National Exams December 2010

04-CHEM-A2, Mechanical and Thermal Operations

3 hours duration

NOTES

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper, a clear statement of any assumptions made.
2. The examination is an OPEN BOOK EXAM.
3. Candidates may use any **non-communicating** calculator.
4. All problems are worth 20 marks. **Two problems** from **each** of sections A and B must be attempted. A **fifth** problem from **either section** must also be attempted.
5. **Only the first five** questions as they appear in the answer book will be marked.
6. State all assumptions clearly.

Section A: Mechanical Operations

A1. **[20 marks overall]** A slider bearing consists of a sleeve surrounding a cylindrical shaft. The shaft is free to move axially within the sleeve and the gap between the shaft and sleeve is packed with grease. The grease acts as a lubricant, isolating the metal surfaces and supports the axial stress resulting from the shaft motion. The diameter of the shaft is 1 in. and the sleeve has a diameter of 1.02 in. and is 2 in. long.

(a) **[5 marks]** If you want to limit the total force on the sleeve to less than 0.5 lb_f when the shaft is moving axially at 20 ft/s, what should the viscosity of the grease be in Poise?

(b) **[5 marks]** What is the magnitude of the momentum flux and in which direction is the momentum being transported?

(c) **[5 marks]** If one were to use a grease with a viscosity of 400 cP, what is the force (in lb_f) exerted on the shaft when it moves axially at 20 ft/s?

(d) **[5 marks]** The sleeve is cooled to a temperature of 150°F, and it is desired to keep the shaft temperature below 200°F. The properties of the grease are: SG = 0.85; specific heat = 0.5 Btu/(lb_m °F); and thermal conductivity = 0.06 Btu/(hr·ft °F). What is the cooling rate in Btu/hr (*i.e.* the rate that heat must be removed by a coolant) to ensure the temperature of the shaft does not exceed 200°F.

A2. **[20 marks]** A paint sample is tested in a Couette (cup-and-bob) viscometer that has an outer radius of 50 mm, an inner radius of 49 mm, and a bob length of 100 mm. When the outer cylinder is rotated at 4 rpm the torque on the bob is 0.0151 Nm, and when rotated at 20 rpm it is 0.0226 Nm.

(a) **[5 marks]** What are the corresponding values of the shear stress and shear rate for these two data points?

(b) **[5 marks]** What can you conclude about the rheological properties of the paint sample

(c) **[5 marks]** Explain which of the following models (and why) might be used to describe the paint: (1) Newtonian; (2) Bingham plastic; (3) power law?

(d) **[5 marks]** Determine the rheological parameters for any of the above models that could be used to describe the paint.

A3. **[20 marks overall]** A high pressure cylinder containing nitrogen at 200 psig and 70°F is connected to a reactor by □-in ID stainless steel ($\varepsilon = 8x10^{-5}$-in) tubing, 20 ft long. The pressure in the reactor is 15 psig. A pressure regulator at the upstream end of the tubing is used to control the pressure, and hence the flow rate, of the N_2 in the tubing. **You are to work the following parts of the problem in fps units throughout.**

(a) **[10 marks]** Assuming isothermal flow, is the regulator controls the pressure entering the tubing at 25 psig, what is the mass flow rate (lb_m/s) of N_2?

(b) **[10 marks]** If the regulator fails, so that the full cylinder pressure is applied to the tubing, assuming choked flow, what is the mass flow rate (lb_m/s) of N_2?

Useful data: R = 1,543.3 ft·lb_f/lb-mol·°R, MW for N_2 = 28 lb_m/lb-mol, γ = 1.4 and 1 cP = $6.7197x10^{-4}$ lb_m/ft·s.

Section B: Thermal Operations

B1. **[20 marks]** A long, bare 20-gage (D = 0.8118 mm) nichrome wire runs horizontally through a large enclosure maintained at 7°C. The surrounding air is at 27°C. If the temperature of the wire is not to exceed 1227°C, find the maximum electrical current the wire can carry if the air in the enclosure is quiescent. The electrical resistance of the wire is 2.162 W/m and the emissivity of the nichrome is 0.3. The surrounding enclosure can be considered gray. Useful thermo-physical property data [taken from Incropera *et al.* (2007) p 941] is appended on p 5 of the exam paper as Table A4.

B2. **[20 marks overall]** In a chemical processing plant, a large shell-and-tube heat exchanger is used to heat glycerin from 20°C to 34°C using water that enters at 80°C, makes a single pass through the shell, and exits at 48°C. The heat-transfer coefficient for the shell side is 300 W/m^{2}K. Seventy-five ¾-in. (0.0488-in. wall thickness and 0.652-in. *i.d*) steel tubes (k = 15 W/m·K) carry glycerin through the exchanger at a total mass flow rate of 40 kg/s, and each tube makes eight passes through the shell. Find the following

(a) [5 marks] the mass flow rate of the water;
(b) [5 marks] the overall heat transfer coefficient;
(c) [5 marks] the LMTD; and
(d) [5 marks] the total heat transfer surface area of the tubes.

Fig. 1 (overleaf on p 4) gives the LMTD correction factor, F, for a one-shell-pass, two-, four-, six-.... shell passes. Useful thermo-physical property data [taken from Incropera *et al.* (2007) pp 946 and 949] is appended on pp 6 and 7 of the exam paper as Tables A5 and A6.

B3. **[30 marks]** A long furnace used for stress relieving and annealing is 3 m x 3 m in cross section, with side walls and roof at 1700 K and 1400 K as shown in Fig. 2 (overleaf on p 4). What is the radiant heat transfer to the floor of the furnace when it is at 600 K? All the surfaces can be considered gray and diffuse with an emissivity of 0.5.

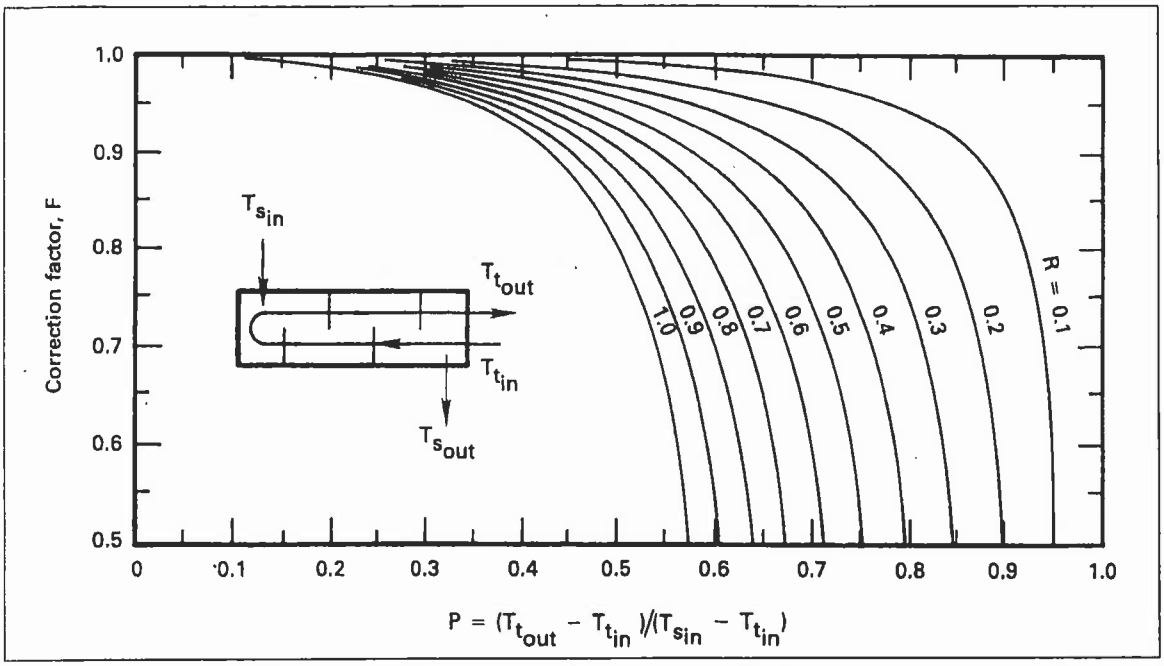

Fig. 1: LMTD correction factor, *F*, for a one-shell-pass, two-, four-, six-...

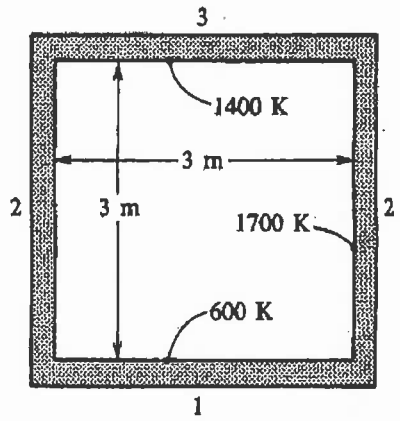

Fig. 2: Cross section of a long annealing furnace

TABLE A.4 Thermophysical Properties of Gases at Atmospheric Pressure

T (K)	ρ (kg/m^3)	c_p (kJ/kg · K)	$\mu \cdot 10^7$ (N · s/m^2)	$\nu \cdot 10^6$ (m^2/s)	$k \cdot 10^3$ (W/m · K)	$\alpha \cdot 10^6$ (m^2/s)	Pr
Air							
100	3.5562	1.032	71.1	2.00	9.34	2.54	0.786
150	2.3364	1.012	103.4	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.720
300	1.1614	1.007	184.6	15.89	26.3	22.5	0.707
350	0.9950	1.009	208.2	20.92	30.0	29.9	0.700
400	0.8711	1.014	230.1	26.41	33.8	38.3	0.690
450	0.7740	1.021	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.030	270.1	38.79	40.7	56.7	0.684
550	0.6329	1.040	288.4	45.57	43.9	66.7	0.683
600	0.5804	1.051	305.8	52.69	46.9	76.9	0.685
650	0.5356	1.063	322.5	60.21	49.7	87.3	0.690
700	0.4975	1.075	338.8	68.10	52.4	98.0	0.695
750	0.4643	1.087	354.6	76.37	54.9	109	0.702
800	0.4354	1.099	369.8	84.93	57.3	120	0.709
850	0.4097	1.110	384.3	93.80	59.6	131	0.716
900	0.3868	1.121	398.1	102.9	62.0	143	0.720
950	0.3666	1.131	411.3	112.2	64.3	155	0.723
1000	0.3482	1.141	424.4	121.9	66.7	168	0.726
1100	0.3166	1.159	449.0	141.8	71.5	195	0.728
1200	0.2902	1.175	473.0	162.9	76.3	224	0.728
1300	0.2679	1.189	496.0	185.1	82	238	0.719
1400	0.2488	1.207	530	213	91	303	0.703
1500	0.2322	1.230	557	240	100	350	0.685
1600	0.2177	1.248	584	268	106	390	0.688
1700	0.2049	1.267	611	298	113	435	0.685
1800	0.1935	1.286	637	329	120	482	0.683
1900	0.1833	1.307	663	362	128	534	0.677
2000	0.1741	1.337	689	396	137	589	0.672
2100	0.1658	1.372	715	431	147	646	0.667
2200	0.1582	1.417	740	468	160	714	0.655
2300	0.1513	1.478	766	506	175	783	0.647
2400	0.1448	1.558	792	547	196	869	0.630
2500	0.1389	1.665	818	589	222	960	0.613
3000	0.1135	2.726	955	841	486	1570	0.536

TABLE A.5 Thermophysical Properties of Saturated Fluids[a]

Saturated Liquids

T (K)	ρ (kg/m^3)	c_p (kJ/kg · K)	$\mu \cdot 10^2$ (N · s/m^2)	$\nu \cdot 10^6$ (m^2/s)	$k \cdot 10^3$ (W/m · K)	$\alpha \cdot 10^7$ (m^2/s)	Pr	$\beta \cdot 10^3$ (K^{-1})
Engine Oil (Unused)								
273	899.1	1.796	385	4280	147	0.910	47,000	0.70
280	895.3	1.827	217	2430	144	0.880	27,500	0.70
290	890.0	1.868	99.9	1120	145	0.872	12,900	0.70
300	884.1	1.909	48.6	550	145	0.859	6400	0.70
310	877.9	1.951	25.3	288	145	0.847	3400	0.70
320	871.8	1.993	14.1	161	143	0.823	1965	0.70
330	865.8	2.035	8.36	96.6	141	0.800	1205	0.70
340	859.9	2.076	5.31	61.7	139	0.779	793	0.70
350	853.9	2.118	3.56	41.7	138	0.763	546	0.70
360	847.8	2.161	2.52	29.7	138	0.753	395	0.70
370	841.8	2.206	1.86	22.0	137	0.738	300	0.70
380	836.0	2.250	1.41	16.9	136	0.723	233	0.70
390	830.6	2.294	1.10	13.3	135	0.709	187	0.70
400	825.1	2.337	0.874	10.6	134	0.695	152	0.70
410	818.9	2.381	0.698	8.52	133	0.682	125	0.70
420	812.1	2.427	0.564	6.94	133	0.675	103	0.70
430	806.5	2.471	0.470	5.83	132	0.662	88	0.70
Ethylene Glycol [$C_2H_4(OH)_2$]								
273	1130.8	2.294	6.51	57.6	242	0.933	617	0.65
280	1125.8	2.323	4.20	37.3	244	0.933	400	0.65
290	1118.8	2.368	2.47	22.1	248	0.936	236	0.65
300	1114.4	2.415	1.57	14.1	252	0.939	151	0.65
310	1103.7	2.460	1.07	9.65	255	0.939	103	0.65
320	1096.2	2.505	0.757	6.91	258	0.940	73.5	0.65
330	1089.5	2.549	0.561	5.15	260	0.936	55.0	0.65
340	1083.8	2.592	0.431	3.98	261	0.929	42.8	0.65
350	1079.0	2.637	0.342	3.17	261	0.917	34.6	0.65
360	1074.0	2.682	0.278	2.59	261	0.906	28.6	0.65
370	1066.7	2.728	0.228	2.14	262	0.900	23.7	0.65
373	1058.5	2.742	0.215	2.03	263	0.906	22.4	0.65
Glycerin [$C_3H_5(OH)_3$]								
273	1276.0	2.261	1060	8310	282	0.977	85,000	0.47
280	1271.9	2.298	534	4200	284	0.972	43,200	0.47
290	1265.8	2.367	185	1460	286	0.955	15,300	0.48
300	1259.9	2.427	79.9	634	286	0.935	6780	0.48
310	1253.9	2.490	35.2	281	286	0.916	3060	0.49
320	1247.2	2.564	21.0	168	287	0.897	1870	0.50

TABLE A.6 Thermophysical Properties of Saturated Water[a]

Temperature, T (K)	Pressure, p (bars)[b]	Specific Volume (m³/kg)		Heat of Vaporization, h_{fg} (kJ/kg)	Specific Heat (kJ/kg · K)		Viscosity (N · s/m²)		Thermal Conductivity (W/m · K)		Prandtl Number		Surface Tension, $\sigma_f \cdot 10^3$ (N/m)	Expansion Coefficient, $\beta_f \cdot 10^6$ (K⁻¹)	Temperature, T (K)
		$v_f \cdot 10^3$	v_g		$c_{p,f}$	$c_{p,g}$	$\mu_f \cdot 10^6$	$\mu_g \cdot 10^6$	$k_f \cdot 10^3$	$k_g \cdot 10^3$	Pr_f	Pr_g			
273.15	0.00611	1.000	206.3	2502	4.217	1.854	1750	8.02	569	18.2	12.99	0.815	75.5	−68.05	273.15
275	0.00697	1.000	181.7	2497	4.211	1.855	1652	8.09	574	18.3	12.22	0.817	75.3	−32.74	275
280	0.00990	1.000	130.4	2485	4.198	1.858	1422	8.29	582	18.6	10.26	0.825	74.8	46.04	280
285	0.01387	1.000	99.4	2473	4.189	1.861	1225	8.49	590	18.9	8.81	0.833	74.3	114.1	285
290	0.01917	1.001	69.7	2461	4.184	1.864	1080	8.69	598	19.3	7.56	0.841	73.7	174.0	290
295	0.02617	1.002	51.94	2449	4.181	1.868	959	8.89	606	19.5	6.62	0.849	72.7	227.5	295
300	0.03531	1.003	39.13	2438	4.179	1.872	855	9.09	613	19.6	5.83	0.857	71.7	276.1	300
305	0.04712	1.005	29.74	2426	4.178	1.877	769	9.29	620	20.1	5.20	0.865	70.9	320.6	305
310	0.06221	1.007	22.93	2414	4.178	1.882	695	9.49	628	20.4	4.62	0.873	70.0	361.9	310
315	0.08132	1.009	17.82	2402	4.179	1.888	631	9.69	634	20.7	4.16	0.883	69.2	400.4	315
320	0.1053	1.011	13.98	2390	4.180	1.895	577	9.89	640	21.0	3.77	0.894	68.3	436.7	320
325	0.1351	1.013	11.06	2378	4.182	1.903	528	10.09	645	21.3	3.42	0.901	67.5	471.2	325
330	0.1719	1.016	8.82	2366	4.184	1.911	489	10.29	650	21.7	3.15	0.908	66.6	504.0	330
335	0.2167	1.018	7.09	2354	4.186	1.920	453	10.49	656	22.0	2.88	0.916	65.8	535.5	335
340	0.2713	1.021	5.74	2342	4.188	1.930	420	10.69	660	22.3	2.66	0.925	64.9	566.0	340
345	0.3372	1.024	4.683	2329	4.191	1.941	389	10.89	668	22.6	2.45	0.933	64.1	595.4	345
350	0.4163	1.027	3.846	2317	4.195	1.954	365	11.09	668	23.0	2.29	0.942	63.2	624.2	350
355	0.5100	1.030	3.180	2304	4.199	1.968	343	11.29	671	23.3	2.14	0.951	62.3	652.3	355
360	0.6209	1.034	2.645	2291	4.203	1.983	324	11.49	674	23.7	2.02	0.960	61.4	697.9	360
365	0.7514	1.038	2.212	2278	4.209	1.999	306	11.69	677	24.1	1.91	0.969	60.5	707.1	365
370	0.9040	1.041	1.861	2265	4.214	2.017	289	11.89	679	24.5	1.80	0.978	59.5	728.7	370
373.15	1.0133	1.044	1.679	2257	4.217	2.029	279	12.02	680	24.8	1.76	0.984	58.9	750.1	373.15
375	1.0815	1.045	1.574	2252	4.220	2.036	274	12.09	681	24.9	1.70	0.987	58.6	761	375
380	1.2869	1.049	1.337	2239	4.226	2.057	260	12.29	683	25.4	1.61	0.999	57.6	788	380
385	1.5233	1.053	1.142	2225	4.232	2.080	248	12.49	685	25.8	1.53	1.004	56.6	814	385
390	1.794	1.058	0.980	2212	4.239	2.104	237	12.69	686	26.3	1.47	1.013	55.6	841	390
400	2.455	1.067	0.731	2183	4.256	2.158	217	13.05	688	27.2	1.34	1.033	53.6	896	400
410	3.302	1.077	0.553	2153	4.278	2.221	200	13.42	688	28.2	1.24	1.054	51.5	952	410
420	4.370	1.088	0.425	2123	4.302	2.291	185	13.79	688	29.8	1.16	1.075	49.4	1010	420
430	5.699	1.099	0.331	2091	4.331	2.369	173	14.14	685	30.4	1.09	1.10	47.2		430