27/10/2014

UNIVERSITEIT VAN JOHANNESBURG

UNIVERSITY OF JOHANNESBURG

COURSE : ENGINEERING
SUBJECT : THERMOMACHINES 4B

TIME : 3 hours
MARKS: 100

Supplementary Examination 2014

Examiners : **Professor A Nurick**
Dr P F J Henning - 2014/10/27

This paper consists of 2 pages plus attachments
Requirements: Calculator

Attachments:
Information sheet
Steam tables

QUESTION 1

With respect to the design and operation of a steam power plant explain/discuss the following:

1.1 The demand cycle and its implications for the operation of power plant.
1.2 Why it takes some 8 h to 12 h to bring a steam turbine on line from cold. Indicate what problems could be experienced if this time is shortened
1.3 Axial differential expansion between the rotor shaft and casing of a multistage turbine and the location of the axial thrust bearing.
1.4 Why the natural frequency of the shaft and attachments of a steam turbine installed and running in its journal bearings differs from that of the shaft and attachments alone.
1.5 The axis of the combined shaft of a multistage turbine and generator is installed and runs in a shape approximating a catenary.
1.6 The effects of creep on the variation of stress distribution in a rotor shaft with time.
1.7 The air to fuel ratio of the air/coal mixture flowing between a ball or roller mill and the burners in the furnace differs from that of the stoichiometric plus excess air ratio.
1.8 Why are turbine blades connected together in batches at approximately two thirds their length.

(32 Marks)

QUESTION 2

An orifice plate is used to measure the flow of steam in a large diameter duct in a power station. The kinetic energies of the flow in the duct may be considered to be small compared to the internal energy of the steam and may be ignored. The upstream pressure of the steam is 16 MPa and its temperature is 425 °C. The steam passes so quickly through the orifice plate that heat losses are minimal and may be ignored. If the total pressure drop across the orifice plate is 375 kPa calculate:

2.1 The change in temperature of the steam as it passes through the orifice plate.
2.2 The change in entropy of the steam.
2.3 The increase in area on the T-S diagram due to the orifice plate if the temperature of the water in the condenser is 319 K.

(28 Marks)

QUESTION 3

Data available for a 'dried' sample of coal supplied to a power station included:

Nitrogen	**5 %**	
Oxygen	**8 %**	(by difference)
Sulphur	**2 %**	
Hydrogen	**3 %**	(just that in volatile matter)
Ash content	**Not given**	
Water content	**Not given**	
Calorific value of 'dried' coal	**22 MJ/kg**	

The ash content of the 'air dried' coal sample was 25% and that of the 'As Received' sample 23.5%.

Excess air:	**12 % (of Stoichiometric)**
CO_2 mass at a point in the flue gases	**16%**

3.1 Calculate the carbon and ash contents of the 'dried' coal.
3.2 Present in tabular form the percentages of constituents of the 'As Received', 'Air Dried', and 'Dried' coal samples.
3.3 Calculate the stoichiometric mass of air based on an 'As Received' coal sample.
3.4 Calculate and present in tabular form, the exhaust gas analysis (gravimetric, wet), resulting from combustion with total air (including excess air)(in kg/s as well as %).
3.3The percentage of carbon dioxide at a point in the flue gas ducting is measured at 16%. At this point in the system calculate:
3.4.1 The percentage of oxygen in the flue gases.
3.4.2 The mass of air which has leaked into the flue gases per kilogram of "As Received" coal.

(40 Marks)

INFORMATION PAGE:

Atomic weight of hydrogen	*as H:*	***1***
Atomic weight of carbon	*as C:*	***12***
Atomic weight of oxygen	*as O:*	***16***
Atomic weight of sulphur	*as S:*	***32***
Atomic weight of nitrogen	*as N:*	***14***

Oxygen in air (gravimetrc): ***23,15 %***
Oxygen in air (volumetric): ***20,95 %***

$$Q = \frac{1}{100}\{33.79\,C + 143.86\,(H - \frac{O}{8}) + 9.367\,S\}$$

$P_{stag} = P_{stat} + P_{dyn}$

$$dh = \frac{\partial h}{\partial P}dP + \frac{\partial h}{\partial T}dT$$

$$dS = \frac{\partial S}{\partial P}dP + \frac{\partial S}{\partial T}dT$$

$$S_2 - S_1 = C_P \ln\left(\frac{T_2}{T_1}\right) + R\ln(\frac{P_1}{P_2})$$

Table 3

P / MPa	T_{sat} (K)	θ_{sat}	v_f (m³/Mg)	v_g (m³/Mg)	u_f (kJ/kg)	u_g (kJ/kg)	h_f (kJ/kg)	h_{fg} (kJ/kg)	h_g (kJ/kg)	s_f (kJ/(kg·K))	s_{fg} (kJ/(kg·K))	s_g (kJ/(kg·K))
0.0006112	273.16	0.01	1.000	206200	0	2375	0.00	2501	2501	0	9.156	9.156
0.0010	280.1	7.0	1.000	129200	29.37	2385	29.37	2484	2514	0.106	8.869	8.975
0.0015	286.2	13.0	1.001	87980	54.75	2393	54.75	2470	2525	0.196	8.632	8.828
0.0020	290.7	17.5	1.001	67010	73.48	2399	73.49	2460	2533	0.261	8.463	8.724
0.0025	294.2	21.1	1.002	54260	88.47	2404	88.47	2451	2540	0.312	8.331	8.643
0.0030	297.2	24.1	1.003	45670	101.0	2408	101.0	2444	2545	0.354	8.224	8.578
0.0035	299.8	26.7	1.003	39480	111.9	2412	111.9	2438	2550	0.391	8.131	8.522
0.0040	302.1	29.0	1.004	34800	121.4	2415	121.4	2433	2554	0.423	8.052	8.475
0.0045	304.2	31.0	1.005	31140	130.0	2418	130.0	2428	2558	0.451	7.982	8.433
0.0050	306.0	32.9	1.005	28200	137.8	2420	137.8	2423	2561	0.476	7.919	8.395
0.006	309.3	36.2	1.007	23740	151.5	2425	151.5	2416	2567	0.521	7.810	8.331
0.007	312.2	39.0	1.008	20530	163.4	2428	163.4	2409	2572	0.559	7.717	8.276
0.008	314.7	41.5	1.009	18110	173.9	2432	173.9	2403	2577	0.593	7.636	8.229
0.009	316.9	43.8	1.009	16210	183.3	2435	183.3	2397	2581	0.623	7.565	8.188
0.010	319.0	45.8	1.010	14680	191.9	2438	191.9	2393	2584	0.649	7.502	8.151
0.011	320.9	47.7	1.011	13420	199.7	2440	199.7	2388	2588	0.674	7.443	8.117
0.012	322.6	49.4	1.012	12360	207.0	2442	207.0	2384	2591	0.696	7.390	8.086
0.013	324.2	51.1	1.013	11470	213.7	2445	213.7	2380	2594	0.717	7.341	8.058
0.014	325.7	52.6	1.013	10700	220.0	2447	220.1	2376	2596	0.737	7.296	[illegible]
0.015	327.1	54.0	1.014	10020	226.0	2449	226.0	2373	2599	0.755	7.254	[illegible]
0.016	328.5	55.3	1.015	9435	231.6	2450	231.6	2370	2601	0.772	7.215	7.987
0.018	331.0	57.8	1.016	8447	242.0	2454	242.0	2364	2606	0.804	7.142	7.946
0.020	333.2	60.1	1.017	7651	251.5	2457	251.5	2358	2610	0.832	7.077	7.909
0.022	335.3	62.2	1.018	6997	260.2	2459	260.2	2353	2613	0.858	7.018	7.876
0.024	337.2	64.1	1.019	6448	268.2	2462	268.2	2348	2617	0.882	6.964	7.846
0.025	338.1	65.0	1.020	6206	272.0	2463	272.0	2346	2618	0.893	6.939	7.832
0.030	342.3	69.1	1.022	5231	289.3	2468	289.3	2336	2625	0.944	6.825	7.769
0.035	345.9	72.7	1.025	4527	304.3	2473	304.4	2327	2631	0.988	6.729	7.717
0.040	349.0	75.9	1.026	3995	317.7	2477	317.7	2319	2637	1.026	6.645	7.671
0.045	351.9	78.7	1.028	3578	329.6	2481	329.7	2312	2642	1.060	6.571	7.631
0.050	354.5	81.3	1.030	3241	340.6	2484	340.6	2305	2646	1.091	6.504	7.595
0.055	356.9	83.7	1.032	2965	350.6	2487	350.7	2299	2650	1.120	6.443	7.563
0.060	359.1	86.0	1.033	2733	359.9	2490	360.0	2294	2654	1.146	6.388	7.532
0.065	361.2	88.0	1.035	2536	368.6	2492	368.7	2288	2657	1.170	6.336	7.506
0.070	363.1	90.0	1.036	2366	376.8	2495	376.8	2283	2660	1.192	6.289	7.481
0.075	364.9	91.8	1.037	2218	384.4	2497	384.5	2279	2663	1.213	6.245	7.458
0.080	366.7	93.5	1.039	2088	391.7	2499	391.8	2274	2666	1.233	6.203	7.436
0.085	368.3	95.2	1.040	1973	398.6	2501	398.7	2270	2669	1.252	6.164	7.416
0.090	369.9	96.7	1.041	1870	405.2	2503	405.3	2266	2671	1.270	6.126	7.396
0.095	371.4	98.2	1.042	1778	411.5	2505	411.6	2262	2673	1.287	6.091	7.378
0.10	372.8	99.6	1.043	1695	417.5	2506	417.6	2258	2676	1.303	6.058	7.361
0.11	375.5	102.3	1.045	1550	428.8	2509	428.9	2251	2680	1.333	5.996	7.329
0.12	378.0	104.8	1.047	1429	439.3	2512	439.5	2244	2684	1.361	5.939	[illegible]
0.13	380.3	107.1	1.049	1326	449.2	2515	449.3	2238	2687	1.387	5.886	[illegible]
0.14	382.5	109.3	1.051	1237	458.4	2518	458.5	2232	2691	1.411	5.837	[illegible]
0.15	384.5	111.4	1.053	1160	467.1	2520	467.2	2227	2694	1.434	5.791	7.225
0.16	386.5	113.3	1.054	1092	475.3	2522	475.5	2221	2697	1.455	5.748	7.203
0.17	388.3	115.2	1.056	1031	483.2	2524	483.3	2216	2700	1.476	5.707	7.183
0.18	390.1	116.9	1.058	978	490.6	2526	490.8	2211	2702	1.495	5.669	7.164
0.19	391.8	118.6	1.059	929	497.8	2528	498.0	2207	2705	1.513	5.633	7.146
0.20	393.4	120.2	1.061	885.9	504.6	2530	504.8	2202	2707	1.530	5.598	7.128
0.22	396.4	123.3	1.063	810.3	517.5	2533	517.7	2194	2711	1.563	5.534	7.097
0.24	399.2	126.1	1.066	746.9	529.5	2536	529.8	2186	2715	1.593	5.475	7.068
0.26	401.9	128.7	1.069	692.9	540.7	2539	541.0	2178	2719	1.621	5.420	7.041
0.28	404.4	131.2	1.071	646.4	551.3	2541	551.6	2171	2722	1.647	5.369	7.016
0.30	406.7	133.5	1.073	605.9	561.2	2544	561.5	2164	2725	1.672	5.321	6.993
0.32	408.9	135.8	1.076	570.3	570.7	2546	571.0	2157	2728	1.695	5.276	6.971
0.34	411.0	137.9	1.078	538.7	579.6	2548	580.0	2151	2731	1.717	5.234	6.951
0.36	413.0	139.9	1.080	510.6	588.2	2550	588.6	2145	2734	1.738	5.194	6.932
0.38	414.9	141.8	1.082	485.3	596.4	2552	596.9	2139	2736	1.758	5.156	6.914
0.40	416.8	143.6	1.084	462.4	604.3	2554	604.8	2134	2739	1.777	5.120	6.897
0.42	418.5	145.4	1.086	441.7	611.9	2555	612.3	2128	2741	1.795	5.085	6.880
0.44	420.2	147.1	1.087	422.8	619.2	2557	619.7	2123	2743	1.812	5.053	6.865
0.46	421.9	148.7	1.089	405.4	626.2	2558	626.7	2118	2745	1.829	5.021	6.850
0.48	423.5	150.3	1.091	389.5	633.0	2560	633.6	2113	2747	1.845	4.990	6.835

θ is the Celsius temperature

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Table 4
continued

Supercritical temperatures													
400 °C, θ = 400 K, T = 673.15 K				425 °C, θ = 425 K, T = 698.15 K				450 °C, θ = 450 K, T = 723.15 K					
v / m³/Mg	e / kJ/kg	h / kJ/kg	s / kJ/(kg·K)	v / m³/Mg	e / kJ/kg	h / kJ/kg	s / kJ/(kg·K)	v / m³/Mg	e / kJ/kg	h / kJ/kg	s / kJ/(kg·K)	P / MPa	θ_{sat} / K
310700	2969	3279	10.671	322200	3009	3331	10.746	333700	3050	3383	10.820	0.001	7.0
155300	2969	3279	10.351	161100	3009	3331	10.426	166900	3050	3383	10.500	0.002	17.5
77660	2969	3279	10.031	80550	3009	3331	10.107	83430	3050	3383	10.180	0.004	29.0
51770	2969	3279	9.844	53700	3009	3331	9.919	55620	3050	3383	9.993	0.006	36.2
38830	2969	3279	9.711	40270	3009	3331	9.787	41710	3050	3383	9.860	0.008	41.5
31060	2969	3279	9.608	32220	3009	3331	9.684	33370	3050	3383	9.757	0.01	45.8
15530	2969	3279	9.288	16110	3009	3331	9.364	16680	3049	3383	9.437	0.02	60.1
7763	2968	3279	8.968	8051	3009	3331	9.043	8340	3049	3383	9.117	0.04	75.9
5174	2968	3279	8.780	5366	3008	3330	8.856	5559	3049	3383	8.929	0.06	86.0
3879	2968	3278	8.647	4024	3008	3330	8.723	4168	3049	3382	8.796	0.08	93.5
3103	2968	3278	8.544	3218	3008	3330	8.620	3334	3049	3382	8.693	0.10	99.6
2067	2967	3277	8.356	2144	3008	3329	8.432	2222	3048	3382	8.505	0.15	111.4
1549	2967	3276	8.222	1607	3007	3328	8.298	1665	3048	3381	8.372	0.20	120.2
1031	2965	3275	8.034	1070	3006	3327	8.110	1109	3047	3380	8.184	0.30	133.5
773	2964	3273	7.899	802	3005	3326	7.975	831	3046	3378	8.050	0.40	143.6
617.2	2963	3272	7.794	640.7	3004	3324	7.871	664.1	3045	3377	7.945	0.5	151.8
13.7	2962	3270	7.709	533.3	3003	3323	7.785	552.9	3044	3376	7.860	0.6	158.8
49.7	2961	3269	7.636	456.6	3002	3322	7.713	473.4	3043	3375	7.787	0.7	165.0
34.2	2960	3267	7.572	399.1	3001	3320	7.650	413.8	3042	3373	7.724	0.8	170.4
341.1	2959	3266	7.516	354.3	3000	3319	7.594	367.5	3041	3372	7.669	0.9	175.4
306.6	2957	3264	7.466	318.5	2999	3317	7.544	330.4	3040	3371	7.619	1.0	179.9
203.0	2952	3256	7.270	211.1	2994	3310	7.349	219.1	3036	3364	7.425	1.5	198.3
151.2	2946	3248	7.129	157.4	2988	3303	7.208	163.5	3031	3358	7.286	2.0	212.4
99.33	2934	3232	6.923	103.6	2977	3288	7.006	107.8	3021	3344	7.085	3.0	233.8
73.39	2921	3215	6.771	76.72	2966	3273	6.857	79.99	3011	3331	6.938	4.0	250.3
57.80	2908	3197	6.649	60.57	2955	3257	6.737	63.27	3000	3317	6.820	5	263.9
47.38	2894	3179	6.544	49.79	2943	3241	6.635	52.12	2990	3303	6.721	6	275.6
39.92	2880	3160	6.451	42.07	2930	3225	6.546	44.14	2979	3288	6.635	7	285.8
34.31	2866	3140	6.367	36.27	2918	3208	6.466	38.15	2968	3273	6.558	8	295.0
29.93	2850	3120	6.289	31.75	2905	3191	6.392	33.48	2957	3258	6.487	9	303.3
26.41	2834	3098	6.216	28.12	2891	3173	6.324	29.74	2945	3242	6.422	10	311.0
23.51	2818	3076	6.146	25.15	2877	3154	6.259	26.67	2933	3226	6.361	11	318.0
21.08	2800	3053	6.079	22.66	2863	3135	6.198	24.11	2920	3210	6.303	12	324.6
19.01	2782	3029	6.013	20.54	2848	3115	6.138	21.94	2908	3193	6.248	13	330.8
17.22	2763	3004	5.949	18.72	2832	3095	6.081	20.07	2895	3176	6.195	14	336.6
15.66	2743	2978	5.885	17.13	2816	3073	6.025	18.45	2881	3158	6.144	15	342.1
14.27	2721	2950	5.821	15.74	2800	3051	5.970	17.02	2868	3140	6.095	16	347.3
13.03	2699	2920	5.757	14.49	2782	3029	5.916	15.76	2853	3121	6.046	17	352.3
1.91	2675	2889	5.693	13.38	2764	3005	5.862	14.63	2839	3102	5.999	18	357.0
0.89	2649	2856	5.626	12.38	2745	2981	5.809	13.62	2824	3083	5.952	19	361.4
52	2621	2820	5.558	11.47	2726	2955	5.755	12.71	2808	3062	5.906	20	365.7
62	2558	2740	5.411	9.869	2683	2900	5.646	11.11	2776	3020	5.815	22	373.7
38	2480	2642	5.244	8.500	2636	2841	5.534	9.766	2741	2975	5.724	24	
5.287	2377	2515	5.037	7.306	2584	2774	5.416	8.613	2704	2928	5.633	26	
3.857	2231	2339	4.763	6.246	2525	2700	5.290	7.611	2664	2877	5.540	28	
2.806	2075	2159	4.485	5.296	2457	2616	5.154	6.731	2621	2823	5.446	30	°C (sat)
2.107	1920	1994	4.222	3.438	2258	2378	4.783	4.954	2500	2674	5.199	35	
1.911	1859	1936	4.121	2.539	2102	2204	4.512	3.696	2368	2516	4.951	40	
1.804	1821	1902	4.058	2.189	2018	2116	4.369	2.916	2250	2381	4.742	45	
1.732	1792	1879	4.010	2.009	1965	2065	4.282	2.488	2164	2288	4.595	50	
1.678	1769	1862	3.972	1.897	1927	2031	4.219	2.242	2103	2227	4.494	55	
1.635	1750	1848	3.939	1.817	1898	2007	4.171	2.086	2059	2184	4.420	60	
1.599	1733	1837	3.911	1.756	1874	1988	4.131	1.976	2024	2152	4.362	65	
1.569	1718	1828	3.885	1.707	1853	1972	4.096	1.893	1995	2127	4.314	70	
1.542	1704	1820	3.862	1.667	1835	1960	4.066	1.829	1971	2108	4.274	75	
1.518	1692	1814	3.841	1.632	1819	1950	4.040	1.776	1950	2092	4.240	80	
1.497	1681	1808	3.822	1.602	1805	1941	4.015	1.731	1931	2078	4.209	85	
1.478	1670	1803	3.804	1.575	1791	1933	3.993	1.693	1915	2067	4.182	90	
1.461	1660	1799	3.786	1.551	1779	1927	3.973	1.660	1900	2058	4.157	95	
1.444	1651	1795	3.770	1.530	1768	1921	3.953	1.631	1886	2049	4.134	100	

1 MPa = 10^6 N/m² = 10 bar

27/10/2014

2014/10/29

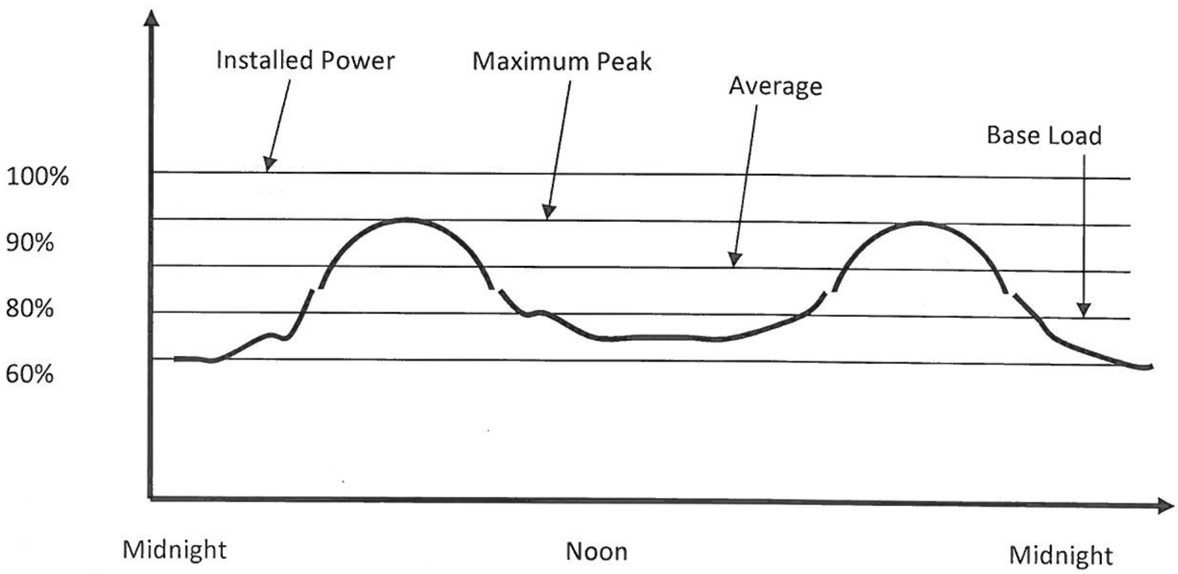
Thermomachines 4B
Memorandum – Supplementary Examination 2014

QUESTION 1

With respect to the design and operation of a steam power plant explain/discuss the following:

1.1 The demand cycle and its implications for the operation of power plant.

- Typical demand curve shown in figure.



Typical daily Electrical Power Demand

- Peak demand occurs twice per day, typically in the morning from 7h00 to 9h00 and in the evening from 5h00 to 9h00.
- Power for the base load is typically provided by efficient less costly power plant such as steam turbines to meet a constant demand.
- Due to the time it takes to bring steam plant on line peak demand is usually supplied by power plant such as hydroelectric, gas, and/or diesel
- During periods of low demand water is pumped upstream of hydroelectric schemes to allow power to be drawn during peak periods.

1.2 Why it takes some 8 h to 12 h to bring a steam turbine on line from cold. Indicate what problems could be experienced if this time is shortened

- Steam at elevated temperatures enters turbines at specific points in the turbines.

- This results in uneven heating of the casing and the rotor.
- Uneven heating can result in distortion of components of the casing and the turbine rotor.
- This can result in thermal stresses and distortions of turbine components.
- To reduce the negative effects of uneven heating the rate of increase of temperature components, and in particular, differential heating of the components is controlled by raising the components to working temperatures slowly.
- The process typically takes from 8 h to 12 h.

1.3 Axial differential expansion between the rotor shaft and casing of a multistage turbine and the location of the axial thrust bearing.

- During start-up, run-down, and operation of a steam turbine effective operating temperatures of the rotor and casing will differ.
- The different temperature distributions result in different expansions of the rotor and casing, particularly in the longitudinal direction.
- The different expansions will result in clearances between components fixed to the shaft and to the casing moving relative to each other.
- The relative movements are monitored by the supervisory gear to ensure that the relative expansions remain within limits and do not result in any contact between moving and stationary components.
- The axial position between the rotor and casing can only be fixed at one location. This is usually at some point close to the HP and IP turbines.

1.4 Why the natural frequency of the shaft of a steam turbine installed and running in its journal bearings differs from that of the shaft alone.

- When a rotor shaft is running in pressurised hydrodynamic bearings a layer of oil exists between the journal bearing and the shaft.
- The mean pressure of the oil is a function of the gap between the shaft and the bearing.
- To carry the weight of the shaft the gap at the bottom of the bearing is smaller than at the top.
- In effect the force between the shaft and bearing varies with the thickness of the oil layer constituting a 'spring'.
- The net result is that the rotor shaft is an element of a multi-body dynamic system which could include the masses of the pedestals and any stiffness in their support.
- The effective stiffness acting on the shaft now includes additional effects altering the natural frequency of the shaft.

1.5 The axis of the combined shaft of a multistage turbine and generator is installed and runs in a shape approximating a catenary.

- The shaft of each turbine and the generator, since they are not infinitely stiff, will bend under the weight of the shaft itself and the mass is carries.
- This means that the couplings at the end of each shaft, which are normal to the shaft will bend with the shaft with the distance between the top ends of the couplings being increased.

- Adjacent couplings on the ends of two shafts, which will be bolted together will not, due to the bending of the shafts, be parallel.
- If adjacent couplings are then bolted together the shafts will be bent and stresses will be induced into the shafts.
- To eliminate these induced stresses the heights of the shaft bearings are mounted in a catenary ensuring that the ends of the individual shafts are parallel to each other before being bolted together.
- Typically, the centre-line of the combined shaft will be about 20 mm below the ends for 500 MW turbines.

1.6 The effects of creep on the variation of stress distribution in a rotor shaft with time.

- Steam turbine shafts and other highly stressed components are subjected to temperatures and stresses at which creep occurs.
- Steam turbines operate under these conditions for long periods of time.
- Since the rate of creep depends on the temperature and stress and these vary in steam turbine components the rate of creep will vary in the components.
- The relative movement of materials due to creep results in a redistribution of stresses including radial and longitudinal stresses in turbine shafts.
- This results in stresses in some regions of a shaft increasing to higher values than those at the beginning of the life of the turbine, and some stresses being reduced.
- These stress changes need to be taken into account in the design of highly stressed components such as shafts.
-

1.7 The air to fuel ratio of the air/coal mixture flowing between a ball or roller mill and the burners in the furnace differs from that of the stoichiometric plus excess air ratio.

- Typical stoichiometric air to fuel ratios for coal are of the order of 5.5:1.
- Excess air ratios are of the order of 10% to 20% giving a mean air to fuel ratio of approximately 6.3:1.
- Spontaneous combustion can occur in mixtures of air and coal causing explosions under certain conditions.
- Spontaneous combustion cannot take place if the air to fuel ratio is lower than 4.5:1 to 4.8:1.
- To avoid explosions it is necessary to ensure that air to coal mass ratios are below this limit throughout the plant, and particularly where there are airborne coal particles in conveying air.
- Air to coal mass ratios in tube mills are of the order of 1.0:1 to 1.3:1 and in the pulverised fuel conveying ducts of the order of 1.7:1 to 2.1:1.
- it is unlikely that explosions will occur in these plant components under normal plant operation.
- Secondary air is used to increase the air to fuel ratios at the burners to that required for complete, or nearly complete, combustion

1.8 Why are turbine blades connected together in batches at approximately two thirds their length.

- Typically turbine blades, particularly in the last stages of the LP turbines are long and thin.
- They are susceptible to vibrations.
- Vibrations can lead to high vibration stresses and fatigue resulting in failure of the blades and catastrophic disintegration of the turbine.
- To increase the stiffness and natural frequency of the blades they are connected together in batches.
- A continuous circular ring is not used as this could result in stresses in the ring which could be imposed on the blades.

QUESTION 2

An orifice plate is used to measure the flow of steam in a large diameter duct in a power station. The velocities in the duct maybe considered to be small compared to the internal energy of the steam and may be ignored. The upstream pressure of the steam is 16 MPa and its temperature is 425 °C. The steam passes so quickly through the orifice plate that heat losses are minimal and may be ignored. If the total pressure drop across the orifice plate is 375 kPa calculate:

2.1 The change in temperature of the steam as it passes through the valve.

The enthalpy of the superheated region is a function of the temperature and the pressure only of the steam. Since the enthalpy of the steam is constant as it expands through the valve, a change in the enthalpy of the steam in the expansion through the valve is given by:

$$dh = 0 = \frac{\partial h}{\partial P} dP + \frac{\partial h}{\partial T} dT \quad (1)$$

The change in temperature across the valve is given by:

$$dT = -\frac{(\frac{\partial h}{\partial P})_0}{(\frac{\partial h}{\partial T})_0} dP \quad (2)$$

where $(\frac{\partial h}{\partial P})_0$ and $(\frac{\partial h}{\partial T})_0$ are the local gradients of h with the pressure and temperature in the area of the T-S diagram of interest. Similarly the change in entropy is given by:

$$dS = \frac{\partial S}{\partial P} dP + \frac{\partial S}{\partial T} dT \quad (3)$$

Substituting equation (2) into equation (3) gives:

$$dS = (\frac{\partial S}{\partial P})_0 dP - (\frac{\partial S}{\partial T})_0 \frac{(\frac{\partial h}{\partial P})_0}{(\frac{\partial h}{\partial T})_0} dP \quad (4)$$

$$dS = [(\frac{\partial S}{\partial P})_0 - (\frac{\partial S}{\partial T})_0 \frac{(\frac{\partial h}{\partial P})_0}{(\frac{\partial h}{\partial T})_0}] dP \quad (5)$$

Temperature and entropy of the steam from steam tables in the vicinity of the operating point of the orifice plate are given in the following table:

T (°C)		425	450
P (MPa)			
16	h (kJ/kg)	3051	3140
	S (kJ/kg K)	5.970	6.095
17	h (kJ/kg)	3029	3121
	S (kJ/kg K)	5.916	6.046

$$(\frac{\partial S}{\partial P})_0 = \frac{5.916-5.970}{17-16} = \mathbf{-0.054\ kJ/\ kg\ K\ MPa} \quad (6)$$

$$(\frac{\partial S}{\partial T})_0 = \frac{6.095-5.970}{450-425} = \mathbf{0.005\ kJ/\ kg\ K^{\ 2}} \quad (7)$$

$$(\frac{\partial h}{\partial P})_0 = \frac{3029-3051}{17-16} = \mathbf{-22\ kJ/\ kg\ MPa} \quad (8)$$

$$(\frac{\partial h}{\partial T})_0 = \frac{3140-3051}{450-425} = 3.56\ kJ/kg\ K \quad (9)$$

The change in temperature is:

$$dT = -\frac{(\frac{\partial h}{\partial P})_0}{(\frac{\partial h}{\partial T})_0} dP = -\frac{-22}{3.56}(-0.35) = -2.16^oC \quad (10)$$

2.2 The change in entropy of the steam.

The change in entropy of the steam as it passes through the orifice plate is given by:

$$dS = [(\frac{\partial S}{\partial P})_0 - \left(\frac{\partial S}{\partial T})_0 \frac{(\frac{\partial h}{\partial P})_0}{(\frac{\partial h}{\partial T})_0}\right] dP = \left[-0.054 - 0.005 \times \frac{-22}{3.56}\right](-0.35) = \mathbf{0.0081\ kJ/kg\ K} \quad (11)$$

2.3 The increase in area on the T-S diagram due to the orifice plate if the temperature of the water in the condenser is 319 K.

The increase in area will be given by:

$$dA = dS \times (T_{orifice\ plate} - T_{condenser}) = 0.0081 \times (425 + 273 - 319) = 3.07\ kJ/kg$$

Question 3

Data available for a 'dried' sample of coal supplied to a power station included:

Nitrogen	**5 %**	
Oxygen	**8 %**	(by difference)
Sulphur	**2 %**	
Hydrogen	**3 %**	(just that in volatile matter)
Ash content	**Not given**	
Water content	**Not given**	
Calorific value of 'dried' coal	**22 MJ/kg**	

The ash content of the 'air dried' coal sample was 25% and that of the 'as received' sample 23.5%.

Excess air:	**12 % (of Stoichiometric)**
Co_2 mass at a point in the flue gases	**16%**

3.1 Calculate the carbon and ash contents of the 'dried' coal.

The CV of a coal sample may be calculated using the Dulong equation:

$$Q = \frac{1}{100}\{33.97C + 143.86\left(H - \frac{O}{8}\right) + 9.367S\} \tag{1}$$

$$22 = \frac{1}{100}\{33.97C + 143.86\left(3 - \frac{8}{8}\right) + 9.367 \times 2\} \tag{2}$$

$$2200 = 33.97C + 287.72 + 18.73 \tag{3}$$

$$C = \frac{2200 - 287.72 - 18.73}{33.97} = 55.74\ \% \tag{4}$$

The only other constituent missing from the constituents is the ash in sample. This is given by:

$$Ash = 100 - 5 - 8 - 2 - 3 - 55.74 = 26.26\ \% \tag{5}$$

3.2 Present in tabular form the percentage of the 'as received', 'air dried', and 'dried' coal samples.

The percentage of ash in the 'Air Dried' sample is 25% and thus to obtain the percentages of the constituents of the 'Air Dried' sample the constituents of the 'Dried' sample must be multiplied by:

$$= \frac{25}{26.26} = 0.9528 \tag{6}$$

The inherent moisture in the 'Air Dried' sample will then be given by:

$$H_2O_{inh} = 100 - \%\ of\ (N + O + S + C + Ash) \tag{7}$$

	As Received	Air Dried	Dried
	(%)	(%)	(%)
Nitrogen	4.474486	4.760091	5
Oxygen	7.159177	7.616146	8
Total carbon	49.88157	53.0655	55.74
Ash	23.5	25	26.26
Sulphur	1.789794	1.904037	2
Hydrogen	2.684692	2.856055	3
Total Moisture	10.51028	4.798172	0
Surface Moisture	6	0	0
Inherent moisture	4.510282	4.798172	5
Total =	100	100	100

$$H_2O_{inh} = 100 - 4.760 - 7.616 - 53.066 - 25 - 1.904 - 2.856 = 4.798\,\% \quad (7)$$

The 'As Received' sample constituents may be calculated on the same basis.

The percentage of ash in the 'As Received' sample is 23.5% and thus to obtain the percentages of the constituents of the 'As Received' sample the constituents of the 'Air Dried' sample must be multiplied by:

$$= \frac{23.5}{25} = 0.94 \quad (8)$$

The surface moisture in the 'As Received' sample will then be given by:

$$H_2O_{inh} = 100 - \%\, of\ (N + O + S + C + Ash - H_2O_{inh}) \quad (9)$$

$$H_2O_{surf} = 100 - 4.475 - 7.159 - 49.882 - 23.5 - 1.790 - 2.685 - 4.510 = 6\,\% \quad (10)$$

3.3 Calculate the stoichiometric mass of air based on an 'As Received' coal sample.

The stoichiometric quantity of air based on an 'as received" sample of fuel required may be calculated based on oxidising the constituents in the 'as received" column of the above table.

The mass of oxygen required to completely oxidise the carbon is:

$$= 0.4988 \times \frac{32}{12} = 1.330\ kg/kg \quad (11)$$

The mass of oxygen required to oxidise the sulphur:

$$= 0.0179 \times \frac{32}{32} = 0.0179\ kg/kg \quad (12)$$

The mass of oxygen required to oxidise the hydrogen is:

$$= 0.0269 \times \frac{32}{4} = 0.2152\ kg/kg \tag{13}$$

Thus the total mass of oxygen required from the air is:

$$1.330 + 0.0179 + 0.2152 - 0.0716 = 1.4915\ kg/kg \tag{14}$$

Thus the mass of air required per kg of "as received" coal is:

$$\frac{1.4915}{0.2315} = 6.443\ kg/kg \tag{15}$$

The mass of nitrogen in the stoichiometric air is:

$$6.443 \times (1 - 0.2315) = 4.9814\ kg/kg \tag{16}$$

The mass of excess air per kilogram of "as received" fuel will then be:

$$6.443 \times 0.12 = 0.7732\ kg/kg \tag{17}$$

The total mass of the inputs per "as received" fuel is then:

$$1 + 6.443 + 0.7732 = 8.216\ kg/kg \tag{18}$$

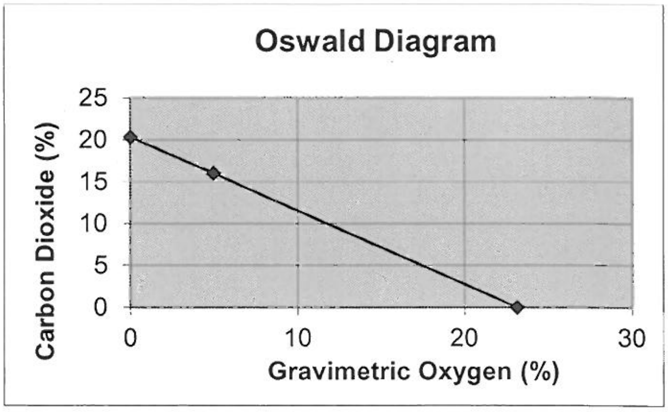
3.4 Calculate and present in tabular form, the exhaust gas analysis (gravimetric, wet), resulting from combustion with total air (including excess air)(in kg/s as well as %).

	Inputs (As Received)				Outputs		Excluding Ash		No Excess Air	
	Mass	Stoich. Air	Excess Air	Totals	Mass		Mass		Mass	
	(kg)	(kg)	(kg)	(kg)	(kg)	(%)	(kg)	(%)	(kg)	(%)
Nitrogen	0.044745	4.950677	0.594081	5.589503	5.589503	56.57	5.589503	57.18	4.995422	55.49
Oxygen	0.071592	1.491323	0.178959	1.741874	0.178959	1.81	0.178959	1.83	0	0
Carbon	0.498816	0	0	0.498816	0	0	0	0	0	0
Hydrogen	0.235	0	0	0.235	0	0	0	0	0	0
Sulphur	0.017898	0	0	0.017898	0	0	0	0	0	0
H_2O	0.026847	0	0	0.026847	2.141847	21.68	2.141847	21.91	2.141847	23.79
Ash	0.105103	0	0	0.105103	0.105103	1.06	0	0	0	0
CO_2	0	0	0	0	1.828991	18.51	1.828991	18.71	1.828991	20.32
SO_2	0	0	0	0	0.035796	0.36	0.035796	0.37	0.035796	0.4
Total	1	6.442	0.773	8.215	9.8802	99.99	9.7751	100	9.0021	100

3.3 The percentage of carbon dioxide at a point in the flue gas ducting is measured at 16%. At this point in the system calculate:

3.3.1 The percentage of oxygen in the flue gases.

The percentage of CO_2 in flue gases after stoichiometric combustion was 16%. The Oswald diagram for the exhaust gases is:



The percentage oxygen in the flue gases may be obtained using similar triangles:

$$\frac{23.15-x}{16} = \frac{23.15}{20.32} \tag{19}$$

i.e.

$$x = 23.15 - 16 \times \frac{23.15}{20.32} = 4.922\ \% \tag{20}$$

All the O_2 in the flue gases is due to excess air and air leakage into the flue gases. If the mass of flue gas, excluding excess air and air leakage, per kg of "as received" coal is $g_f\ kg/kg$ and the mass of excess air and air leakage per kg of "as received" coal is $a\,kg$ the portion of O_2 is:

$$P_{O_2} = \frac{0.2315 \times a}{g_f + a} \tag{21}$$

and:

$$a = \frac{P_{O_2} \times g_f}{0.2315 - P_{O_2}} \tag{22}$$

$$g_f = masses\ of\ N_2, CO_2, SO_2, and\ water = 4.996 + 1.829 + 0.0358 + 2.142 = 9.0038$$

Substituting:

$$a = \frac{0.04922 \times 9.0038}{0.2315 - 0.04922} = 2.4312\ \ kg/kg \tag{23}$$

The mass of excess air in the flue gases is 0.773 kg/kg

Thus the leaked air is:

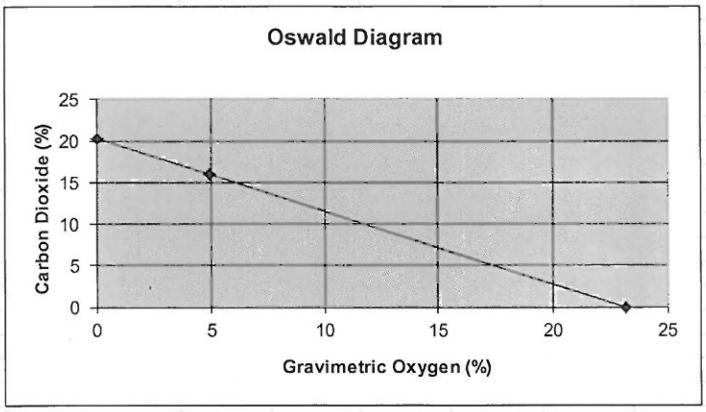
$$= 2.4312 - 0.773 = 1.658\ kg/kg \tag{1}$$

OSTWALD Diagram

x	y
0	20.32
4.922	16
23.15	0

Air leakage

Measured CO_2 in flue gases (%) = 17



Mass of flue gases/kg coal = 9.002056

Mass of air/kg coal = 2.430772

	Flue Gas with No Excess Air (kg/kg)	Air in Flue gas (kg/kg)	Excess Air (kg)	Air leakage into Flue Gas (kg/kg)	Total Mass (kg)	Check (%)
Nitrogen	4.995422	1.868049	0.594081	1.273967	6.86347	60.03
Oxygen	0	0.562724	0.178959	0.383765	0.562724	4.92
CO_2	1.828991	0	0		1.828991	16
H_2O	2.141847	0	0		2.141847	18.73
SO_2	0.035796	0	0		0.035796	0.31
	9.002056	2.430772	0.77304	1.657732	11.43283	99.99

Mass of air leakage (kg/kg) = 1.658

UNIVERSITEIT VAN JOHANNESBURG — UNIVERSITY OF JOHANNESBURG

COURSE : ENGINEERING
SUBJECT : THERMOMACHINES 4B

TIME : 3 hours
MARKS: 100

Supplementary Examination 2014

Examiners : **Professor A Nurick**
Dr P F J Henning

This paper consists of 2 pages plus attachments
Requirements: Calculator

Attachments:
Information sheet
Steam tables

QUESTION 1

With respect to the design and operation of a steam power plant explain/discuss the following:

1.1 The demand cycle and its implications for the operation of power plant.
1.2 Why it takes some 8 h to 12 h to bring a steam turbine on line from cold. Indicate what problems could be experienced if this time is shortened
1.3 Axial differential expansion between the rotor shaft and casing of a multistage turbine and the location of the axial thrust bearing.
1.4 Why the natural frequency of the shaft and attachments of a steam turbine installed and running in its journal bearings differs from that of the shaft and attachments alone.
1.5 The axis of the combined shaft of a multistage turbine and generator is installed and runs in a shape approximating a catenary.
1.6 The effects of creep on the variation of stress distribution in a rotor shaft with time.
1.7 The air to fuel ratio of the air/coal mixture flowing between a ball or roller mill and the burners in the furnace differs from that of the stoichiometric plus excess air ratio.
1.8 Why are turbine blades connected together in batches at approximately two thirds their length.

(32 Marks)

QUESTION 2

An orifice plate is used to measure the flow of steam in a large diameter duct in a power station. The kinetic energies of the flow in the duct may be considered to be small compared to the internal energy of the steam and may be ignored. The upstream pressure of the steam is 16 MPa and its temperature is 425 °C. The steam passes so quickly through the orifice plate that heat losses are minimal and may be ignored. If the total pressure drop across the orifice plate is 375 kPa calculate:

2.1 The change in temperature of the steam as it passes through the orifice plate.
2.2 The change in entropy of the steam.
2.3 The increase in area on the T-S diagram due to the orifice plate if the temperature of the water in the condenser is 319 K.

(28 Marks)

QUESTION 3

Data available for a 'dried' sample of coal supplied to a power station included:

Nitrogen	**5 %**	
Oxygen	**8 %**	(by difference)
Sulphur	**2 %**	
Hydrogen	**3 %**	(just that in volatile matter)
Ash content	**Not given**	
Water content	**Not given**	
Calorific value of 'dried' coal	**22 MJ/kg**	

The ash content of the 'air dried' coal sample was 25% and that of the 'As Received' sample 23.5%.

Excess air:	**12 % (of Stoichiometric)**
CO_2 mass at a point in the flue gases	**16%**

3.1 Calculate the carbon and ash contents of the 'dried' coal.
3.2 Present in tabular form the percentages of constituents of the 'As Received', 'Air Dried', and 'Dried' coal samples.
3.3 Calculate the stoichiometric mass of air based on an 'As Received' coal sample.
3.4 Calculate and present in tabular form, the exhaust gas analysis (gravimetric, wet), resulting from combustion with total air (including excess air)(in kg/s as well as %).
3.3The percentage of carbon dioxide at a point in the flue gas ducting is measured at 16%. At this point in the system calculate:
3.4.1 The percentage of oxygen in the flue gases.
3.4.2 The mass of air which has leaked into the flue gases per kilogram of "As Received" coal.

(40 Marks)

Table 3

P / MPa	T_{sat} / K	θ_{sat}	v_f / m³/Mg	v_g	e_f / kJ/kg	e_g	h_f / kJ/kg	h_{fg}	h_g	s_f / kJ/(kg·K)	s_{fg}	s_g
0.0006112	273.16	0.01	1.000	206200	0	2375	0.00	2501	2501	0	9.156	9.156
0.0010	280.1	7.0	1.000	129200	29.37	2385	29.37	2484	2514	0.106	8.869	8.975
0.0015	286.2	13.0	1.001	87980	54.75	2393	54.75	2470	2525	0.196	8.632	8.828
0.0020	290.7	17.5	1.001	67010	73.48	2399	73.49	2460	2533	0.261	8.463	8.724
0.0025	294.2	21.1	1.002	54260	88.47	2404	88.47	2451	2540	0.312	8.331	8.643
0.0030	297.2	24.1	1.003	45670	101.0	2408	101.0	2444	2545	0.354	8.224	8.578
0.0035	299.8	26.7	1.003	39480	111.9	2412	111.9	2438	2550	0.391	8.131	8.522
0.0040	302.1	29.0	1.004	34800	121.4	2415	121.4	2433	2554	0.423	8.052	8.475
0.0045	304.2	31.0	1.005	31140	130.0	2418	130.0	2428	2558	0.451	7.982	8.433
0.0050	306.0	32.9	1.005	28200	137.8	2420	137.8	2423	2561	0.476	7.919	8.395
0.006	309.3	36.2	1.007	23740	151.5	2425	151.5	2416	2567	0.521	7.810	8.331
0.007	312.2	39.0	1.008	20530	163.4	2428	163.4	2409	2572	0.559	7.717	8.276
0.008	314.7	41.5	1.009	18110	173.9	2432	173.9	2403	2577	0.593	7.636	8.229
0.009	316.9	43.8	1.009	16210	183.3	2435	183.3	2397	2581	0.623	7.565	8.188
0.010	319.0	45.8	1.010	14680	191.9	2438	191.9	2393	2584	0.649	7.502	8.151
0.011	320.9	47.7	1.011	13420	199.7	2440	199.7	2388	2588	0.674	7.443	8.117
0.012	322.6	49.4	1.012	12360	207.0	2442	207.0	2384	2591	0.696	7.390	8.086
0.013	324.2	51.1	1.013	11470	213.7	2445	213.7	2380	2594	0.717	7.341	8.058
0.014	325.7	52.6	1.013	10700	220.0	2447	220.1	2376	2596	0.737	7.296	8.0[illegible]
0.015	327.1	54.0	1.014	10020	226.0	2449	226.0	2373	2599	0.755	7.254	8.0[illegible]
0.016	328.5	55.3	1.015	9435	231.6	2450	231.6	2370	2601	0.772	7.215	7.987
0.018	331.0	57.8	1.016	8447	242.0	2454	242.0	2364	2606	0.804	7.142	7.946
0.020	333.2	60.1	1.017	7651	251.5	2457	251.5	2358	2610	0.832	7.077	7.909
0.022	335.3	62.2	1.018	6997	260.2	2459	260.2	2353	2613	0.858	7.018	7.876
0.024	337.2	64.1	1.019	6448	268.2	2462	268.2	2348	2617	0.882	6.964	7.846
0.025	338.1	65.0	1.020	6206	272.0	2463	272.0	2346	2618	0.893	6.939	7.832
0.030	342.3	69.1	1.022	5231	289.3	2468	289.3	2336	2625	0.944	6.825	7.769
0.035	345.9	72.7	1.025	4527	304.3	2473	304.4	2327	2631	0.988	6.729	7.717
0.040	349.0	75.9	1.026	3995	317.7	2477	317.7	2319	2637	1.026	6.645	7.671
0.045	351.9	78.7	1.028	3578	329.6	2481	329.7	2312	2642	1.060	6.571	7.631
0.050	354.5	81.3	1.030	3241	340.6	2484	340.6	2305	2646	1.091	6.504	7.595
0.055	356.9	83.7	1.032	2965	350.6	2487	350.7	2299	2650	1.120	6.443	7.563
0.060	359.1	86.0	1.033	2733	359.9	2490	360.0	2294	2654	1.146	6.388	7.532
0.065	361.2	88.0	1.035	2536	368.6	2492	368.7	2288	2657	1.170	6.336	7.506
0.070	363.1	90.0	1.036	2366	376.8	2495	376.8	2283	2660	1.192	6.289	7.481
0.075	364.9	91.8	1.037	2218	384.4	2497	384.5	2279	2663	1.213	6.245	7.458
0.080	366.7	93.5	1.039	2088	391.7	2499	391.8	2274	2666	1.233	6.203	7.436
0.085	368.3	95.2	1.040	1973	398.6	2501	398.7	2270	2669	1.252	6.164	7.416
0.090	369.9	96.7	1.041	1870	405.2	2503	405.3	2266	2671	1.270	6.126	7.396
0.095	371.4	98.2	1.042	1778	411.5	2505	411.6	2262	2673	1.287	6.091	7.378
0.10	372.8	99.6	1.043	1695	417.5	2506	417.6	2258	2676	1.303	6.058	7.361
0.11	375.5	102.3	1.045	1550	428.8	2509	428.9	2251	2680	1.333	5.996	7.329
0.12	378.0	104.8	1.047	1429	439.3	2512	439.5	2244	2684	1.361	5.939	7.30[illegible]
0.13	380.3	107.1	1.049	1326	449.2	2515	449.3	2238	2687	1.387	5.886	7.2[illegible]
0.14	382.5	109.3	1.051	1237	458.4	2518	458.5	2232	2691	1.411	5.837	7.24[illegible]
0.15	384.5	111.4	1.053	1160	467.1	2520	467.2	2227	2694	1.434	5.791	7.225
0.16	386.5	113.3	1.054	1092	475.3	2522	475.5	2221	2697	1.455	5.748	7.203
0.17	388.3	115.2	1.056	1031	483.2	2524	483.3	2216	2700	1.476	5.707	7.183
0.18	390.1	116.9	1.058	978	490.6	2526	490.8	2211	2702	1.495	5.669	7.164
0.19	391.8	118.6	1.059	929	497.8	2528	498.0	2207	2705	1.513	5.633	7.146
0.20	393.4	120.2	1.061	885.9	504.6	2530	504.8	2202	2707	1.530	5.598	7.128
0.22	396.4	123.3	1.063	810.3	517.5	2533	517.7	2194	2711	1.563	5.534	7.097
0.24	399.2	126.1	1.066	746.9	529.5	2536	529.8	2186	2715	1.593	5.475	7.068
0.26	401.9	128.7	1.069	692.9	540.7	2539	541.0	2178	2719	1.621	5.420	7.041
0.28	404.4	131.2	1.071	646.4	551.3	2541	551.6	2171	2722	1.647	5.369	7.016
0.30	406.7	133.5	1.073	605.9	561.2	2544	561.5	2164	2725	1.672	5.321	6.993
0.32	408.9	135.8	1.076	570.3	570.7	2546	571.0	2157	2728	1.695	5.276	6.971
0.34	411.0	137.9	1.078	538.7	579.6	2548	580.0	2151	2731	1.717	5.234	6.951
0.36	413.0	139.9	1.080	510.6	588.2	2550	588.6	2145	2734	1.738	5.194	6.932
0.38	414.9	141.8	1.082	485.3	596.4	2552	596.9	2139	2736	1.758	5.156	6.914
0.40	416.8	143.6	1.084	462.4	604.3	2554	604.8	2134	2739	1.777	5.120	6.897
0.42	418.5	145.4	1.086	441.7	611.9	2555	612.3	2128	2741	1.795	5.085	6.880
0.44	420.2	147.1	1.087	422.8	619.2	2557	619.7	2123	2743	1.812	5.053	6.865
0.46	421.9	148.7	1.089	405.4	626.2	2558	626.7	2118	2745	1.829	5.021	6.850
0.48	423.5	150.3	1.091	389.5	633.0	2560	633.6	2113	2747	1.845	4.990	6.835

θ is the Celsius temperature

Table 4
continued

Supercritical temperatures

400 °C, θ = 400 K, T = 673.15 K				425 °C, θ = 425 K, T = 698.15 K				450 °C, θ = 450 K, T = 723.15 K					
v m³/Mg	e kJ/kg	h kJ/kg	s kJ/(kg·K)	v m³/Mg	e kJ/kg	h kJ/kg	s kJ/(kg·K)	v m³/Mg	e kJ/kg	h kJ/kg	s kJ/(kg·K)	P MPa	θ_{sat} K
310700	2969	3279	10.671	322200	3009	3331	10.746	333700	3050	3383	10.820	0.001	7.0
155300	2969	3279	10.351	161100	3009	3331	10.426	166900	3050	3383	10.500	0.002	17.5
77660	2969	3279	10.031	80550	3009	3331	10.107	83430	3050	3383	10.180	0.004	29.0
51770	2969	3279	9.844	53700	3009	3331	9.919	55620	3050	3383	9.993	0.006	36.2
38830	2969	3279	9.711	40270	3009	3331	9.787	41710	3050	3383	9.860	0.008	41.5
31060	2969	3279	9.608	32220	3009	3331	9.684	33370	3050	3383	9.757	0.01	45.8
15530	2969	3279	9.288	16110	3009	3331	9.364	16680	3049	3383	9.437	0.02	60.1
7763	2968	3279	8.968	8051	3009	3331	9.043	8340	3049	3383	9.117	0.04	75.9
5174	2968	3279	8.780	5366	3008	3330	8.856	5559	3049	3383	8.929	0.06	86.0
3879	2968	3278	8.647	4024	3008	3330	8.723	4168	3049	3382	8.796	0.08	93.5
3103	2968	3278	8.544	3218	3008	3330	8.620	3334	3049	3382	8.693	0.10	99.6
2067	2967	3277	8.356	2144	3008	3329	8.432	2222	3048	3382	8.505	0.15	111.4
1549	2967	3276	8.222	1607	3007	3328	8.298	1665	3048	3381	8.372	0.20	120.2
1031	2965	3275	8.034	1070	3006	3327	8.110	1109	3047	3380	8.184	0.30	133.5
773	2964	3273	7.899	802	3005	3326	7.975	831	3046	3378	8.050	0.40	143.6
617.2	2963	3272	7.794	640.7	3004	3324	7.871	664.1	3045	3377	7.945	0.5	151.8
[illegible]3.7	2962	3270	7.709	533.3	3003	3323	7.785	552.9	3044	3376	7.860	0.6	158.8
[illegible]9.7	2961	3269	7.636	456.6	3002	3322	7.713	473.4	3043	3375	7.787	0.7	165.0
[illegible]4.2	2960	3267	7.572	399.1	3001	3320	7.650	413.8	3042	3373	7.724	0.8	170.4
341.1	2959	3266	7.516	354.3	3000	3319	7.594	367.5	3041	3372	7.669	0.9	175.4
306.6	2957	3264	7.466	318.5	2999	3317	7.544	330.4	3040	3371	7.619	1.0	179.9
203.0	2952	3256	7.270	211.1	2994	3310	7.349	219.1	3036	3364	7.425	1.5	198.3
151.2	2946	3248	7.129	157.4	2988	3303	7.208	163.5	3031	3358	7.286	2.0	212.4
99.33	2934	3232	6.923	103.6	2977	3288	7.006	107.8	3021	3344	7.085	3.0	233.8
73.39	2921	3215	6.771	76.72	2966	3273	6.857	79.99	3011	3331	6.938	4.0	250.3
57.80	2908	3197	6.649	60.57	2955	3257	6.737	63.27	3000	3317	6.820	5	263.9
47.38	2894	3179	6.544	49.79	2943	3241	6.635	52.12	2990	3303	6.721	6	275.6
39.92	2880	3160	6.451	42.07	2930	3225	6.546	44.14	2979	3288	6.635	7	285.8
34.31	2866	3140	6.367	36.27	2918	3208	6.466	38.15	2968	3273	6.558	8	295.0
29.93	2850	3120	6.289	31.75	2905	3191	6.392	33.48	2957	3258	6.487	9	303.3
26.41	2834	3098	6.216	28.12	2891	3173	6.324	29.74	2945	3242	6.422	10	311.0
23.51	2818	3076	6.146	25.15	2877	3154	6.259	26.67	2933	3226	6.361	11	318.0
21.08	2800	3053	6.079	22.66	2863	3135	6.198	24.11	2920	3210	6.303	12	324.6
19.01	2782	3029	6.013	20.54	2848	3115	6.138	21.94	2908	3193	6.248	13	330.8
17.22	2763	3004	5.949	18.72	2832	3095	6.081	20.07	2895	3176	6.195	14	336.6
15.66	2743	2978	5.885	17.13	2816	3073	6.025	18.45	2881	3158	6.144	15	342.1
14.27	2721	2950	5.821	15.74	2800	3051	5.970	17.02	2868	3140	6.095	16	347.3
13.03	2699	2920	5.757	14.49	2782	3029	5.916	15.76	2853	3121	6.046	17	352.3
[illegible]1.91	2675	2889	5.693	13.38	2764	3005	5.862	14.63	2839	3102	5.999	18	357.0
[illegible]0.89	2649	2856	5.626	12.38	2745	2981	5.809	13.62	2824	3083	5.952	19	361.4
[illegible]52	2621	2820	5.558	11.47	2726	2955	5.755	12.71	2808	3062	5.906	20	365.7
[illegible]62	2558	2740	5.411	9.869	2683	2900	5.646	11.11	2776	3020	5.815	22	373.7
[illegible]38	2480	2642	5.244	8.500	2636	2841	5.534	9.766	2741	2975	5.724	24	
5.287	2377	2515	5.037	7.306	2584	2774	5.416	8.613	2704	2928	5.633	26	
3.857	2231	2339	4.763	6.246	2525	2700	5.290	7.611	2664	2877	5.540	28	
2.806	2075	2159	4.485	5.296	2457	2616	5.154	6.731	2621	2823	5.446	30	°C
2.107	1920	1994	4.222	3.438	2258	2378	4.783	4.954	2500	2674	5.199	35	(sat)
1.911	1859	1936	4.121	2.539	2102	2204	4.512	3.696	2368	2516	4.951	40	
1.804	1821	1902	4.058	2.189	2018	2116	4.369	2.916	2250	2381	4.742	45	
1.732	1792	1879	4.010	2.009	1965	2065	4.282	2.488	2164	2288	4.595	50	
1.678	1769	1862	3.972	1.897	1927	2031	4.219	2.242	2103	2227	4.494	55	
1.635	1750	1848	3.939	1.817	1898	2007	4.171	2.086	2059	2184	4.420	60	
1.599	1733	1837	3.911	1.756	1874	1988	4.131	1.976	2024	2152	4.362	65	
1.569	1718	1828	3.885	1.707	1853	1972	4.096	1.893	1995	2127	4.314	70	
1.542	1704	1820	3.862	1.667	1835	1960	4.066	1.829	1971	2108	4.274	75	
1.518	1692	1814	3.841	1.632	1819	1950	4.040	1.776	1950	2092	4.240	80	
1.497	1681	1808	3.822	1.602	1805	1941	4.015	1.731	1931	2078	4.209	85	
1.478	1670	1803	3.804	1.575	1791	1933	3.993	1.693	1915	2067	4.182	90	
1.461	1660	1799	3.786	1.551	1779	1927	3.973	1.660	1900	2058	4.157	95	
1.444	1651	1795	3.770	1.530	1768	1921	3.953	1.631	1886	2049	4.134	100	

1 MPa = 10^6 N/m² = 10 bar