UNIVERSITY OF
KWAZULU-NATAL

INYUVESI
YAKWAZULU-NATALI

SCHOOL OF ENGINEERING

MAIN EXAMINATIONS: JUNE 2023

COURSE AND CODE: MASS AND ENERGY BALANCES ENCH2MB

DURATION: 2 HOURS

TOTAL MARKS: 100

INTERNAL EXAMINERS: DR J POCOCK

INTERNAL MODERATOR: MS N. MASEKO

EXTERNAL MODERATOR: DR M LASICH

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.

1. Styrene is being produced in a catalytic reactor by dehydrogenation of ethylbenzene (reaction 1). There are two unwanted side reactions, one of which is the decomposition of ethylbenzene (reaction 2) to form benzene and ethene whilst the other is hydrogenation of ethylbenzene due to the presence of the hydrogen formed in reaction 1 to form toluene and methane (reaction 3).

Reaction 1: $C_8H_{10} \rightarrow C_8H_8 + H_2$

Reaction 2: $C_8H_{10} \rightarrow C_6H_6 + C_2H_4$

Reaction 3: $C_8H_{10} + H_2 \rightarrow C_7H_8 + CH_4$

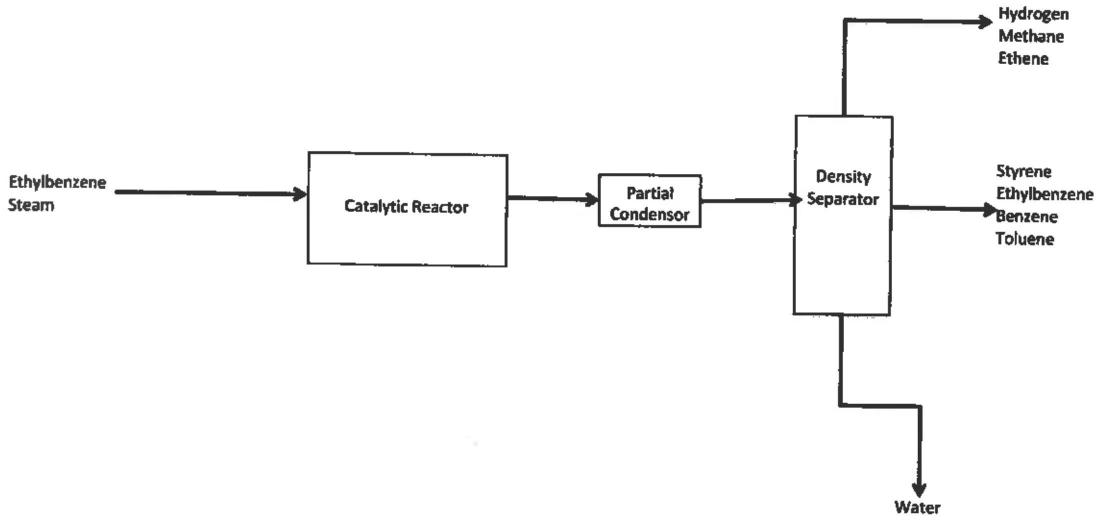
The reactor temperature is maintained by feeding superheated steam at a ratio of 11 mols steam/mol ethylbenzene into the reactor.

Under these conditions, the conversion of ethlybenzene is 40% through reaction 1, with 10% converted by reaction 2 and 5% through reaction 3.

After the reactor, the product gas is cooled in a partial condenser to room temperature and enters a density separator.

Here, a waste water stream (from the condensed steam) is drawn off at the bottom, an organic liquid stream comprising the remaining ethylbenzene, the styrene, benzene and toluene is drawn off at the middle of the separator, and a gas stream containing the hydrogen, ethene and methane is drawn off at the top.

A block diagram of the process is given on the next page. For a basis of 100 mol/minute of ethylbenzene entering the reactor:



a. Determine the degrees of freedom initially for the reactor and the density separator. (10 marks)

b. Solve the balances to determine the molar flows in each of the streams from the density separator. (20 marks)

TOTAL // 30 MARKS

2. Humid air at a flowrate of $10m^3$/hour is being drawn into a cooling tower to cool waste water from an air-conditioning system in an office block. The air entering the cooling tower enters with a dry-bulb temperature of 18°C and a wet-bulb temperature of 10°C. On exit from the cooling tower, the air is saturated at a temperature of 25°C.

   a. How much heat is being removed from the waste water per hour of operation? (15 marks)

   b. How much of the waste water is transferred into the air (in kg/hour)? (10 marks)

A psychrometric chart is provided on page 5

TOTAL// 25 MARKS

3. Saturated steam at 150°C, 1 bar pressure and a flowrate of 150 kg/minute is being mixed with superheated steam at 400°C, 5 bar pressure to provide a utility heating steam at 300°C, 1 bar pressure. Using the provided steam tables, determine the flowrate of the superheated steam used and the flowrate of the final utility heating steam formed.

Steam tables are provided on pages 6 and 7

TOTAL// 20 MARKS

4. One mole of an ideal gas undergoes the following reversible process.

   a. The gas is compressed isothermally from 50°C, 1.5 bar pressure to a pressure of 4 bar.
   b. The gas is then isobarically heated to 120°C
   c. It is finally returned to its initial state by adiabatic expansion.

For each stage of the reversible process, determine the work done by or on the gas (specify which at each stage), the heat added or removed (specify which at each stage), and the change in internal energy and enthalpy of the gas (specify whether these increase or decrease).

TOTAL// 25 MARKS

Data:

$C_V = 1.5R$ J/mol.K

$R = 8.314$J/mol.K

Useful Equations:

Equations of State for Gases:

Ideal Gases: $\frac{P\hat{V}}{RT} = 1$

Virial Equation of State: $\frac{P\hat{V}}{RT} = 1 + \frac{B}{\hat{V}}$ Where: $B = \frac{RT_c}{P_c}(B_0 + \omega B_1)$

And: $B_0 = 0.083 - \frac{0.422}{T_r^{1.6}}$

$B_1 = 0.139 - \frac{0.172}{T_r^{4.2}}$

$T_r = \frac{T}{T_c}$ where T, T_c are in K

$P_r = \frac{P}{P_c}$

For reversible processes with one mole of an ideal gas:

$$\frac{PV}{RT} = 1$$

$$dU = dQ - dW$$
$$dU = C_V dT$$
$$dH = dU + d(PV)$$
$$dH = C_P dT$$
$$C_P = C_V + R$$

Isobaric Processes $dW = PdV$

Isochoric Processes $dW = 0$

Isothermal Processes $W = RT\ln\frac{P_1}{P_2}$

Adiabatic Processes $W = \frac{P_1V_1 - P_2V_2}{\gamma - 1}$ where $\gamma = \frac{C_P}{C_V}$

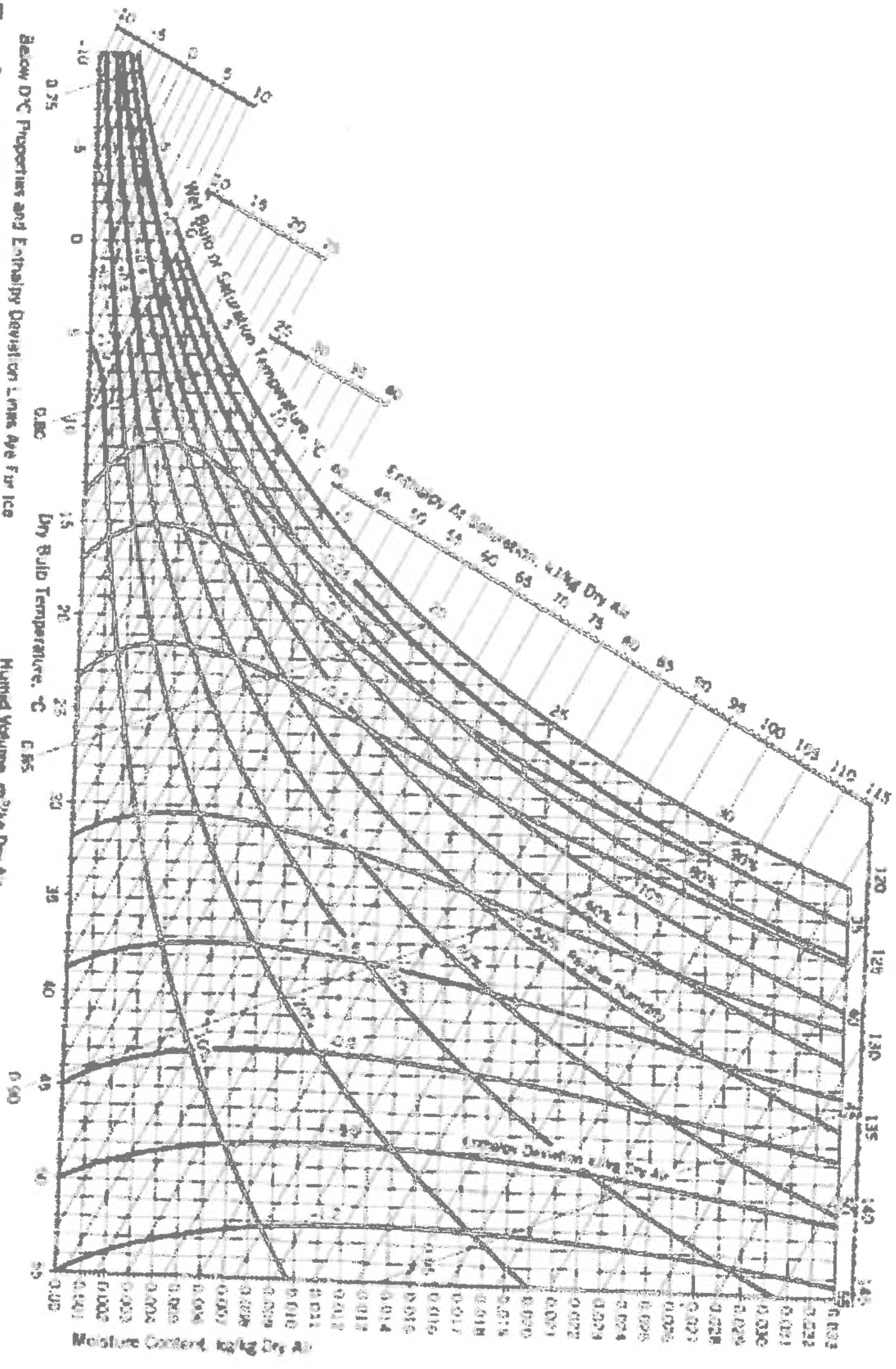


Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

Table B.7 Properties of Superheated Steam*

P(bar) (T_{sat} °C)		Sat'd Water	Sat'd Steam	Temperature (°C) → 50	75	100	150	200	250	300	350
0.0	$\hat{H}$	—	—	2595	2642	2689	2784	2880	2978	3077	3177
(—)	$\hat{U}$	—	—	2446	2481	2517	2589	2662	2736	2812	2890
	$\hat{V}$	—	—	—	—	—	—	—	—	—	—
0.1	$\hat{H}$	191.8	2584.8	2593	2640	2688	2783	2880	2977	3077	3177
(45.8)	$\hat{U}$	191.8	2438.0	2444	2480	2516	2588	2661	2736	2812	2890
	$\hat{V}$	0.00101	14.7	14.8	16.0	17.2	19.5	21.8	24.2	26.5	28.7
0.5	$\hat{H}$	340.6	2646.0	209.3	313.9	2683	2780	2878	2979	3076	3177
(81.3)	$\hat{U}$	340.6	2484.0	209.2	313.9	2512	2586	2660	2735	2811	2889
	$\hat{V}$	0.00103	3.24	0.00101	0.00103	3.41	3.89	4.35	4.83	5.29	5.75
1.0	$\hat{H}$	417.5	2675.4	209.3	314.0	2676	2776	2875	2975	3074	3176
(99.6)	$\hat{U}$	417.5	2506.1	209.2	313.9	2507	2583	2658	2734	2811	2889
	$\hat{V}$	0.00104	1.69	0.00101	0.00103	1.69	1.94	2.17	2.40	2.64	2.87
5.0	$\hat{H}$	640.1	2747.5	209.7	314.3	419.4	632.2	2855	2961	3065	3168
(151.8)	$\hat{U}$	639.6	2560.2	209.2	313.8	418.8	631.6	2643	2724	2803	2883
	$\hat{V}$	0.00109	0.375	0.00101	0.00103	0.00104	0.00109	0.425	0.474	0.522	0.571
10	$\hat{H}$	762.6	2776.2	210.1	314.7	419.7	632.5	2827	2943	3052	3159
(179.9)	$\hat{U}$	761.5	2582	209.1	313.7	418.7	631.4	2621	2710	2794	2876
	$\hat{V}$	0.00113	0.194	0.00101	0.00103	0.00104	0.00109	0.206	0.233	0.258	0.282
20	$\hat{H}$	908.6	2797.2	211.0	315.5	420.5	633.1	852.6	2902	3025	3139
(212.4)	$\hat{U}$	906.2	2598.2	209.0	313.5	418.4	630.9	850.2	2679	2774	2862
	$\hat{V}$	0.00118	0.0996	0.00101	0.00102	0.00104	0.00109	0.00116	0.111	0.125	0.139
40	$\hat{H}$	1087.4	2800.3	212.7	317.1	422.0	634.3	853.4	1085.8	2962	3095
(250.3)	$\hat{U}$	1082.4	2601.3	208.6	313.0	417.8	630.0	848.8	1080.8	2727	2829
	$\hat{V}$	0.00125	0.04975	0.00101	0.00102	0.00104	0.00109	0.00115	0.00125	0.0588	0.0665
60	$\hat{H}$	1213.7	2785.0	214.4	318.7	423.5	635.6	854.2	1085.8	2885	3046
(275.6)	$\hat{U}$	1205.8	2590.4	208.3	312.6	417.3	629.1	847.3	1078.3	2668	2792
	$\hat{V}$	0.00132	0.0325	0.00101	0.00102	0.00104	0.00109	0.00115	0.00125	0.0361	0.0422
80	$\hat{H}$	1317.1	2759.9	216.1	320.3	425.0	636.8	855.1	1085.8	2787	2990
(295.0)	$\hat{U}$	1306.0	2571.7	208.1	312.3	416.7	628.2	845.9	1075.8	2593	2750
	$\hat{V}$	0.00139	0.0235	0.00101	0.00102	0.00104	0.00109	0.00115	0.00124	0.0243	0.0299
100	$\hat{H}$	1408.0	2727.7	217.8	322.9	426.5	638.1	855.9	1085.8	1343.4	2926
(311.0)	$\hat{U}$	1393.5	2547.3	207.8	311.7	416.1	627.3	844.4	1073.4	1329.4	2702
	$\hat{V}$	0.00145	0.0181	0.00101	0.00102	0.00104	0.00109	0.00115	0.00124	0.00140	0.0224
150	$\hat{H}$	1611.0	2615.0	222.1	326.0	430.3	641.3	858.1	1086.2	1338.2	2695
(342.1)	$\hat{U}$	1586.1	2459.9	207.0	310.7	414.7	625.0	841.0	1067.7	1317.6	2523
	$\hat{V}$	0.00166	0.0103	0.00101	0.00102	0.00104	0.00108	0.00114	0.00123	0.00138	0.0115
200	$\hat{H}$	1826.5	2418.4	226.4	330.0	434.0	644.5	860.4	1086.7	1334.3	1647.1
(365.7)	$\hat{U}$	1785.7	2300.8	206.3	309.7	413.2	622.9	837.7	1062.2	1307.1	1613.7
	$\hat{V}$	0.00204	0.00585	0.00100	0.00102	0.00103	0.00108	0.00114	0.00122	0.00136	0.00167
221.2 (P_c)	$\hat{H}$	2100	2100	228.2	331.7	435.7	645.8	861.4	1087.0	1332.8	1635.5
(374.15 (T_c))	$\hat{U}$	2037.8	2037.8	206.0	309.2	412.6	622.0	836.3	1060.0	1302.9	1600.3
	$\hat{V}$	0.00317	0.00317	0.00100	0.00102	0.00103	0.00108	0.00114	0.00122	0.00135	0.00163
250	$\hat{H}$	—	—	230.7	334.0	437.8	647.7	862.8	1087.5	1331.1	1625.0
(—)	$\hat{U}$	—	—	205.7	308.7	412.1	620.8	834.4	1057.0	1297.5	1585.0
	$\hat{V}$	—	—	0.00100	0.00101	0.00103	0.00108	0.00113	0.00122	0.00135	0.00160
300	$\hat{H}$	—	—	235.0	338.1	441.6	650.9	865.2	1088.4	1328.7	1609.9
(—)	$\hat{U}$	—	—	205.0	307.7	410.8	618.7	831.3	1052.1	1288.7	1563.3
	$\hat{V}$	—	—	0.0009990	0.00101	0.00103	0.00107	0.00113	0.00121	0.00133	0.00155
500	$\hat{H}$	—	—	251.5	354.2	456.8	664.2	875.4	1093.6	1323.7	1576.3
(—)	$\hat{U}$	—	—	202.4	304.0	405.5	611.0	819.7	1034.3	1259.3	1504.1
	$\hat{V}$	—	—	0.0009911	0.00100	0.00102	0.00106	0.00111	0.00119	0.00129	0.00144
1000	$\hat{H}$	—	—	293.9	394.3	495.1	698.0	903.5	1113.0	1329.7	1559.5
(—)	$\hat{U}$	—	—	196.5	295.7	395.1	594.4	795.3	999.0	1207.1	1419.0
	$\hat{V}$	—	—	0.0009737	0.0009852	0.0009990	0.00104	0.00108	0.00114	0.00122	0.00131

*Adapted from R. W. Haywood, *Thermodynamic Tables in SI (Metric) Units*, Cambridge University Press, London, 1968. Water is a liquid in the enclosed region between 50°C and 350°C. $\hat{H}$ = specific enthalpy (kJ/kg), $\hat{U}$ = specific internal energy (kJ/kg), $\hat{V}$ = specific volume (m^3/kg). Note: kJ/kg × 0.4303 = Btu/lb_m.

(continued)

Table B.7 (Continued)

P(bar) (T_{sat} °C)		Temperature (°C) → 400	450	500	550	600	650	700	750
0.0 (—)	$\hat{H}$	3280	3384	3497	3597	3706	3816	3929	4043
	$\hat{U}$	2969	3050	3132	3217	3303	3390	3480	3571
	$\hat{V}$	—	—	—	—	—	—	—	—
0.1 (45.8)	$\hat{H}$	3280	3384	3489	3596	3706	3816	3929	4043
	$\hat{U}$	2969	3050	3132	3217	3303	3390	3480	3571
	$\hat{V}$	31.1	33.3	35.7	38.0	40.3	42.6	44.8	47.2
0.5 (81.3)	$\hat{H}$	3279	3383	3489	3596	3705	3816	3929	4043
	$\hat{U}$	2968	3049	3132	3216	3302	3390	3480	3571
	$\hat{V}$	6.21	6.67	7.14	7.58	8.06	8.55	9.01	9.43
1.0 (99.6)	$\hat{H}$	3278	3382	3488	3596	3705	3816	3928	4042
	$\hat{U}$	2968	3049	3132	3216	3302	3390	3479	3570
	$\hat{V}$	3.11	3.33	3.57	3.80	4.03	4.26	4.48	4.72
5.0 (151.8)	$\hat{H}$	3272	3379	3484	3592	3702	3813	3926	4040
	$\hat{U}$	2964	3045	3128	3213	3300	3388	3477	3569
	$\hat{V}$	0.617	0.664	0.711	0.758	0.804	0.850	0.897	0.943
10 (179.9)	$\hat{H}$	3264	3371	3478	3587	3697	3809	3923	4038
	$\hat{U}$	2958	3041	3124	3210	3296	3385	3475	3567
	$\hat{V}$	0.307	0.330	0.353	0.377	0.402	0.424	0.448	0.472
20 (212.4)	$\hat{H}$	3249	3358	3467	3578	3689	3802	3916	4032
	$\hat{U}$	2946	3031	3115	3202	3290	3379	3470	3562
	$\hat{V}$	0.151	0.163	0.175	0.188	0.200	.0211	0.223	0.235
40 (250.3)	$\hat{H}$	3216	3331	3445	3559	3673	3788	3904	4021
	$\hat{U}$	2922	3011	3100	3186	3278	3368	3460	3554
	$\hat{V}$	0.0734	0.0799	0.0864	0.0926	0.0987	0.105	0.111	0.117
60 (275.6)	$\hat{H}$	3180	3303	3422	3539	3657	3774	3892	4011
	$\hat{U}$	2896	2991	3083	3174	3265	3357	3451	3545
	$\hat{V}$	0.0474	0.0521	0.0566	0.0609	0.0652	0.0693	0.0735	0.0776
80 (295.0)	$\hat{H}$	3142	3274	3399	3520	3640	3759	3879	4000
	$\hat{U}$	2867	2969	3065	3159	3252	3346	3442	3537
	$\hat{V}$	0.0344	0.0382	0.0417	0.0452	0.0483	0.0515	0.0547	0.0578
100 (311.0)	$\hat{H}$	3100	3244	3375	3500	3623	3745	3867	3989
	$\hat{U}$	2836	2946	3047	3144	3240	3335	3431	3528
	$\hat{V}$	0.0264	0.0298	0.0328	0.0356	0.0383	0.0410	0.0435	0.0461
150 (342.1)	$\hat{H}$	2975	3160	3311	3448	3580	3708	3835	3962
	$\hat{U}$	2744	2883	2999	3105	3207	3307	3407	3507
	$\hat{V}$	0.0157	0.0185	0.0208	0.0229	0.0249	0.0267	0.0286	0.0304
200 (365.7)	$\hat{H}$	2820	3064	3341	3394	3536	3671	3804	3935
	$\hat{U}$	2622	2810	2946	3063	3172	3278	3382	3485
	$\hat{V}$	0.009950	0.0127	0.0148	0.0166	0.0182	0.197	0.211	0.0225
221.2 (P_c) (374.15 (T_c))	$\hat{H}$	2733	3020	3210	3370	3516	3655	3790	3923
	$\hat{U}$	2553	2776	2922	3045	3157	3265	3371	3476
	$\hat{V}$	0.008157	0.0110	0.0130	0.0147	0.0162	0.0176	0.0190	0.0202
250 (—)	$\hat{H}$	2582	2954	3166	3337	3490	3633	3772	3908
	$\hat{U}$	2432	2725	2888	3019	3137	3248	3356	3463
	$\hat{V}$	0.006013	0.009174	0.0111	0.0127	0.0141	0.0153	0.0166	0.0178
300 (—)	$\hat{H}$	2162	2826	3085	3277	3443	3595	3740	3880
	$\hat{U}$	2077	2623	2825	2972	3100	3218	3330	3441
	$\hat{V}$	0.002830	0.006734	0.008680	0.0102	0.0114	0.0126	0.0136	0.0147
500 (—)	$\hat{H}$	1878	2293	2723	3021	3248	3439	3610	3771
	$\hat{U}$	1791	2169	2529	2765	2946	3091	3224	3350
	$\hat{V}$	0.001726	0.002491	0.003882	0.005112	0.006112	0.007000	0.007722	0.008418
1000 (—)	$\hat{H}$	1798	2051	2316	2594	2857	3105	3324	3526
	$\hat{U}$	1653	1888	2127	2369	2591	2795	2971	3131
	$\hat{V}$	0.001446	0.001628	0.001893	0.002246	0.002668	0.003106	0.003536	0.003953