UNIVERSITY OF
KWAZULU-NATAL

INYUVESI
YAKWAZULU-NATALI

SCHOOL OF ENGINEERING

MAIN EXAMINATIONS: JUNE 2023

COURSE AND CODE: HEAT TRANSFER ENCH3HE

DURATION: 3 HOURS

TOTAL MARKS: 100

INTERNAL EXAMINERS: Dr. P. Ndlovu
Mrs. A. Singh

INTERNAL MODERATOR: Dr. S. Moodley

EXTERNAL MODERATOR: Dr. A.K.Tumba

INSTRUCTIONS:

1. **ALL** questions should be attempted.
2. Any programmable or non-programmable calculator may be used provided it has been cleared of any information that would subvert the purpose of the examination.
3. Calculations must be shown in sufficient detail to illustrate your understanding of the procedure.
4. **Two answer books are provided. Label them Book A and Book B. Answer Section A in Book A and Section B in Book B.**
5. This examination paper, together with all associated diagrams **MUST BE HANDED IN TOGETHER WITH YOUR SCRIPT.**

Student Number:

SECTION A

QUESTION 1

A two shell pass – four tube pass heat exchanger is to be used to heat 10 000kg/h of pressurised water from 35 ^{0}C to 120 ^{0}C. The heating medium is water at a temperature of 300 ^{0}C, and flow rate of 5000 kg/h. Use the effectiveness-NTU method to calculate the required heat transfer area if the overall heat transfer coefficient is 1500 W/m^2.K.

Properties of water are on page 8.

Effectiveness-NTU relations are on page 9.

Since the exit temperature of the heating medium is not provided, evaluate properties of the heating medium at 500 K as required for your calculations

TOTAL /16/

QUESTION 2

Hot oil flowing through a bundle of tubes is cooled by air in cross flow over the tubes. The air enters at 20 ^{0}C with a velocity of 7 m/s. The tubes are in a staggered arrangement with nine rows of tubes in the air flow direction and 12 tubes in each row. The outside diameter of the tubes is 20 mm, with a transverse pitch of 40 mm and longitudinal pitch of 45 mm. The surface temperature may be assumed to be constant at 60 ^{0}C. Calculate the air-side convection coefficient and the rate of heat transfer for the bundle of tubes.

Properties of air are provided on page 7.

Equations and tables may be found on pages 5 and 6.

TOTAL /17/

QUESTION 3

3.1 Saturated steam at a pressure of 0.105 bar condenses on a square array of 100 tubes of diameter 8 mm. If the condensation rate for the array is 10.8 kg/min, calculate the length of each tube. The tube surface temperature is 27 ^{0}C.

Properties of water are on page 8.

Correlations are provided on page 6.

(11)

3.2 Explain the variation of the heat transfer coefficient in the different pool boiling regimes. In which regime are engineering devices usually operated and why?

(6)

TOTAL/17/

SECTION B

QUESTION 4

A cooling tower is used to extract 27 431 MJ/hr of heat from hot water in counter-current flow with air. The air has a wet-bulb temperature of 23.9 ^{0}C. The water will enter the tower at 48.9^{0}C and leave at 29.4 ^{0}C. Given that G_x = 6356.9 kg/hr.m^2 and G_y'= 6835.4 kg/hr.m^2:

4.1 Tabulate the enthalpy values against temperature and construct the equilibrium curve and operating line of the process on the graph paper provided. Show the area that represents the potential for transfer area. (12)

4.2 Determine the minimum gas flowrate (4)

TOTAL/16/

QUESTION 5

A system of four process streams is represented in the figure below. The pinch temperature is 85 °C and ΔT_{min} = 10 °C. Design a maximum energy recovery (MER) network for this process.

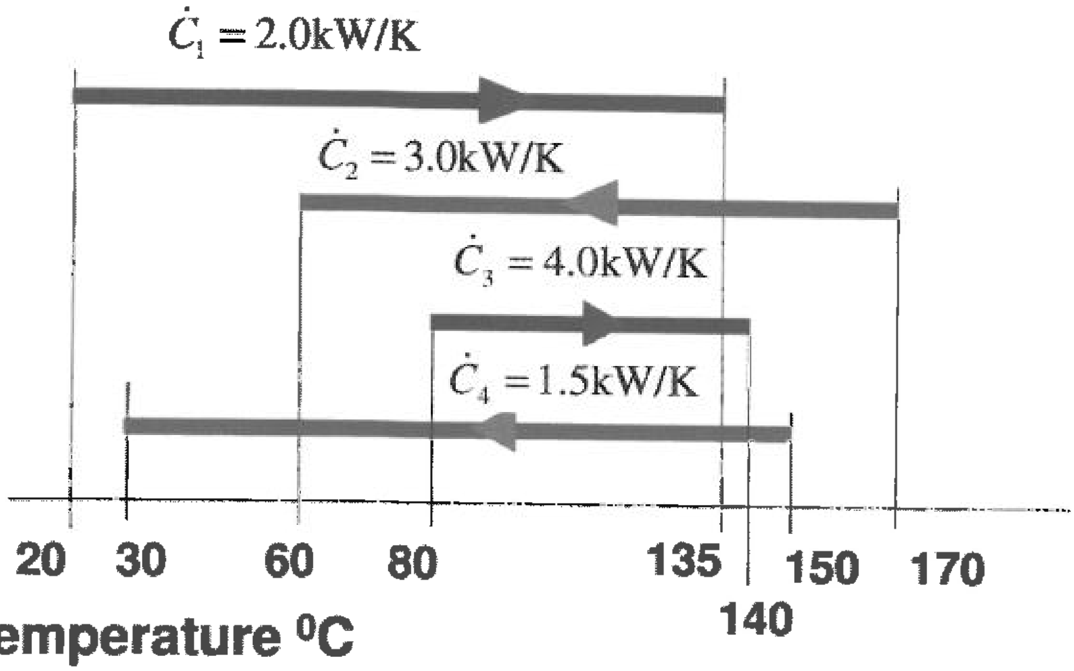


Figure 1: Schematic of Heat – Enthalpy flow and temperature

TOTAL /20/

QUESTION 6

An aqueous solution at 15.5°C, and containing 4% solids, is to be concentrated to 20% solids. A single effect evaporator with a heat transfer surface area of 37.2 m^2 and an overall heat transfer coefficient of 2000 W m^{-2} K^{-1} is to be used. The dry saturated steam is at a pressure of 200 kPa and the evaporator operates under a vacuum of 81.3 k Pa. If the boiling point rise is 5 K, calculate the evaporator capacity.

TOTAL/14/

TABLE 1: Some convection heat transfer correlations for external flow

Correlation	Geometry	Conditions
$\overline{Nu}_D = 0{,}3 + \{0{,}62\mathrm{Re}_D^{1/2}\mathrm{Pr}^{1/3} \times \left[1+(0{,}4/\mathrm{Pr})^{2/3}\right]^{-1/4}\} \times \left[1+(\mathrm{Re}_D/282{,}000)^{5/8}\right]^{4/5}$ (1)	Cylinder	Average, T_f, $\mathrm{Re}_D \mathrm{Pr} > 0{,}2$
$\overline{Nu}_D = 2 + (0{,}4\mathrm{Re}_D^{1/2} + 0{,}06\mathrm{Re}_D^{2/3})\mathrm{Pr}^{0{,}4} \times (\mu/\mu_s)^{1/4}$ (2)	Sphere	Average, T_x, $3{,}5 < \mathrm{Re}_{D,\max} < 7{,}6\times10^4$, $0{,}71 < \mathrm{Pr} < 380$, $1{,}0 < (\mu/\mu_s) < 3{,}2$
$\overline{Nu}_D = C\,\mathrm{Re}_{D,\max}^{m}\,\mathrm{Pr}^{0{,}36}(\mathrm{Pr}/\mathrm{Pr}_s)^{1/4}$ (3)	Tube bank	Average, $\overline{T}$, $1000 < \mathrm{Re}_{D,\max} < 2\times10^6$, $0{,}7 < \mathrm{Pr} < 500$, $N_L \geq 20$. For $N_L < 20$, $\overline{Nu}_D = C_2\,\overline{Nu}_D\big/_{N_L\geq 20}$ (4)

Equations:

Estimate T_o from:

$$\frac{T_s - T_o}{T_s - T_i} = \exp\left(-\frac{\pi D N \bar{h}}{\rho V N_T S_T C_P}\right) \qquad (5)$$

where N = total no. of tubes in bank.
N_T = no. of tubes in transverse plane.

Heat transfer per unit length of tubes:

$$q' = N\left(\bar{h}\pi D \Delta T_{lm}\right) \qquad (6)$$

To calculate maximum velocity (in-line arrangement):

$$V_{\max} = \frac{S_T}{S_T - D}V \qquad (7)$$

To calculate maximum velocity (staggered arrangement):

Maximum velocity occurs on diagonal plane if:

$$S_D = \left[S_L^2 + \left(\frac{S_T}{2}\right)^2\right]^{1/2} < \frac{S_T + D}{2} \qquad (8)$$

$$\text{Then } V_{max} = \frac{S_T}{2\,(S_D - D)}\,V \qquad (9)$$

If equation (8) does not hold then V_{max} occurs on the transverse plane and may be calculated using equation (7)

TABLE 2: Constants of Equation (3) for the tube bank in cross flow

Configuration	$Re_{D,max}$	C	m
Aligned	$10\text{-}10^2$	0,80	0,40
Staggered	$10\text{-}10^2$	0,90	0,40
Aligned	$10^2\text{-}10^3\}$	Approximate as a single (isolated) cylinder	
Staggered	$10^2\text{-}10^3\}$		
Aligned ($S_T/S_L > 0.7$)	$10^3\text{-}2 \times 10^5$	0,27	0,63
Staggered ($S_T/S_L < 2$)	$10^3\text{-}2 \times 10^5$	$0,35\ (S_T/S_L)^{1/5}$	0,60
Staggered ($S_T/S_L > 2$)	$10^3\text{-}2 \times 10^5$	0,40	0,60
Aligned	$2 \times 10^5\text{-}2 \times 10^6$	0,021	0,84
Staggered	$2 \times 10^5\text{-}2 \times 10^6$	0,022	0,84

TABLE 3: Correction factor C_2 of Equation (4) for $N_L < 20$ ($Re_D > 10^3$)

N_L	1	2	3	4	5	7	10	13	16
Aligned	0,70	0,80	0,86	0,90	0,92	0,95	0,97	0,98	0,99
Staggered	0,64	0,76	0,84	0,89	0,92	0,95	0,97	0,98	0,99

CONDENSATION

Film Condensation on radial surfaces: Vertical tier of N horizontal tubes

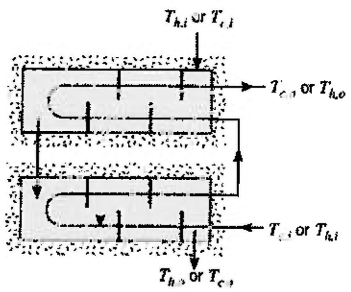
$$\overline{h_D} = 0{,}729\left[\frac{g\rho_l(\rho_l-\rho_v)\,k_l^3\,h'_{fg}}{N\,\mu_l(T_{sat}-T_s)D}\right]^{1/4}$$

$$h'_{fg} = h_{fg} + 0.80C_{p,l}(T_s - T_{sat})$$

TABLE 4: Properties of Air at Atmospheric Pressure

T (K)	ρ (kg/m^3)	c_p (kJ/kg.K)	$\mu . 10^7$ (N.s/m^2)	$\nu . 10^6$ (m^2/s)	$k . 10^3$ (W/m.K)	$\alpha . 10^6$ (m^2/s)	Pr
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	406	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

Fig 3: Effectiveness of a shell and tube heat exchanger with two shell passes and any multiple of four tube passes (four, eight, etc. tube passes)



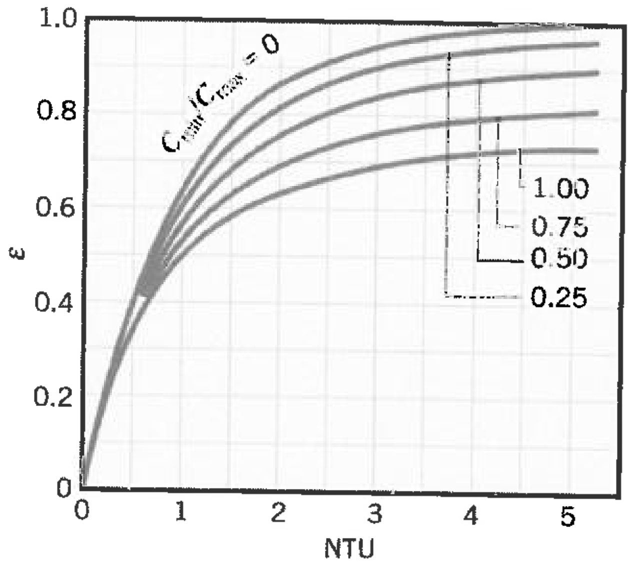
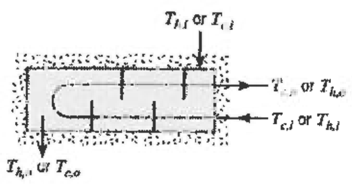


Fig 4: Effectiveness of a shell and tube heat exchanger with one shell and any multiple of two tube passes (two, four, etc. tube passes)



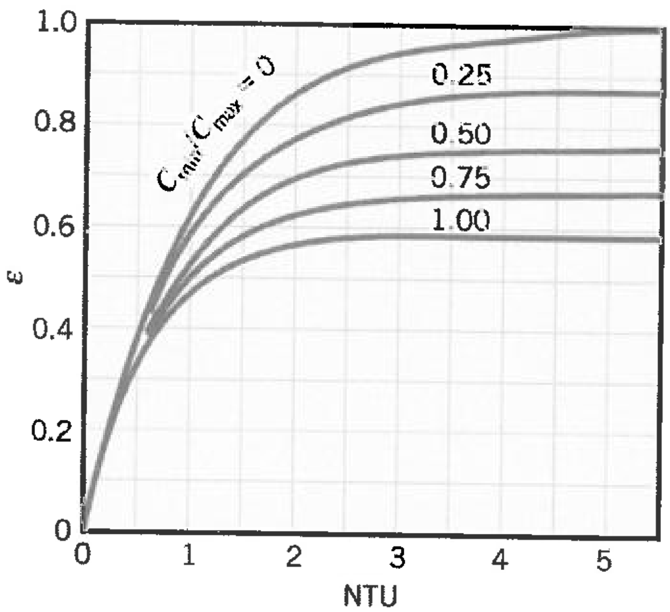


FIGURE 5 :Psychrometric Chart

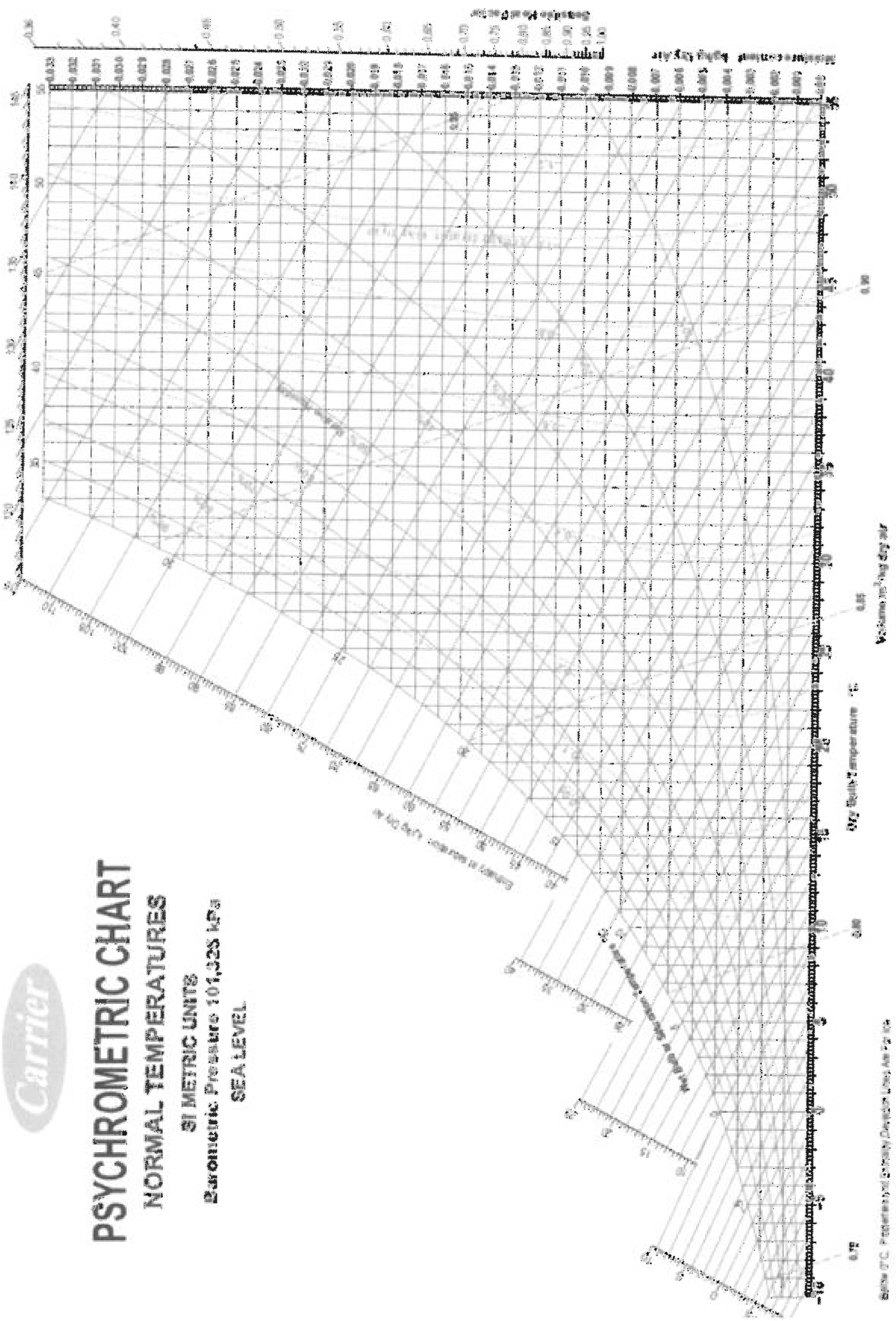


TABLE 6: Steam Tables

Saturated Steam: Pressure Table

Press. kPa P	Temp °C T	Specific Volume Sat. Liquid $\hat{V}^L$	Sat. Vapor $\hat{V}^V$	Internal Energy Sat. Liquid $\hat{U}^L$	Evap. $\Delta\hat{U}$	Sat. Vapor $\hat{U}^V$	Enthalpy Sat. Liquid $\hat{H}^L$	Evap. $\Delta\hat{H}$	Sat. Vapor $\hat{H}^V$	Entropy Sat. Liquid $\hat{S}^L$	Evap. $\Delta\hat{S}$	Sat. Vapor $\hat{S}^V$
0.6113	0.01	0.001 000	206.14	0.00	2375.3	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	9.1562
1.0	6.98	0.001 000	129.21	29.30	2355.7	2385.0	29.30	2484.9	2514.2	0.1059	8.8697	8.9756
1.5	13.03	0.001 001	87.98	54.71	2338.6	2393.3	54.71	2470.6	2525.3	0.1957	8.6322	8.8279
2.0	17.50	0.001 001	67.00	73.48	2326.0	2399.5	73.48	2460.0	2533.5	0.2607	8.4629	8.7237
2.5	21.08	0.001 002	54.25	88.48	2315.9	2404.4	88.49	2451.6	2540.0	0.3120	8.3311	8.6432
3.0	24.08	0.001 003	45.67	101.04	2307.5	2408.5	101.05	2444.5	2545.5	0.3545	8.2231	8.5776
4.0	28.96	0.001 004	34.80	121.45	2293.7	2415.2	121.46	2432.9	2554.4	0.4226	8.0520	8.4746
5.0	32.88	0.001 005	28.19	137.81	2282.7	2420.5	137.82	2423.7	2561.5	0.4764	7.9187	8.3951
7.5	40.29	0.001 008	19.24	168.78	2261.7	2430.5	168.79	2406.0	2574.8	0.5764	7.6750	8.2515
10	45.81	0.001 010	14.67	191.82	2246.1	2437.9	191.83	2392.8	2584.7	0.6493	7.5009	8.1502
15	53.97	0.001 014	10.02	225.92	2222.8	2448.7	225.94	2373.1	2599.1	0.7549	7.2536	8.0085
20	60.06	0.001 017	7.649	251.38	2205.4	2456.7	251.40	2358.3	2609.7	0.8320	7.0766	7.9085
25	64.97	0.001 020	6.204	271.90	2191.2	2463.1	271.93	2346.3	2618.2	0.8931	6.9383	7.8314
30	69.10	0.001 022	5.229	289.20	2179.2	2468.4	289.23	2336.1	2625.3	0.9439	6.8247	7.7686
40	75.87	0.001 027	3.993	317.53	2159.5	2477.0	317.58	2319.2	2636.8	1.0259	6.6441	7.6700
50	81.33	0.001 030	3.240	340.44	2143.4	2483.9	340.49	2305.4	2645.9	1.0910	6.5029	7.5939
75	91.78	0.001 037	2.217	384.31	2112.4	2496.7	384.39	2278.6	2663.0	1.2130	6.2434	7.4564
MPa												
0.100	99.63	0.001 043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001 048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001 053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001 057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001 061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271
0.225	124.00	0.001 064	0.7933	520.47	2013.1	2533.6	520.72	2191.3	2712.1	1.5706	5.5173	7.0878
0.250	127.44	0.001 067	0.7187	535.10	2002.1	2537.2	535.37	2181.5	2716.9	1.6072	5.4455	7.0527
0.275	130.60	0.001 070	0.6573	548.59	1991.9	2540.5	548.89	2172.4	2721.3	1.6408	5.3801	7.0209
0.300	133.55	0.001 073	0.6058	561.15	1982.4	2543.6	561.47	2163.8	2725.3	1.6718	5.3201	6.9919
0.325	136.30	0.001 076	0.5620	572.90	1973.5	2546.4	573.25	2155.8	2729.0	1.7006	5.2646	6.9652
0.350	138.88	0.001 079	0.5243	583.95	1965.0	2548.9	584.33	2148.1	2732.4	1.7275	5.2130	6.9405
0.375	141.32	0.001 081	0.4914	594.40	1956.9	2551.3	594.81	2140.8	2735.6	1.7528	5.1647	6.9175
0.40	143.63	0.001 084	0.4625	604.31	1949.3	2553.6	604.74	2133.8	2738.6	1.7766	5.1193	6.8959
0.45	147.93	0.001 088	0.4140	622.77	1934.9	2557.6	623.25	2120.7	2743.9	1.8207	5.0359	6.8565
0.50	151.86	0.001 093	0.3749	639.68	1921.6	2561.2	640.23	2108.5	2748.7	1.8607	4.9606	6.8213
0.55	155.48	0.001 097	0.3427	655.32	1909.2	2564.5	655.93	2097.0	2753.0	1.8973	4.8920	6.7893
0.60	158.85	0.001 101	0.3157	669.90	1897.5	2567.4	670.56	2086.3	2756.8	1.9312	4.8288	6.7600
0.65	162.01	0.001 104	0.2927	683.56	1886.5	2570.1	684.28	2076.0	2760.3	1.9627	4.7703	6.7331
0.70	164.97	0.001 108	0.2729	696.44	1876.1	2572.5	697.22	2066.3	2763.5	1.9922	4.7158	6.7080
0.75	167.78	0.001 112	0.2556	708.64	1866.1	2574.7	709.47	2057.0	2766.4	2.0200	4.6647	6.6847
0.80	170.43	0.001 115	0.2404	720.22	1856.6	2576.8	721.11	2048.0	2769.1	2.0462	4.6166	6.6628
0.85	172.96	0.001 118	0.2270	731.27	1847.4	2578.7	732.22	2039.4	2771.6	2.0710	4.5711	6.6421
0.90	175.38	0.001 121	0.2150	741.83	1838.6	2580.5	742.83	2031.1	2773.9	2.0946	4.5280	6.6226
0.95	177.69	0.001 124	0.2042	751.95	1830.2	2582.1	753.02	2023.1	2776.1	2.1172	4.4869	6.6041

$\hat{V}$ [=] m³/kg; $\hat{U}, \hat{H}$ [=] J/g = kJ/kg; $\hat{S}$ [=] kJ/kg K