

Compressible Flow Exam – Fall 2007  
Calculator Allowed & Tables Provided

**Problem 1)** Consider steady flow of a perfect gas through a constant area duct.

- a) (15 pts) If the flow is assumed to be adiabatic with no external work derive a relationship between the temperature and entropy assuming there is friction in the duct. You can assume one-dimensional flow and that there is a fixed mass flow and total enthalpy. A convenient starting point could be the thermodynamic relationship for a pure substance derivable from the first and second laws of thermodynamics,

$$Tds = du - \frac{p}{\rho^2} d\rho .$$

- b) (5 pts) Discuss the paths along this Fanno Line curve for both the subsonic and supersonic branches of this curve and the point of maximum entropy.
- c) (5pts) If one was to relax the constraints on the flow duct what could you do to this duct to keep the flow's Mach number constant throughout?

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**Problem 2)** Consider a converging-diverging nozzle with a throat area of  $65.5 \text{ cm}^2$  and an exit area of  $77 \text{ cm}^2$  which exits into a room at  $101 \text{ kPa}$ . The nozzle is supplied with clean dry air ( $\gamma=1.4$  and  $R=287 \text{ J/kg K}$ ) at a fixed stagnation temperature of  $300 \text{ K}$  and a supply pressure that can be varied.

- a) (3 pts) What is the “design” Mach number of this nozzle and what is meant by this phrase?
- b) (5 pts) What is the exit Mach number if the stagnation pressure is  $150 \text{ kPa}$ ? Sketch and describe the pressure through out the nozzle. Sketch and describe any waves in the flow throughout the nozzle and at the exit.
- c) (5 pts) What is the exit Mach number if the stagnation pressure is  $505 \text{ kPa}$ ? Sketch and describe the pressure through out the nozzle. Sketch and describe the flow throughout and exit the nozzle
- d) (6pts) Determine the maximum mass flow rate and the minimum supply pressure with which this can be achieved? Discuss how the mass flow rate changes as a function of the pressure ratio.
- e) (6 pts) If a storage tank of air at  $1400 \text{ kPa}$  and  $300 \text{ K}$  with a volume of  $32 \text{ m}^3$  is attached to the nozzle how long would it take to drain this tank at the mass flow rate determined in part d). State all assumptions that you are making.

# Isentropic Flow Tables

TABLE B.1 Isentropic Flow Table ( $\gamma = 1.4$ )

$M$	$T/T_o$	$p/p_o$	$\rho/\rho_o$	$A/A^*$	$M$	$T/T_o$	$p/p_o$	$\rho/\rho_o$	$A/A^*$
0.00	1.0000	1.0000	1.0000	$\infty$	0.94	0.8498	0.5658	0.6658	1.0031
0.02	0.9999	0.9997	0.9998	28.9421	0.96	0.8444	0.5532	0.6551	1.0014
0.04	0.9997	0.9989	0.9992	14.4815	0.98	0.8389	0.5407	0.6445	1.0003
0.06	0.9993	0.9975	0.9982	9.6659	1.00	0.8333	0.5283	0.6339	1.0000
0.08	0.9987	0.9955	0.9968	7.2616	1.02	0.8278	0.5160	0.6234	1.0003
0.10	0.9980	0.9930	0.9950	5.8218	1.04	0.8222	0.5039	0.6129	1.0013
0.12	0.9971	0.9900	0.9928	4.8643	1.06	0.8165	0.4919	0.6024	1.0029
0.14	0.9961	0.9864	0.9903	4.1824	1.08	0.8108	0.4800	0.5920	1.0051
0.16	0.9949	0.9823	0.9873	3.6727	1.10	0.8052	0.4684	0.5817	1.0079
0.18	0.9936	0.9776	0.9840	3.2779	1.12	0.7994	0.4568	0.5714	1.0113
0.20	0.9921	0.9725	0.9803	2.9635	1.14	0.7937	0.4455	0.5612	1.0153
0.22	0.9904	0.9668	0.9762	2.7076	1.16	0.7879	0.4343	0.5511	1.0198
0.24	0.9886	0.9607	0.9718	2.4956	1.18	0.7822	0.4232	0.5411	1.0248
0.26	0.9867	0.9541	0.9670	2.3173	1.20	0.7764	0.4124	0.5311	1.0304
0.28	0.9846	0.9470	0.9619	2.1656	1.22	0.7706	0.4017	0.5213	1.0366
0.30	0.9823	0.9395	0.9564	2.0351	1.24	0.7648	0.3912	0.5115	1.0432
0.32	0.9799	0.9315	0.9506	1.9219	1.26	0.7590	0.3809	0.5019	1.0504
0.34	0.9774	0.9231	0.9445	1.8229	1.28	0.7532	0.3708	0.4923	1.0581
0.36	0.9747	0.9143	0.9380	1.7358	1.30	0.7474	0.3609	0.4829	1.0663
0.38	0.9719	0.9052	0.9313	1.6587	1.32	0.7416	0.3512	0.4736	1.0750
0.40	0.9690	0.8956	0.9243	1.5901	1.34	0.7358	0.3417	0.4644	1.0842
0.42	0.9659	0.8857	0.9170	1.5289	1.36	0.7300	0.3323	0.4553	1.0940
0.44	0.9627	0.8755	0.9094	1.4740	1.38	0.7242	0.3232	0.4463	1.1042
0.46	0.9594	0.8650	0.9016	1.4246	1.40	0.7184	0.3142	0.4374	1.1149
0.48	0.9559	0.8541	0.8935	1.3801	1.42	0.7126	0.3055	0.4287	1.1262
0.50	0.9524	0.8430	0.8852	1.3398	1.44	0.7069	0.2969	0.4201	1.1379
0.52	0.9487	0.8317	0.8766	1.3034	1.46	0.7011	0.2886	0.4116	1.1501
0.54	0.9449	0.8201	0.8679	1.2703	1.48	0.6954	0.2804	0.4032	1.1629
0.56	0.9410	0.8082	0.8589	1.2403	1.50	0.6897	0.2724	0.3950	1.1762
0.58	0.9370	0.7962	0.8498	1.2130	1.52	0.6840	0.2646	0.3869	1.1899
0.60	0.9328	0.7840	0.8405	1.1882	1.54	0.6783	0.2570	0.3789	1.2042
0.62	0.9286	0.7716	0.8310	1.1656	1.56	0.6726	0.2496	0.3710	1.2190
0.64	0.9243	0.7591	0.8213	1.1451	1.58	0.6670	0.2423	0.3633	1.2344
0.66	0.9199	0.7465	0.8115	1.1265	1.60	0.6614	0.2353	0.3557	1.2502
0.68	0.9153	0.7338	0.8016	1.1097	1.62	0.6558	0.2284	0.3483	1.2666
0.70	0.9107	0.7209	0.7916	1.0944	1.64	0.6502	0.2217	0.3409	1.2836
0.72	0.9061	0.7080	0.7814	1.0806	1.66	0.6447	0.2151	0.3337	1.3010
0.74	0.9013	0.6951	0.7712	1.0681	1.68	0.6392	0.2088	0.3266	1.3190
0.76	0.8964	0.6821	0.7609	1.0570	1.70	0.6337	0.2026	0.3197	1.3376
0.78	0.8915	0.6691	0.7505	1.0471	1.72	0.6283	0.1966	0.3129	1.3567
0.80	0.8865	0.6560	0.7400	1.0382	1.74	0.6229	0.1907	0.3062	1.3764
0.82	0.8815	0.6430	0.7295	1.0305	1.76	0.6175	0.1850	0.2996	1.3967
0.84	0.8763	0.6300	0.7189	1.0237	1.78	0.6121	0.1794	0.2931	1.4175
0.86	0.8711	0.6170	0.7083	1.0179	1.80	0.6068	0.1740	0.2868	1.4390
0.88	0.8659	0.6041	0.6977	1.0129	1.82	0.6015	0.1688	0.2806	1.4610
0.90	0.8606	0.5913	0.6870	1.0089	1.84	0.5963	0.1637	0.2745	1.4836
0.92	0.8552	0.5785	0.6764	1.0056	1.86	0.5910	0.1587	0.2686	1.5069

TABLE B.1 (Continued)

$M$	$T/T_o$	$p/p_o$	$\rho/\rho_o$	$A/A^*$	$M$	$T/T_o$	$p/p_o$	$\rho/\rho_o$	$A/A^*$
1.88	0.5859	0.1539	0.2627	1.5308	3.02	0.3541	0.0264	0.0746	4.3160
1.90	0.5807	0.1492	0.2570	1.5553	3.04	0.3511	0.0256	0.0730	4.3989
1.92	0.5756	0.1447	0.2514	1.5804	3.06	0.3481	0.0249	0.0715	4.4835
1.94	0.5705	0.1403	0.2459	1.6062	3.08	0.3452	0.0242	0.0700	4.5696
1.96	0.5655	0.1360	0.2405	1.6326	3.10	0.3422	0.0234	0.0685	4.6573
1.98	0.5605	0.1318	0.2352	1.6597	3.12	0.3393	0.0228	0.0671	4.7467
2.00	0.5556	0.1278	0.2300	1.6875	3.14	0.3365	0.0221	0.0657	4.8377
2.02	0.5506	0.1239	0.2250	1.7160	3.16	0.3337	0.0215	0.0643	4.9304
2.04	0.5458	0.1201	0.2200	1.7451	3.18	0.3309	0.0208	0.0630	5.0248
2.06	0.5409	0.1164	0.2152	1.7750	3.20	0.3281	0.0202	0.0617	5.1210
2.08	0.5361	0.1128	0.2104	1.8056	3.22	0.3253	0.0196	0.0604	5.2189
2.10	0.5313	0.1094	0.2058	1.8369	3.24	0.3226	0.0191	0.0591	5.3186
2.12	0.5266	0.1060	0.2013	1.8690	3.26	0.3199	0.0185	0.0579	5.4201
2.14	0.5219	0.1027	0.1968	1.9018	3.28	0.3173	0.0180	0.0567	5.5234
2.16	0.5173	0.0996	0.1925	1.9354	3.30	0.3147	0.0175	0.0555	5.6286
2.18	0.5127	0.0965	0.1882	1.9698	3.32	0.3121	0.0170	0.0544	5.7358
2.20	0.5081	0.0935	0.1841	2.0050	3.34	0.3095	0.0165	0.0533	5.8448
2.22	0.5036	0.0906	0.1800	2.0409	3.36	0.3069	0.0160	0.0522	5.9558
2.24	0.4991	0.0878	0.1760	2.0777	3.38	0.3044	0.0156	0.0511	6.0687
2.26	0.4947	0.0851	0.1721	2.1153	3.40	0.3019	0.0151	0.0501	6.1837
2.28	0.4903	0.0825	0.1683	2.1538	3.42	0.2995	0.0147	0.0491	6.3007
2.30	0.4859	0.0800	0.1646	2.1931	3.44	0.2970	0.0143	0.0481	6.4198
2.32	0.4816	0.0775	0.1609	2.2333	3.46	0.2946	0.0139	0.0471	6.5409
2.34	0.4773	0.0751	0.1574	2.2744	3.48	0.2922	0.0135	0.0462	6.6642
2.36	0.4731	0.0728	0.1539	2.3164	3.50	0.2899	0.0131	0.0452	6.7896
2.38	0.4688	0.0706	0.1505	2.3593	3.52	0.2875	0.0127	0.0443	6.9172
2.40	0.4647	0.0684	0.1472	2.4031	3.54	0.2852	0.0124	0.0434	7.0471
2.42	0.4606	0.0663	0.1439	2.4479	3.56	0.2829	0.0120	0.0426	7.1791
2.44	0.4565	0.0643	0.1408	2.4936	3.58	0.2806	0.0117	0.0417	7.3135
2.46	0.4524	0.0623	0.1377	2.5403	3.60	0.2784	0.0114	0.0409	7.4501
2.48	0.4484	0.0604	0.1346	2.5880	3.62	0.2762	0.0111	0.0401	7.5891
2.50	0.4444	0.0585	0.1317	2.6367	3.64	0.2740	0.0108	0.0393	7.7305
2.52	0.4405	0.0567	0.1288	2.6865	3.66	0.2718	0.0105	0.0385	7.8742
2.54	0.4366	0.0550	0.1260	2.7372	3.68	0.2697	0.0102	0.0378	8.0204
2.56	0.4328	0.0533	0.1232	2.7891	3.70	0.2675	0.0099	0.0370	8.1691
2.58	0.4289	0.0517	0.1205	2.8420	3.72	0.2654	0.0096	0.0363	8.3202
2.60	0.4252	0.0501	0.1179	2.8960	3.74	0.2633	0.0094	0.0356	8.4739
2.62	0.4214	0.0486	0.1153	2.9511	3.76	0.2613	0.0091	0.0349	8.6302
2.64	0.4177	0.0471	0.1128	3.0073	3.78	0.2592	0.0089	0.0342	8.7891
2.66	0.4141	0.0457	0.1103	3.0647	3.80	0.2572	0.0086	0.0335	8.9506
2.68	0.4104	0.0443	0.1079	3.1233	3.82	0.2552	0.0084	0.0329	9.1148
2.70	0.4068	0.0430	0.1056	3.1830	3.84	0.2532	0.0082	0.0323	9.2817
2.72	0.4033	0.0417	0.1033	3.2440	3.86	0.2513	0.0080	0.0316	9.4513
2.74	0.3998	0.0404	0.1010	3.3061	3.88	0.2493	0.0077	0.0310	9.6237
2.76	0.3963	0.0392	0.0989	3.3695	3.90	0.2474	0.0075	0.0304	9.7990
2.78	0.3928	0.0380	0.0967	3.4342	3.92	0.2455	0.0073	0.0299	9.9771
2.80	0.3894	0.0368	0.0946	3.5001	3.94	0.2436	0.0071	0.0293	10.1581
2.82	0.3860	0.0357	0.0926	3.5674	3.96	0.2418	0.0069	0.0287	10.3420
2.84	0.3827	0.0347	0.0906	3.6359	3.98	0.2399	0.0068	0.0282	10.5289
2.86	0.3794	0.0336	0.0886	3.7058	4.00	0.2381	0.0066	0.0277	10.7188
2.88	0.3761	0.0326	0.0867	3.7771	4.02	0.2363	0.0064	0.0271	10.9117
2.90	0.3729	0.0317	0.0849	3.8498	4.04	0.2345	0.0062	0.0266	11.1077
2.92	0.3696	0.0307	0.0831	3.9238	4.06	0.2327	0.0061	0.0261	11.3068
2.94	0.3665	0.0298	0.0813	3.9993	4.08	0.2310	0.0059	0.0256	11.5091
2.96	0.3633	0.0289	0.0796	4.0763	4.10	0.2293	0.0058	0.0252	11.7147
2.98	0.3602	0.0281	0.0779	4.1547	4.12	0.2275	0.0056	0.0247	11.9234
3.00	0.3571	0.0272	0.0762	4.2346	4.14	0.2258	0.0055	0.0242	12.1354

# Normal-Shock Tables

TABLE C.1 Normal-Shock Table ( $\gamma = 1.4$ )

$M_1$	$M_2$	$p_2/p_1$	$T_2/T_1$	$\rho_2/\rho_1$	$p_{02}/p_{01}$	$P_{02}/P_1$
1.00	1.0000	1.0000	1.0000	1.0000	1.0000	1.8929
1.02	0.9805	1.0471	1.0132	1.0334	1.0000	1.9379
1.04	0.9620	1.0952	1.0263	1.0671	0.9999	1.9844
1.06	0.9444	1.1442	1.0393	1.1009	0.9998	2.0325
1.08	0.9277	1.1941	1.0522	1.1349	0.9994	2.0819
1.10	0.9118	1.2450	1.0649	1.1691	0.9989	2.1328
1.12	0.8966	1.2968	1.0776	1.2034	0.9982	2.1851
1.14	0.8820	1.3495	1.0903	1.2378	0.9973	2.2388
1.16	0.8682	1.4032	1.1029	1.2723	0.9961	2.2937
1.18	0.8549	1.4578	1.1154	1.3069	0.9946	2.3500
1.20	0.8422	1.5133	1.1280	1.3416	0.9928	2.4075
1.22	0.8300	1.5698	1.1405	1.3764	0.9907	2.4663
1.24	0.8183	1.6272	1.1531	1.4112	0.9884	2.5263
1.26	0.8071	1.6855	1.1657	1.4460	0.9857	2.5875
1.28	0.7963	1.7448	1.1783	1.4808	0.9827	2.6500
1.30	0.7860	1.8050	1.1909	1.5157	0.9794	2.7136
1.32	0.7760	1.8661	1.2035	1.5505	0.9758	2.7784
1.34	0.7664	1.9282	1.2162	1.5854	0.9718	2.8444
1.36	0.7572	1.9912	1.2290	1.6202	0.9676	2.9115
1.38	0.7483	2.0551	1.2418	1.6549	0.9630	2.9798
1.40	0.7397	2.1200	1.2547	1.6897	0.9582	3.0492
1.42	0.7314	2.1858	1.2676	1.7243	0.9531	3.1198
1.44	0.7235	2.2525	1.2807	1.7589	0.9476	3.1915
1.46	0.7157	2.3202	1.2938	1.7934	0.9420	3.2643
1.48	0.7083	2.3888	1.3069	1.8278	0.9360	3.3382
1.50	0.7011	2.4583	1.3202	1.8621	0.9298	3.4133
1.52	0.6941	2.5288	1.3336	1.8963	0.9233	3.4894
1.54	0.6874	2.6002	1.3470	1.9303	0.9166	3.5667
1.56	0.6809	2.6725	1.3606	1.9643	0.9097	3.6450
1.58	0.6746	2.7458	1.3742	1.9981	0.9026	3.7244
1.60	0.6684	2.8200	1.3880	2.0317	0.8952	3.8050
1.62	0.6625	2.8951	1.4018	2.0653	0.8877	3.8866
1.64	0.6568	2.9712	1.4158	2.0986	0.8799	3.9693
1.66	0.6512	3.0482	1.4299	2.1318	0.8720	4.0531
1.68	0.6458	3.1261	1.4440	2.1649	0.8639	4.1379
1.70	0.6405	3.2050	1.4583	2.1977	0.8557	4.2238
1.72	0.6355	3.2848	1.4727	2.2304	0.8474	4.3108
1.74	0.6305	3.3655	1.4873	2.2629	0.8389	4.3989
1.76	0.6257	3.4472	1.5019	2.2952	0.8302	4.4880
1.78	0.6210	3.5298	1.5167	2.3273	0.8215	4.5782
1.80	0.6165	3.6133	1.5316	2.3592	0.8127	4.6695
1.82	0.6121	3.6978	1.5466	2.3909	0.8038	4.7618
1.84	0.6078	3.7832	1.5617	2.4224	0.7948	4.8552
1.86	0.6036	3.8695	1.5770	2.4537	0.7857	4.9497
1.88	0.5996	3.9568	1.5924	2.4848	0.7765	5.0452
1.90	0.5956	4.0450	1.6079	2.5157	0.7674	5.1418

TABLE C.1 (Continued)

$M_1$	$M_2$	$p_2/p_1$	$T_2/T_1$	$\rho_2/\rho_1$	$p_{o2}/p_{o1}$	$p_{o2}/p_1$
1.92	0.5918	4.1341	1.6236	2.5463	0.7581	5.2394
1.94	0.5880	4.2242	1.6394	2.5767	0.7488	5.3381
1.96	0.5844	4.3152	1.6553	2.6069	0.7395	5.4378
1.98	0.5808	4.4071	1.6713	2.6369	0.7302	5.5386
2.00	0.5774	4.5000	1.6875	2.6667	0.7209	5.6404
2.02	0.5740	4.5938	1.7038	2.6962	0.7115	5.7433
2.04	0.5707	4.6885	1.7203	2.7255	0.7022	5.8473
2.06	0.5675	4.7842	1.7369	2.7545	0.6928	5.9523
2.08	0.5643	4.8808	1.7536	2.7833	0.6835	6.0583
2.10	0.5613	4.9783	1.7705	2.8119	0.6742	6.1654
2.12	0.5583	5.0768	1.7875	2.8402	0.6649	6.2735
2.14	0.5554	5.1762	1.8046	2.8683	0.6557	6.3827
2.16	0.5525	5.2765	1.8219	2.8962	0.6464	6.4929
2.18	0.5498	5.3778	1.8393	2.9238	0.6373	6.6042
2.20	0.5471	5.4800	1.8569	2.9512	0.6281	6.7165
2.22	0.5444	5.5831	1.8746	2.9784	0.6191	6.8298
2.24	0.5418	5.6872	1.8924	3.0053	0.6100	6.9442
2.26	0.5393	5.7922	1.9104	3.0319	0.6011	7.0597
2.28	0.5368	5.8981	1.9285	3.0584	0.5921	7.1762
2.30	0.5344	6.0050	1.9468	3.0845	0.5833	7.2937
2.32	0.5321	6.1128	1.9652	3.1105	0.5745	7.4122
2.34	0.5297	6.2215	1.9838	3.1362	0.5658	7.5319
2.36	0.5275	6.3312	2.0025	3.1617	0.5572	7.6525
2.38	0.5253	6.4418	2.0213	3.1869	0.5486	7.7742
2.40	0.5231	6.5533	2.0403	3.2119	0.5401	7.8969
2.42	0.5210	6.6658	2.0595	3.2367	0.5317	8.0207
2.44	0.5189	6.7792	2.0788	3.2612	0.5234	8.1455
2.46	0.5169	6.8935	2.0982	3.2855	0.5152	8.2713
2.48	0.5149	7.0088	2.1178	3.3095	0.5071	8.3982
2.50	0.5130	7.1250	2.1375	3.3333	0.4990	8.5261
2.52	0.5111	7.2421	2.1574	3.3569	0.4911	8.6551
2.54	0.5092	7.3602	2.1774	3.3803	0.4832	8.7851
2.56	0.5074	7.4792	2.1976	3.4034	0.4754	8.9161
2.58	0.5056	7.5991	2.2179	3.4263	0.4677	9.0482
2.60	0.5039	7.7200	2.2383	3.4490	0.4601	9.1813
2.62	0.5022	7.8418	2.2590	3.4714	0.4526	9.3155
2.64	0.5005	7.9645	2.2797	3.4937	0.4452	9.4506
2.66	0.4988	8.0882	2.3006	3.5157	0.4379	9.5869
2.68	0.4972	8.2128	2.3217	3.5374	0.4307	9.7241
2.70	0.4956	8.3383	2.3429	3.5590	0.4236	9.8624
2.72	0.4941	8.4648	2.3642	3.5803	0.4166	10.0017
2.74	0.4926	8.5922	2.3858	3.6015	0.4097	10.1421
2.76	0.4911	8.7205	2.4074	3.6224	0.4028	10.2835
2.78	0.4896	8.8498	2.4292	3.6431	0.3961	10.4259
2.80	0.4882	8.9800	2.4512	3.6636	0.3895	10.5694
2.82	0.4868	9.1111	2.4733	3.6838	0.3829	10.7139
2.84	0.4854	9.2432	2.4955	3.7039	0.3765	10.8594
2.86	0.4840	9.3762	2.5179	3.7238	0.3701	11.0060
2.88	0.4827	9.5101	2.5405	3.7434	0.3639	11.1536
2.90	0.4814	9.6450	2.5632	3.7629	0.3577	11.3022
2.92	0.4801	9.7808	2.5861	3.7821	0.3517	11.4519
2.94	0.4788	9.9175	2.6091	3.8012	0.3457	11.6026
2.96	0.4776	10.0552	2.6322	3.8200	0.3398	11.7544
2.98	0.4764	10.1938	2.6555	3.8387	0.3340	11.9072
3.00	0.4752	10.3333	2.6790	3.8571	0.3283	12.0610
3.02	0.4740	10.4738	2.7026	3.8754	0.3227	12.2158
3.04	0.4729	10.6152	2.7264	3.8935	0.3172	12.3717

TABLE F.1 Fanno Line Flow ( $\gamma = 1.4$ )

$M$	$T/T^*$	$p/p^*$	$p_o/p_o^*$	$\rho/\rho^*$	$fL_{\max}/D$
0.00	1.2000	$\infty$	$\infty$	$\infty$	$\infty$
0.02	1.1999	54.7701	28.9421	45.6454	1778.4499
0.04	1.1996	27.3817	14.4815	22.8254	440.3522
0.06	1.1991	18.2508	9.6659	15.2200	193.0311
0.08	1.1985	13.6843	7.2616	11.4182	106.7182
0.10	1.1976	10.9435	5.8218	9.1378	66.9216
0.12	1.1966	9.1156	4.8643	7.6182	45.4080
0.14	1.1953	7.8093	4.1824	6.5333	32.5113
0.16	1.1939	6.8291	3.6727	5.7200	24.1978
0.18	1.1923	6.0662	3.2779	5.0879	18.5427
0.20	1.1905	5.4554	2.9635	4.5826	14.5333
0.22	1.1885	4.9554	2.7076	4.1694	11.5961
0.24	1.1863	4.5383	2.4956	3.8255	9.3865
0.26	1.1840	4.1851	2.3173	3.5347	7.6876
0.28	1.1815	3.8820	2.1656	3.2857	6.3572
0.30	1.1788	3.6191	2.0351	3.0702	5.2993
0.32	1.1759	3.3887	1.9219	2.8818	4.4467
0.34	1.1729	3.1853	1.8229	2.7158	3.7520
0.36	1.1697	3.0042	1.7358	2.5684	3.1801
0.38	1.1663	2.8420	1.6587	2.4367	2.7054
0.40	1.1628	2.6958	1.5901	2.3184	2.3085
0.42	1.1591	2.5634	1.5289	2.2115	1.9744
0.44	1.1553	2.4428	1.4740	2.1145	1.6915
0.46	1.1513	2.3326	1.4246	2.0261	1.4509
0.48	1.1471	2.2313	1.3801	1.9451	1.2453
0.50	1.1429	2.1381	1.3398	1.8708	1.0691
0.52	1.1384	2.0519	1.3034	1.8024	0.9174
0.54	1.1339	1.9719	1.2703	1.7391	0.7866
0.56	1.1292	1.8975	1.2403	1.6805	0.6736
0.58	1.1244	1.8282	1.2130	1.6260	0.5757
0.60	1.1194	1.7634	1.1882	1.5753	0.4908
0.62	1.1143	1.7026	1.1656	1.5279	0.4172
0.64	1.1091	1.6456	1.1451	1.4836	0.3533
0.66	1.1038	1.5919	1.1265	1.4421	0.2979
0.68	1.0984	1.5413	1.1097	1.4032	0.2498
0.70	1.0929	1.4935	1.0944	1.3665	0.2081
0.72	1.0873	1.4482	1.0806	1.3320	0.1721
0.74	1.0815	1.4054	1.0681	1.2994	0.1411
0.76	1.0757	1.3647	1.0570	1.2686	0.1145
0.78	1.0698	1.3261	1.0471	1.2395	0.0917
0.80	1.0638	1.2893	1.0382	1.2119	0.0723
0.82	1.0578	1.2542	1.0305	1.1858	0.0559
0.84	1.0516	1.2208	1.0237	1.1609	0.0423
0.86	1.0454	1.1889	1.0179	1.1373	0.0310
0.88	1.0391	1.1583	1.0129	1.1148	0.0218
0.90	1.0327	1.1291	1.0089	1.0934	0.0145

$M$	$T/T^*$	$p/p^*$	$p_o/p_o^*$	$\rho/\rho^*$	$fL_{\max}/D$
0.92	1.0263	1.1011	1.0056	1.0730	0.0089
0.94	1.0198	1.0743	1.0031	1.0535	0.0048
0.96	1.0132	1.0485	1.0014	1.0348	0.0021
0.98	1.0066	1.0238	1.0003	1.0170	0.0005
1.00	1.0000	1.0000	1.0000	1.0000	0.0000
1.02	0.9933	0.9771	1.0003	0.9837	0.0005
1.04	0.9866	0.9551	1.0013	0.9681	0.0018
1.06	0.9798	0.9338	1.0029	0.9531	0.0038
1.08	0.9730	0.9133	1.0051	0.9387	0.0066
1.10	0.9662	0.8936	1.0079	0.9249	0.0099
1.12	0.9593	0.8745	1.0113	0.9116	0.0138
1.14	0.9524	0.8561	1.0153	0.8988	0.0182
1.16	0.9455	0.8383	1.0198	0.8865	0.0230
1.18	0.9386	0.8210	1.0248	0.8747	0.0281
1.20	0.9317	0.8044	1.0304	0.8633	0.0336
1.22	0.9247	0.7882	1.0366	0.8524	0.0394
1.24	0.9178	0.7726	1.0432	0.8418	0.0455
1.26	0.9108	0.7574	1.0504	0.8316	0.0517
1.28	0.9038	0.7427	1.0581	0.8218	0.0582
1.30	0.8969	0.7285	1.0663	0.8123	0.0648
1.32	0.8899	0.7147	1.0750	0.8031	0.0716
1.34	0.8829	0.7012	1.0842	0.7942	0.0785
1.36	0.8760	0.6882	1.0940	0.7856	0.0855
1.38	0.8690	0.6755	1.1042	0.7773	0.0926
1.40	0.8621	0.6632	1.1149	0.7693	0.0997
1.42	0.8551	0.6512	1.1262	0.7615	0.1069
1.44	0.8482	0.6396	1.1379	0.7540	0.1142
1.46	0.8413	0.6282	1.1501	0.7467	0.1215
1.48	0.8344	0.6172	1.1629	0.7397	0.1288
1.50	0.8276	0.6065	1.1762	0.7328	0.1361
1.52	0.8207	0.5960	1.1899	0.7262	0.1433
1.54	0.8139	0.5858	1.2042	0.7198	0.1506
1.56	0.8071	0.5759	1.2190	0.7135	0.1579
1.58	0.8004	0.5662	1.2344	0.7074	0.1651
1.60	0.7937	0.5568	1.2502	0.7016	0.1724
1.62	0.7869	0.5476	1.2666	0.6958	0.1795
1.64	0.7803	0.5386	1.2836	0.6903	0.1867
1.66	0.7736	0.5299	1.3010	0.6849	0.1938
1.68	0.7670	0.5213	1.3190	0.6796	0.2008
1.70	0.7605	0.5130	1.3376	0.6745	0.2078
1.72	0.7539	0.5048	1.3567	0.6696	0.2147
1.74	0.7474	0.4969	1.3764	0.6648	0.2216
1.76	0.7410	0.4891	1.3967	0.6601	0.2284
1.78	0.7345	0.4815	1.4175	0.6555	0.2352
1.80	0.7282	0.4741	1.4390	0.6511	0.2419
1.82	0.7218	0.4668	1.4610	0.6467	0.2485
1.84	0.7155	0.4597	1.4836	0.6425	0.2551
1.86	0.7093	0.4528	1.5069	0.6384	0.2616
1.88	0.7030	0.4460	1.5308	0.6344	0.2680
1.90	0.6969	0.4394	1.5553	0.6305	0.2743
1.92	0.6907	0.4329	1.5804	0.6267	0.2806
1.94	0.6847	0.4265	1.6062	0.6230	0.2868
1.96	0.6786	0.4203	1.6326	0.6193	0.2929
1.98	0.6726	0.4142	1.6597	0.6158	0.2990
2.00	0.6667	0.4082	1.6875	0.6124	0.3050
2.02	0.6608	0.4024	1.7160	0.6090	0.3109
2.04	0.6549	0.3967	1.7451	0.6057	0.3168
2.06	0.6491	0.3911	1.7750	0.6025	0.3225
2.08	0.6433	0.3856	1.8056	0.5994	0.3282



TABLE E.1 Prandtl-Meyer Functions ( $\gamma = 1.4$ )

$M$	$\nu$	$\mu$	$M$	$\nu$	$\mu$
1.00	0.0000	90.0000	1.92	24.1506	31.3882
1.02	0.1257	78.6351	1.94	24.7123	31.0285
1.04	0.3510	74.0576	1.96	25.2711	30.6774
1.06	0.6367	70.6300	1.98	25.8269	30.3347
1.08	0.9680	67.8084	2.00	26.3798	30.0000
1.10	1.3362	65.3800	2.02	26.9295	29.6730
1.12	1.7350	63.2345	2.04	27.4762	29.3535
1.14	2.1600	61.3056	2.06	28.0197	29.0411
1.16	2.6073	59.5497	2.08	28.5600	28.7357
1.18	3.0743	57.9362	2.10	29.0971	28.4369
1.20	3.5582	56.4427	2.12	29.6308	28.1446
1.22	4.0572	55.0520	2.14	30.1613	27.8585
1.24	4.5694	53.7507	2.16	30.6884	27.5785
1.26	5.0931	52.5280	2.18	31.2121	27.3043
1.28	5.6272	51.3752	2.20	31.7325	27.0357
1.30	6.1703	50.2849	2.22	32.2494	26.7726
1.32	6.7213	49.2509	2.24	32.7629	26.5148
1.34	7.2794	48.2682	2.26	33.2730	26.2621
1.36	7.8435	47.3321	2.28	33.7796	26.0144
1.38	8.4130	46.4387	2.30	34.2828	25.7715
1.40	8.9870	45.5847	2.32	34.7825	25.5332
1.42	9.5650	44.7670	2.34	35.2787	25.2995
1.44	10.1464	43.9830	2.36	35.7715	25.0702
1.46	10.7305	43.2302	2.38	36.2607	24.8452
1.48	11.3169	42.5066	2.40	36.7465	24.6243
1.50	11.9052	41.8103	2.42	37.2289	24.4075
1.52	12.4949	41.1395	2.44	37.7077	24.1945
1.54	13.0856	40.4927	2.46	38.1831	23.9854
1.56	13.6770	39.8683	2.48	38.6551	23.7800
1.58	14.2686	39.2652	2.50	39.1236	23.5782
1.60	14.8604	38.6822	2.52	39.5886	23.3799
1.62	15.4518	38.1181	2.54	40.0503	23.1850
1.64	16.0427	37.5719	2.56	40.5085	22.9934
1.66	16.6328	37.0427	2.58	40.9633	22.8051
1.68	17.2220	36.5296	2.60	41.4147	22.6199
1.70	17.8099	36.0319	2.62	41.8628	22.4377
1.72	18.3964	35.5487	2.64	42.3074	22.2586
1.74	18.9814	35.0795	2.66	42.7488	22.0824
1.76	19.5646	34.6235	2.68	43.1868	21.9090
1.78	20.1458	34.1802	2.70	43.6215	21.7385
1.80	20.7251	33.7490	2.72	44.0529	21.5706
1.82	21.3021	33.3293	2.74	44.4810	21.4053
1.84	21.8768	32.9207	2.76	44.9059	21.2427
1.86	22.4492	32.5227	2.78	45.3275	21.0825
1.88	23.0190	32.1349	2.80	45.7459	20.9248
1.90	23.5861	31.7569	2.82	46.1611	20.7695

TABLE E.1 (Continued)

$M$	$\nu$	$\mu$
2.84	46.5731	20.6166
2.86	46.9820	20.4659
2.88	47.3877	20.3175
2.90	47.7903	20.1713
2.92	48.1898	20.0272
2.94	48.5863	19.8852
2.96	48.9796	19.7452
2.98	49.3700	19.6072
3.00	49.7573	19.4712
3.02	50.1417	19.3371
3.04	50.5231	19.2049
3.06	50.9016	19.0745
3.08	51.2771	18.9459
3.10	51.6497	18.8191
3.12	52.0195	18.6939
3.14	52.3864	18.5705
3.16	52.7505	18.4487
3.18	53.1118	18.3285
3.20	53.4703	18.2100
3.22	53.8261	18.0929
3.24	54.1791	17.9774
3.26	54.5294	17.8634
3.28	54.8770	17.7508
3.30	55.2220	17.6397
3.32	55.5643	17.5300
3.34	55.9040	17.4216
3.36	56.2411	17.3147
3.38	56.5756	17.2090
3.40	56.9075	17.1046
3.42	57.2369	17.0016
3.44	57.5639	16.8997
3.46	57.8883	16.7991
3.48	58.2102	16.6997
3.50	58.5298	16.6015
3.52	58.8469	16.5045
3.54	59.1616	16.4086
3.56	59.4739	16.3139
3.58	59.7838	16.2202
3.60	60.0915	16.1276
3.62	60.3968	16.0361
3.64	60.6998	15.9456
3.66	61.0005	15.8562
3.68	61.2990	15.7678
3.70	61.5953	15.6804
3.72	61.8893	15.5939
3.74	62.1812	15.5084
3.76	62.4709	15.4239
3.78	62.7584	15.3402
3.80	63.0438	15.2575
3.82	63.3271	15.1757
3.84	63.6083	15.0948
3.86	63.8874	15.0147
3.88	64.1645	14.9355
3.90	64.4395	14.8572
3.92	64.7125	14.7796

$M$	$\nu$	$\mu$
3.94	64.9836	14.7029
3.96	65.2526	14.6270
3.98	65.5197	14.5519
4.00	65.7848	14.4775
4.02	66.0480	14.4039
4.04	66.3093	14.3311
4.06	66.5688	14.2590
4.08	66.8263	14.1876
4.10	67.0820	14.1170
4.12	67.3359	14.0470
4.14	67.5879	13.9778
4.16	67.8381	13.9092
4.18	68.0866	13.8414
4.20	68.3332	13.7741
4.22	68.5782	13.7076
4.24	68.8213	13.6417
4.26	69.0628	13.5764
4.28	69.3026	13.5118
4.30	69.5406	13.4477
4.32	69.7770	13.3843
4.34	70.0118	13.3215
4.36	70.2449	13.2593
4.38	70.4763	13.1976
4.40	70.7062	13.1366
4.42	70.9344	13.0761
4.44	71.1611	13.0161
4.46	71.3862	12.9567
4.48	71.6097	12.8979
4.50	71.8317	12.8396
4.52	72.0522	12.7818
4.54	72.2712	12.7246
4.56	72.4887	12.6678
4.58	72.7046	12.6116
4.60	72.9192	12.5559
4.62	73.1322	12.5006
4.64	73.3438	12.4459
4.66	73.5540	12.3916
4.68	73.7628	12.3378
4.70	73.9701	12.2845
4.72	74.1761	12.2316
4.74	74.3807	12.1792
4.76	74.5839	12.1273
4.78	74.7858	12.0758
4.80	74.9863	12.0247
4.82	75.1855	11.9741
4.84	75.3833	11.9239
4.86	75.5799	11.8741
4.88	75.7752	11.8247
4.90	75.9691	11.7757
4.92	76.1619	11.7272
4.94	76.3533	11.6790
4.96	76.5435	11.6313
4.98	76.7325	11.5839
5.00	76.9202	11.5370