Is this process (3 SSSF flows mixing in the adiabatic chamber as described above) possible? Justify answer
(e) Calculate the irreversibility of the process if the environment is at $T_o = 25$ °C.