

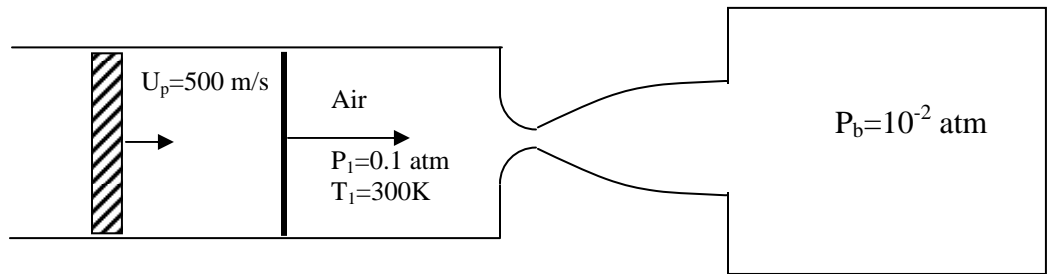
Aerothermodynamics Ph. D. Qualifying Examination

June 2008

READ THESE INSTRUCTIONS

Answer all **five** questions. Please write on one side of the paper only and put your Code Number and appropriate question number on every sheet. **Begin each question on a separate sheet of paper.** To obtain complete credit, your work must be neat and your complete procedure shown. Draw neat sketches and list your assumptions. Ask for clarification if the meaning of a question is unclear to you.

Problem 1. A shock tunnel uses the conditions behind the reflected shock as the stagnation conditions for the supersonic nozzle. For the tunnel shown below, a combustion-driven piston moving at 500 m/s generates the incident shock. After the shock reflects the static temperature is 860 K. The nozzle is designed with an area ratio (A_{exit}/A^*) that gives an exit Mach number of $M_{exit}=4$ (assuming $\gamma=1.4$) under isentropic flow conditions. The back pressure for the nozzle is shown below. Determine the velocity at the *exit plane* of the supersonic nozzle.

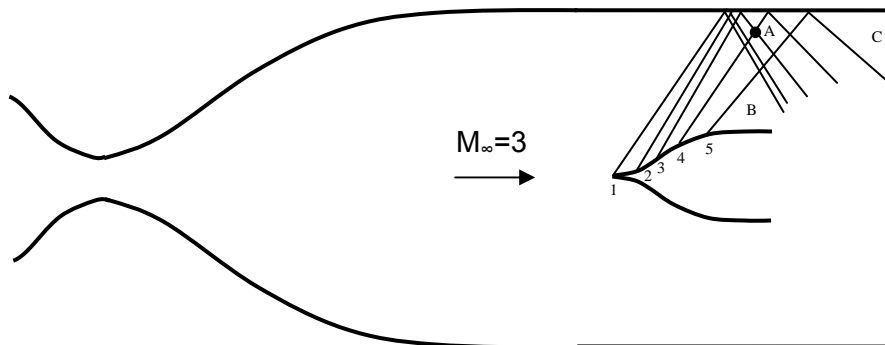


You may find the supplementary equations at the end of this exam useful.

Problem 2. A 2D (planar) missile model is placed in a Mach 3 wind tunnel. The nose of the model is contoured as shown. Five characteristics are shown originating from the model, which then reflect from the straight top wall. The local wall angle at the origin of each characteristic is given in the table below.

- Determine: (i) the Mach number at the point marked A
(ii) the Mach number in region B.
(iii) the Mach number in region C.

Point	1	2	3	4	5
Angle	0°	4°	10°	5°	0°



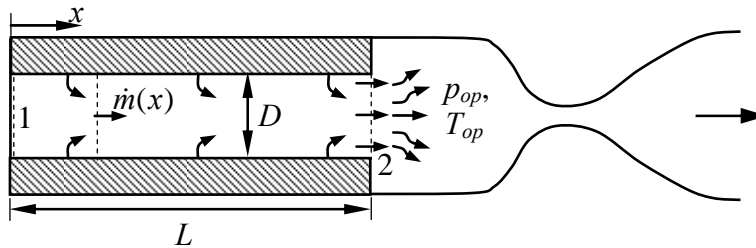
Problem 3. Air is flowing over a flat plate at a Mach number of 0.85 forming a laminar boundary layer. The static temperature of the air stream is 300 K. The flat plate has a thickness $t = 1$ cm and is made of stainless steel (conductivity $k = 18$ W/m-K). The bottom end of the flat plate is held at a fixed temperature of 25 C. Assume a mechanism is available to uniformly heat or cool the thick flat plate with a uniform volumetric heating/cooling rate \dot{q} (W/m³).

- For what value of \dot{q} will there be no heat transfer at the plate-flow interface
- What is the amount of heat transfer at the bottom surface for conditions in (a).
- Sketch the temperature profile through the boundary layer and the thickness of the plate for the above case. (Note: to receive full credit you must show all features of the profile properly with clear labels).

Problem 4. An ideal gas is flowing down a cylindrical tube with constant inner diameter D , which is closed at the left end. Mass is uniformly injected from the wall into the flow at a constant flux G [mass flow rate/area]. Assume the flow may be modeled as quasi 1-D, and neglect the effects of friction.

- Show that $\frac{p(x)}{p_1} = \frac{1}{2} \left[1 + \sqrt{1 - 4RT(x) \left(\frac{4Gx}{p_1 D} \right)^2} \right]$, where p_1 is the pressure at the closed end of the tube, R is the gas constant, and $T(x)$ the local gas temperature.

(b) The gas discharges adiabatically into a plenum before being exhausted through a nozzle. The entire dynamic pressure of the gas is lost in the plenum, i.e. $p_{op} = p_2$. The stagnation pressure and temperature in the plenum are measured to be 2.17 MPa, and 2580 K. If the gas has a molar mass of 20 kg/kmol, $\gamma = 1.20$, $G = 22.5$ kg/m²-s, $D = 0.37$ m, $L = 5$ m, calculate (i) the Mach number M_2 of the gas as it leaves the tube and enters the plenum, and (ii) the pressure p_1 . The universal gas constant $\hat{R} = 8314$ J/kmol-K.



Problem 5. The following numerical method is proposed to solve $\frac{\partial u}{\partial t} = c \frac{\partial u}{\partial x}$:

$$\frac{1}{\Delta t} \left[u_j^{n+1} - \frac{1}{2} (u_{j+1}^n + u_{j-1}^n) \right] = \frac{c}{2\Delta x} [u_{j+1}^n - u_{j-1}^n]$$

(i) Using a test function $u(x, n\Delta t) = \sigma^n e^{ikx}$, find the maximum time-step in terms of grid-size for which the method is stable.

(ii) Is the method consistent (i.e., does it reduce to the original PDE as $\Delta x, \Delta t$ reduce to zero)?

Supplementary Equations

$$J_+ = u + 2a/(\gamma-1)$$

$$J_- = u - 2a/(\gamma-1)$$

$$K_+ = \theta - v$$

$$K_- = \theta + v$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)M_1^2}{(\gamma - 1)M_1^2 + 2}$$

$$\frac{P_2}{P_1} = \frac{2\gamma M_1^2 - (\gamma - 1)}{\gamma + 1}$$

Isentropic Flow Table for $\gamma = 1.4$

M	p/p_o	T/T_o	ρ/ρ_o	A/A^*	$\frac{A}{A^*} \frac{p}{p_o}$	M	p/p_o	T/T_o	ρ/ρ_o	A/A^*	$\frac{A}{A^*} \frac{p}{p_o}$
0.00	1.0000	1.0000	1.0000	∞	∞	1.00	0.5283	0.8333	0.6339	1.0000	0.5283
0.02	0.9997	0.9999	0.9998	28.942	128.9340	1.02	0.5160	0.8278	0.6234	1.0003	0.5162
0.04	0.9989	0.9997	0.9992	14.4815	14.4653	1.04	0.5039	0.8222	0.6129	1.0013	0.5045
0.06	0.9975	0.9993	0.9982	9.6659	9.6416	1.06	0.4919	0.8165	0.6024	1.0029	0.4933
0.08	0.9955	0.9987	0.9968	7.2616	7.2292	1.08	0.4800	0.8108	0.5920	1.0051	0.4825
0.10	0.9930	0.9980	0.9950	5.8218	5.7813	1.10	0.4684	0.8052	0.5817	1.0079	0.4721
0.12	0.9900	0.9971	0.9928	4.8643	4.8156	1.12	0.4568	0.7994	0.5714	1.0113	0.4620
0.14	0.9864	0.9961	0.9903	4.1824	4.1255	1.14	0.4455	0.7937	0.5612	1.0153	0.4523
0.16	0.9823	0.9949	0.9873	3.6727	3.6077	1.16	0.4343	0.7879	0.5511	1.0198	0.4428
0.18	0.9776	0.9936	0.9840	3.2779	3.2047	1.18	0.4232	0.7822	0.5411	1.0248	0.4337
0.20	0.9725	0.9921	0.9803	2.9635	2.8820	1.20	0.4124	0.7764	0.5311	1.0304	0.4249
0.22	0.9668	0.9904	0.9762	2.7076	2.6178	1.22	0.4017	0.7706	0.5213	1.0366	0.4164
0.24	0.9607	0.9886	0.9718	2.4956	2.3975	1.24	0.3912	0.7648	0.5115	1.0432	0.4081
0.26	0.9541	0.9867	0.9670	2.3173	2.2109	1.26	0.3809	0.7590	0.5019	1.0504	0.4001
0.28	0.9470	0.9846	0.9619	2.1656	2.0508	1.28	0.3708	0.7532	0.4923	1.0581	0.3924
0.30	0.9395	0.9823	0.9564	2.0351	1.9119	1.30	0.3609	0.7474	0.4829	1.0663	0.3848
0.32	0.9315	0.9799	0.9506	1.9219	1.7902	1.32	0.3512	0.7416	0.4736	1.0750	0.3775
0.34	0.9231	0.9774	0.9445	1.8229	1.6827	1.34	0.3417	0.7358	0.4644	1.0842	0.3704
0.36	0.9143	0.9747	0.9380	1.7358	1.5871	1.36	0.3323	0.7300	0.4553	1.0940	0.3636
0.38	0.9052	0.9719	0.9313	1.6587	1.5014	1.38	0.3232	0.7242	0.4463	1.1042	0.3569
0.40	0.8956	0.9690	0.9243	1.5901	1.4242	1.40	0.3142	0.7184	0.4374	1.1149	0.3504
0.42	0.8857	0.9659	0.9170	1.5289	1.3542	1.42	0.3055	0.7126	0.4287	1.1262	0.3440
0.44	0.8755	0.9627	0.9094	1.4740	1.2905	1.44	0.2969	0.7069	0.4201	1.1379	0.3379
0.46	0.8650	0.9594	0.9016	1.4246	1.2322	1.46	0.2886	0.7011	0.4116	1.1501	0.3319
0.48	0.8541	0.9559	0.8935	1.3801	1.1788	1.48	0.2804	0.6954	0.4032	1.1629	0.3261
0.50	0.8430	0.9524	0.8852	1.3398	1.1295	1.50	0.2724	0.6897	0.3950	1.1762	0.3204
0.52	0.8317	0.9487	0.8766	1.3034	1.0840	1.52	0.2646	0.6840	0.3869	1.1899	0.3149
0.54	0.8201	0.9449	0.8679	1.2703	1.0417	1.54	0.2570	0.6783	0.3789	1.2042	0.3095
0.56	0.8082	0.9410	0.8589	1.2403	1.0024	1.56	0.2496	0.6726	0.3710	1.2190	0.3042
0.58	0.7962	0.9370	0.8498	1.2130	0.9658	1.58	0.2423	0.6670	0.3633	1.2344	0.2991
0.60	0.7840	0.9328	0.8405	1.1882	0.9316	1.60	0.2353	0.6614	0.3557	1.2502	0.2941
0.62	0.7716	0.9286	0.8310	1.1656	0.8995	1.62	0.2284	0.6558	0.3483	1.2666	0.2893
0.64	0.7591	0.9243	0.8213	1.1451	0.8693	1.64	0.2217	0.6502	0.3409	1.2836	0.2845
0.66	0.7465	0.9199	0.8115	1.1265	0.8410	1.66	0.2151	0.6447	0.3337	1.3010	0.2799
0.68	0.7338	0.9153	0.8016	1.1097	0.8142	1.68	0.2088	0.6392	0.3266	1.3190	0.2754
0.70	0.7209	0.9107	0.7916	1.0944	0.7890	1.70	0.2026	0.6337	0.3197	1.3376	0.2710
0.72	0.7080	0.9061	0.7814	1.0806	0.7651	1.72	0.1966	0.6283	0.3129	1.3567	0.2667
0.74	0.6951	0.9013	0.7712	1.0681	0.7424	1.74	0.1907	0.6229	0.3062	1.3764	0.2625
0.76	0.6821	0.8964	0.7609	1.0570	0.7209	1.76	0.1850	0.6175	0.2996	1.3967	0.2584
0.78	0.6691	0.8915	0.7505	1.0471	0.7005	1.78	0.1794	0.6121	0.2931	1.4175	0.2544
0.80	0.6560	0.8865	0.7400	1.0382	0.6811	1.80	0.1740	0.6068	0.2868	1.4390	0.2504
0.82	0.6430	0.8815	0.7295	1.0305	0.6626	1.82	0.1688	0.6015	0.2806	1.4610	0.2466
0.84	0.6300	0.8763	0.7189	1.0237	0.6449	1.84	0.1637	0.5963	0.2745	1.4836	0.2429
0.86	0.6170	0.8711	0.7083	1.0179	0.6281	1.86	0.1587	0.5910	0.2686	1.5069	0.2392
0.88	0.6041	0.8659	0.6977	1.0129	0.6119	1.88	0.1539	0.5859	0.2627	1.5308	0.2356
0.90	0.5913	0.8606	0.6870	1.0089	0.5965	1.90	0.1492	0.5807	0.2570	1.5553	0.2321
0.92	0.5785	0.8552	0.6764	1.0056	0.5817	1.92	0.1447	0.5756	0.2514	1.5804	0.2287
0.94	0.5658	0.8498	0.6658	1.0031	0.5675	1.94	0.1403	0.5705	0.2459	1.6062	0.2253
0.96	0.5532	0.8444	0.6551	1.0014	0.5539	1.96	0.1360	0.5655	0.2405	1.6326	0.2220
0.98	0.5407	0.8389	0.6445	1.0003	0.5409	1.98	0.1318	0.5605	0.2352	1.6597	0.2188
1.00	0.5283	0.8333	0.6339	1.0000	0.5283	2.00	0.1278	0.5556	0.2300	1.6875	0.2157

Isentropic Flow Table for $\gamma = 1.4$

M	p/p_o	T/T_o	ρ/ρ_o	A/A^*	$\frac{A}{A^*} \frac{p}{p_o}$	M	p/p_o	T/T_o	ρ/ρ_o	A/A^*	$\frac{A}{A^*} \frac{p}{p_o}$
2.00	0.1278	0.5556	0.2300	1.6875	0.2157	3.00	2.722 E-2	0.3571	7.623 E-2	4.2346	0.1153
2.02	0.1239	0.5506	0.2250	1.7160	0.2126	3.05	2.526 E-2	0.3496	7.226 E-2	4.4410	0.1122
2.04	0.1201	0.5458	0.2200	1.7451	0.2096	3.10	2.345 E-2	0.3422	6.852 E-2	4.6573	0.1092
2.06	0.1164	0.5409	0.2152	1.7750	0.2066	3.15	2.177 E-2	0.3351	6.499 E-2	4.8838	0.1063
2.08	0.1128	0.5361	0.2104	1.8056	0.2037	3.20	2.023 E-2	0.3281	6.165 E-2	5.1210	0.1036
2.10	0.1094	0.5313	0.2058	1.8369	0.2009	3.25	1.880 E-2	0.3213	5.851 E-2	5.3691	0.1009
2.12	0.1060	0.5266	0.2013	1.8690	0.1981	3.30	1.748 E-2	0.3147	5.554 E-2	5.6286	9.837 E-2
2.14	0.1027	0.5219	0.1968	1.9018	0.1954	3.35	1.625 E-2	0.3082	5.274 E-2	5.9000	9.590 E-2
2.16	9.956 E-2	0.5173	0.1925	1.9354	0.1927	3.40	1.512 E-2	0.3019	5.009 E-2	6.1837	9.353 E-2
2.18	9.649 E-2	0.5127	0.1882	1.9698	0.1901	3.45	1.408 E-2	0.2958	4.759 E-2	6.4801	9.123 E-2
2.20	9.352 E-2	0.5081	0.1841	2.0050	0.1875	3.50	1.311 E-2	0.2899	4.523 E-2	6.7896	8.902 E-2
2.22	9.064 E-2	0.5036	0.1800	2.0409	0.1850	3.55	1.221 E-2	0.2841	4.300 E-2	7.1128	8.688 E-2
2.24	8.785 E-2	0.4991	0.1760	2.0777	0.1825	3.60	1.138 E-2	0.2784	4.089 E-2	7.4501	8.482 E-2
2.26	8.514 E-2	0.4947	0.1721	2.1153	0.1801	3.65	1.062 E-2	0.2729	3.890 E-2	7.8020	8.282 E-2
2.28	8.251 E-2	0.4903	0.1683	2.1538	0.1777	3.70	9.903 E-3	0.2675	3.702 E-2	8.1691	8.090 E-2
2.30	7.997 E-2	0.4859	0.1646	2.1931	0.1754	3.75	9.242 E-3	0.2623	3.524 E-2	8.5517	7.904 E-2
2.32	7.751 E-2	0.4816	0.1609	2.2333	0.1731	3.80	8.629 E-3	0.2572	3.355 E-2	8.9506	7.723 E-2
2.34	7.512 E-2	0.4773	0.1574	2.2744	0.1709	3.85	8.060 E-3	0.2522	3.195 E-2	9.3661	7.549 E-2
2.36	7.281 E-2	0.4731	0.1539	2.3164	0.1687	3.90	7.532 E-3	0.2474	3.044 E-2	9.7990	7.381 E-2
2.38	7.057 E-2	0.4688	0.1505	2.3593	0.1665	3.95	7.042 E-3	0.2427	2.902 E-2	10.2496	7.217 E-2
2.40	6.840 E-2	0.4647	0.1472	2.4031	0.1644	4.00	6.586 E-3	0.2381	2.766 E-2	10.7188	7.059 E-2
2.42	6.630 E-2	0.4606	0.1439	2.4479	0.1623	4.05	6.163 E-3	0.2336	2.638 E-2	11.2069	6.906 E-2
2.44	6.426 E-2	0.4565	0.1408	2.4936	0.1602	4.10	5.769 E-3	0.2293	2.516 E-2	11.7147	6.758 E-2
2.46	6.229 E-2	0.4524	0.1377	2.5403	0.1582	4.15	5.403 E-3	0.2250	2.401 E-2	12.2427	6.614 E-2
2.48	6.038 E-2	0.4484	0.1346	2.5880	0.1563	4.20	5.062 E-3	0.2208	2.292 E-2	12.7916	6.475 E-2
2.50	5.853 E-2	0.4444	0.1317	2.6367	0.1543	4.25	4.745 E-3	0.2168	2.189 E-2	13.3622	6.340 E-2
2.52	5.674 E-2	0.4405	0.1288	2.6865	0.1524	4.30	4.449 E-3	0.2129	2.090 E-2	13.9549	6.209 E-2
2.54	5.500 E-2	0.4366	0.1260	2.7372	0.1505	4.35	4.174 E-3	0.2090	1.997 E-2	14.5706	6.082 E-2
2.56	5.332 E-2	0.4328	0.1232	2.7891	0.1487	4.40	3.918 E-3	0.2053	1.909 E-2	15.2099	5.959 E-2
2.58	5.169 E-2	0.4289	0.1205	2.8420	0.1469	4.45	3.678 E-3	0.2016	1.825 E-2	15.8735	5.839 E-2
2.60	5.012 E-2	0.4252	0.1179	2.8960	0.1451	4.50	3.455 E-3	0.1980	1.745 E-2	16.5622	5.723 E-2
2.62	4.859 E-2	0.4214	0.1153	2.9511	0.1434	4.55	3.247 E-3	0.1945	1.669 E-2	17.2767	5.610 E-2
2.64	4.711 E-2	0.4177	0.1128	3.0073	0.1417	4.60	3.053 E-3	0.1911	1.597 E-2	18.0178	5.500 E-2
2.66	4.568 E-2	0.4141	0.1103	3.0647	0.1400	4.65	2.871 E-3	0.1878	1.529 E-2	18.7862	5.393 E-2
2.68	4.429 E-2	0.4104	0.1079	3.1233	0.1383	4.70	2.701 E-3	0.1846	1.464 E-2	19.5828	5.290 E-2
2.70	4.295 E-2	0.4068	0.1056	3.1830	0.1367	4.75	2.543 E-3	0.1814	1.402 E-2	20.4084	5.189 E-2
2.72	4.165 E-2	0.4033	0.1033	3.2440	0.1351	4.80	2.394 E-3	0.1783	1.343 E-2	21.2637	5.091 E-2
2.74	4.039 E-2	0.3998	0.1010	3.3061	0.1335	4.85	2.255 E-3	0.1753	1.287 E-2	22.1497	4.996 E-2
2.76	3.917 E-2	0.3963	9.885 E-2	3.3695	0.1320	4.90	2.126 E-3	0.1724	1.233 E-2	23.0671	4.903 E-2
2.78	3.799 E-2	0.3928	9.671 E-2	3.4342	0.1305	4.95	2.004 E-3	0.1695	1.182 E-2	24.0169	4.813 E-2
2.80	3.685 E-2	0.3894	9.463 E-2	3.5001	0.1290	5.00	1.890 E-3	0.1667	1.134 E-2	25.0000	4.725 E-2
2.82	3.574 E-2	0.3860	9.259 E-2	3.5674	0.1275	5.10	1.683 E-3	0.1612	1.044 E-2	27.0696	4.640 E-2
2.84	3.467 E-2	0.3827	9.059 E-2	3.6359	0.1261	5.20	1.501 E-3	0.1561	9.620 E-3	29.2833	4.556 E-2
2.86	3.363 E-2	0.3794	8.865 E-2	3.7058	0.1246	5.30	1.341 E-3	0.1511	8.875 E-3	31.6491	4.475 E-2
2.88	3.263 E-2	0.3761	8.675 E-2	3.7771	0.1232	5.40	1.200 E-3	0.1464	8.197 E-3	34.1748	4.396 E-2
2.90	3.165 E-2	0.3729	8.489 E-2	3.8498	0.1219	5.50	1.075 E-3	0.1418	7.578 E-3	36.8690	4.319 E-2
2.92	3.071 E-2	0.3696	8.307 E-2	3.9238	0.1205	5.60	9.643 E-4	0.1375	7.012 E-3	39.7402	4.244 E-2
2.94	2.980 E-2	0.3665	8.130 E-2	3.9993	0.1192	5.70	8.663 E-4	0.1334	6.496 E-3	42.7974	4.171 E-2
2.96	2.891 E-2	0.3633	7.957 E-2	4.0763	0.1178	5.80	7.794 E-4	0.1294	6.023 E-3	46.0500	4.100 E-2
2.98	2.805 E-2	0.3602	7.788 E-2	4.1547	0.1166	5.90	7.021 E-4	0.1256	5.590 E-3	49.5075	4.031 E-2
3.00	2.722 E-2	0.3571	7.623 E-2	4.2346	0.1153	6.00	6.334 E-4	0.1220	5.194 E-3	53.1798	3.963 E-2

Isentropic Flow Table for $\gamma = 1.4$

M	p/p_o	T/T_o	ρ/ρ_o	A/A^*	$\frac{A}{A^*} \frac{p}{p_o}$
6.00	6.334 E-4	0.1220	5.194 E-3	53.1798	3.368 E-2
6.10	5.721 E-4	0.1185	4.829 E-3	57.0772	3.265 E-2
6.20	5.173 E-4	0.1151	4.495 E-3	61.2102	3.167 E-2
6.30	4.684 E-4	0.1119	4.187 E-3	65.5899	3.073 E-2
6.40	4.247 E-4	0.1088	3.904 E-3	70.2274	2.982 E-2
6.50	3.855 E-4	0.1058	3.643 E-3	75.1343	2.896 E-2
6.60	3.503 E-4	0.1030	3.402 E-3	80.3227	2.814 E-2
6.70	3.187 E-4	0.1002	3.180 E-3	85.8049	2.734 E-2
6.80	2.902 E-4	9.758 E-2	2.974 E-3	91.5935	2.658 E-2
6.90	2.646 E-4	9.504 E-2	2.785 E-3	97.7017	2.586 E-2
7.00	2.416 E-4	9.259 E-2	2.609 E-3	104.1429	2.516 E-2
7.10	2.207 E-4	9.024 E-2	2.446 E-3	110.9309	2.448 E-2
7.20	2.019 E-4	8.797 E-2	2.295 E-3	118.0799	2.384 E-2
7.30	1.848 E-4	8.578 E-2	2.155 E-3	125.6046	2.322 E-2
7.40	1.694 E-4	8.367 E-2	2.025 E-3	133.5200	2.262 E-2
7.50	1.554 E-4	8.163 E-2	1.904 E-3	141.8415	2.205 E-2
7.60	1.427 E-4	7.967 E-2	1.792 E-3	150.5849	2.149 E-2
7.70	1.312 E-4	7.777 E-2	1.687 E-3	159.7665	2.096 E-2
7.80	1.207 E-4	7.594 E-2	1.589 E-3	169.4030	2.045 E-2
7.90	1.111 E-4	7.417 E-2	1.498 E-3	179.5114	1.995 E-2
8.00	1.024 E-4	7.246 E-2	1.414 E-3	190.1094	1.947 E-2
8.10	9.449 E-5	7.081 E-2	1.334 E-3	201.2148	1.901 E-2
8.20	8.723 E-5	6.921 E-2	1.260 E-3	212.8461	1.857 E-2
8.30	8.060 E-5	6.767 E-2	1.191 E-3	225.0221	1.814 E-2
8.40	7.454 E-5	6.617 E-2	1.126 E-3	237.7622	1.772 E-2
8.50	6.898 E-5	6.472 E-2	1.066 E-3	251.0862	1.732 E-2
8.60	6.390 E-5	6.332 E-2	1.009 E-3	265.0142	1.693 E-2
8.70	5.923 E-5	6.197 E-2	9.558 E-4	279.5672	1.656 E-2
8.80	5.494 E-5	6.065 E-2	9.059 E-4	294.7661	1.620 E-2
8.90	5.101 E-5	5.938 E-2	8.590 E-4	310.6328	1.584 E-2
9.00	4.739 E-5	5.814 E-2	8.150 E-4	327.1893	1.550 E-2
9.10	4.405 E-5	5.694 E-2	7.737 E-4	344.4584	1.517 E-2
9.20	4.099 E-5	5.578 E-2	7.348 E-4	362.4632	1.486 E-2
9.30	3.816 E-5	5.465 E-2	6.982 E-4	381.2275	1.455 E-2
9.40	3.555 E-5	5.356 E-2	6.638 E-4	400.7753	1.425 E-2
9.50	3.314 E-5	5.249 E-2	6.313 E-4	421.1314	1.396 E-2
9.60	3.092 E-5	5.146 E-2	6.008 E-4	442.3210	1.367 E-2
9.70	2.886 E-5	5.046 E-2	5.719 E-4	464.3698	1.340 E-2
9.80	2.696 E-5	4.949 E-2	5.447 E-4	487.3042	1.314 E-2
9.90	2.520 E-5	4.854 E-2	5.191 E-4	511.1510	1.288 E-2
10.00	2.356 E-5	4.762 E-2	4.948 E-4	535.9375	1.263 E-2

Prandtl-Meyer Table for $\gamma = 1.4$

M	ν	α	M	ν	α	M	ν	α
1.00	0.0000	90.000	2.00	26.380	30.000	3.05	50.713	19.139
1.02	0.1257	78.635	2.02	26.930	29.673	3.10	51.650	18.819
1.04	0.3510	74.058	2.04	27.476	29.353	3.15	52.569	18.509
1.06	0.6367	70.630	2.06	28.020	29.041	3.20	53.470	18.210
1.08	0.9680	67.808	2.08	28.560	28.736	3.25	54.355	17.920
1.10	1.3362	65.380	2.10	29.097	28.437	3.30	55.222	17.640
1.12	1.7350	63.234	2.12	29.631	28.145	3.35	56.073	17.368
1.14	2.1600	61.306	2.14	30.161	27.859	3.40	56.908	17.105
1.16	2.6073	59.550	2.16	30.688	27.578	3.45	57.726	16.849
1.18	3.0743	57.936	2.18	31.212	27.304	3.50	58.530	16.602
1.20	3.5582	56.443	2.20	31.732	27.036	3.55	59.318	16.361
1.22	4.0572	55.052	2.22	32.249	26.773	3.60	60.091	16.128
1.24	4.5694	53.751	2.24	32.763	26.515	3.65	60.850	15.901
1.26	5.0931	52.528	2.26	33.273	26.262	3.70	61.595	15.680
1.28	5.6272	51.375	2.28	33.780	26.014	3.75	62.326	15.466
1.30	6.1703	50.285	2.30	34.283	25.771	3.80	63.044	15.258
1.32	6.7213	49.251	2.32	34.782	25.533	3.85	63.748	15.055
1.34	7.2794	48.268	2.34	35.279	25.300	3.90	64.440	14.857
1.36	7.8435	47.332	2.36	35.771	25.070	3.95	65.118	14.665
1.38	8.4130	46.439	2.38	36.261	24.845	4.00	65.785	14.478
1.40	8.9870	45.585	2.40	36.747	24.624	4.05	66.439	14.295
1.42	9.5650	44.767	2.42	37.229	24.407	4.10	67.082	14.117
1.44	10.146	43.983	2.44	37.708	24.195	4.15	67.713	13.943
1.46	10.731	43.230	2.46	38.183	23.985	4.20	68.333	13.774
1.48	11.317	42.507	2.48	38.655	23.780	4.25	68.942	13.609
1.50	11.905	41.810	2.50	39.124	23.578	4.30	69.541	13.448
1.52	12.495	41.140	2.52	39.589	23.380	4.35	70.129	13.290
1.54	13.086	40.493	2.54	40.050	23.185	4.40	70.706	13.137
1.56	13.677	39.868	2.56	40.508	22.993	4.45	71.274	12.986
1.58	14.269	39.265	2.58	40.963	22.805	4.50	71.832	12.840
1.60	14.860	38.682	2.60	41.415	22.620	4.55	72.380	12.696
1.62	15.452	38.118	2.62	41.863	22.438	4.60	72.919	12.556
1.64	16.043	37.572	2.64	42.307	22.259	4.65	73.449	12.419
1.66	16.633	37.043	2.66	42.749	22.082	4.70	73.970	12.284
1.68	17.222	36.530	2.68	43.187	21.909	4.75	74.482	12.153
1.70	17.810	36.032	2.70	43.621	21.738	4.80	74.986	12.025
1.72	18.396	35.549	2.72	44.053	21.571	4.85	75.482	11.899
1.74	18.981	35.080	2.74	44.481	21.405	4.90	75.969	11.776
1.76	19.565	34.624	2.76	44.906	21.243	4.95	76.449	11.655
1.78	20.146	34.180	2.78	45.327	21.083	5.00	76.920	11.537
1.80	20.725	33.749	2.80	45.746	20.925	5.10	77.841	11.308
1.82	21.302	33.329	2.82	46.161	20.770	5.20	78.732	11.087
1.84	21.877	32.921	2.84	46.573	20.617	5.30	79.596	10.876
1.86	22.449	32.523	2.86	46.982	20.466	5.40	80.433	10.672
1.88	23.019	32.135	2.88	47.388	20.318	5.50	81.245	10.476
1.90	23.586	31.757	2.90	47.790	20.171	5.60	82.032	10.287
1.92	24.151	31.388	2.92	48.190	20.027	5.70	82.796	10.104
1.94	24.712	31.028	2.94	48.586	19.885	5.80	83.537	9.928
1.96	25.271	30.677	2.96	48.980	19.745	5.90	84.256	9.758
1.98	25.827	30.335	2.98	49.370	19.607	6.00	84.955	9.594
2.00	26.380	30.000	3.00	49.757	19.471			

M_1	M_2	p_2/p_1	T_2/T_1	ρ_2/ρ_1	p_{o2}/p_{o1}	A_2^*/A_1^*
1.00	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1.02	0.9805	1.0471	1.0132	1.0334	1.0000	1.0000
1.04	0.9620	1.0952	1.0263	1.0671	0.9999	1.0001
1.06	0.9444	1.1442	1.0393	1.1009	0.9998	1.0002
1.08	0.9277	1.1941	1.0522	1.1349	0.9994	1.0006
1.10	0.9118	1.2450	1.0649	1.1691	0.9989	1.0011
1.12	0.8966	1.2968	1.0776	1.2034	0.9982	1.0018
1.14	0.8820	1.3495	1.0903	1.2378	0.9973	1.0027
1.16	0.8682	1.4032	1.1029	1.2723	0.9961	1.0040
1.18	0.8549	1.4578	1.1154	1.3069	0.9946	1.0055
1.20	0.8422	1.5133	1.1280	1.3416	0.9928	1.0073
1.22	0.8300	1.5698	1.1405	1.3764	0.9907	1.0094
1.24	0.8183	1.6272	1.1531	1.4112	0.9884	1.0118
1.26	0.8071	1.6855	1.1657	1.4460	0.9857	1.0145
1.28	0.7963	1.7448	1.1783	1.4808	0.9827	1.0176
1.30	0.7860	1.8050	1.1909	1.5157	0.9794	1.0211
1.32	0.7760	1.8661	1.2035	1.5505	0.9758	1.0249
1.34	0.7664	1.9282	1.2162	1.5854	0.9718	1.0290
1.36	0.7572	1.9912	1.2290	1.6202	0.9676	1.0335
1.38	0.7483	2.0551	1.2418	1.6549	0.9630	1.0384
1.40	0.7397	2.1200	1.2547	1.6897	0.9582	1.0436
1.42	0.7314	2.1858	1.2676	1.7243	0.9531	1.0492
1.44	0.7235	2.2525	1.2807	1.7589	0.9476	1.0552
1.46	0.7157	2.3202	1.2938	1.7934	0.9420	1.0616
1.48	0.7083	2.3888	1.3069	1.8278	0.9360	1.0684
1.50	0.7011	2.4583	1.3202	1.8621	0.9298	1.0755
1.52	0.6941	2.5288	1.3336	1.8963	0.9233	1.0830
1.54	0.6874	2.6002	1.3470	1.9303	0.9166	1.0910
1.56	0.6809	2.6725	1.3606	1.9643	0.9097	1.0993
1.58	0.6746	2.7458	1.3742	1.9981	0.9026	1.1080
1.60	0.6684	2.8200	1.3880	2.0317	0.8952	1.1171
1.62	0.6625	2.8951	1.4018	2.0653	0.8877	1.1266
1.64	0.6568	2.9712	1.4158	2.0986	0.8799	1.1365
1.66	0.6512	3.0482	1.4299	2.1318	0.8720	1.1468
1.68	0.6458	3.1261	1.4440	2.1649	0.8639	1.1575
1.70	0.6405	3.2050	1.4583	2.1977	0.8557	1.1686
1.72	0.6355	3.2848	1.4727	2.2304	0.8474	1.1801
1.74	0.6305	3.3655	1.4873	2.2629	0.8389	1.1921
1.76	0.6257	3.4472	1.5019	2.2952	0.8302	1.2045
1.78	0.6210	3.5298	1.5167	2.3273	0.8215	1.2173
1.80	0.6165	3.6133	1.5316	2.3592	0.8127	1.2305
1.82	0.6121	3.6978	1.5466	2.3909	0.8038	1.2441
1.84	0.6078	3.7832	1.5617	2.4224	0.7948	1.2582
1.86	0.6036	3.8695	1.5770	2.4537	0.7857	1.2728
1.88	0.5996	3.9568	1.5924	2.4848	0.7765	1.2877
1.90	0.5956	4.0450	1.6079	2.5157	0.7674	1.3032
1.92	0.5918	4.1341	1.6236	2.5463	0.7581	1.3191
1.94	0.5880	4.2242	1.6394	2.5767	0.7488	1.3354
1.96	0.5844	4.3152	1.6553	2.6069	0.7395	1.3522
1.98	0.5808	4.4071	1.6713	2.6369	0.7302	1.3695
2.00	0.5774	4.5000	1.6875	2.6667	0.7209	1.3872

M_1	M_2	p_2/p_1	T_2/T_1	ρ_2/ρ_1	p_{o2}/p_{o1}	A_2^*/A_1^*
2.00	0.5774	4.5000	1.6875	2.6667	0.7209	1.3872
2.02	0.5740	4.5938	1.7038	2.6962	0.7115	1.4054
2.04	0.5707	4.6885	1.7203	2.7255	0.7022	1.4241
2.06	0.5675	4.7842	1.7369	2.7545	0.6928	1.4433
2.08	0.5643	4.8808	1.7536	2.7833	0.6835	1.4630
2.10	0.5613	4.9783	1.7705	2.8119	0.6742	1.4832
2.12	0.5583	5.0768	1.7875	2.8402	0.6649	1.5039
2.14	0.5554	5.1762	1.8046	2.8683	0.6557	1.5252
2.16	0.5525	5.2765	1.8219	2.8962	0.6464	1.5469
2.18	0.5498	5.3778	1.8393	2.9238	0.6373	1.5692
2.20	0.5471	5.4800	1.8569	2.9512	0.6281	1.5920
2.22	0.5444	5.5831	1.8746	2.9784	0.6191	1.6154
2.24	0.5418	5.6872	1.8924	3.0053	0.6100	1.6393
2.26	0.5393	5.7922	1.9104	3.0319	0.6011	1.6638
2.28	0.5368	5.8981	1.9285	3.0584	0.5921	1.6888
2.30	0.5344	6.0050	1.9468	3.0845	0.5833	1.7144
2.32	0.5321	6.1128	1.9652	3.1105	0.5745	1.7406
2.34	0.5297	6.2215	1.9838	3.1362	0.5658	1.7674
2.36	0.5275	6.3312	2.0025	3.1617	0.5572	1.7948
2.38	0.5253	6.4418	2.0213	3.1869	0.5486	1.8228
2.40	0.5231	6.5533	2.0403	3.2119	0.5401	1.8514
2.42	0.5210	6.6658	2.0595	3.2367	0.5317	1.8806
2.44	0.5189	6.7792	2.0788	3.2612	0.5234	1.9105
2.46	0.5169	6.8935	2.0982	3.2855	0.5152	1.9410
2.48	0.5149	7.0088	2.1178	3.3095	0.5071	1.9721
2.50	0.5130	7.1250	2.1375	3.3333	0.4990	2.0039
2.52	0.5111	7.2421	2.1574	3.3569	0.4911	2.0364
2.54	0.5092	7.3602	2.1774	3.3803	0.4832	2.0696
2.56	0.5074	7.4792	2.1976	3.4034	0.4754	2.1035
2.58	0.5056	7.5991	2.2179	3.4263	0.4677	2.1381
2.60	0.5039	7.7200	2.2383	3.4490	0.4601	2.1733
2.62	0.5022	7.8418	2.2590	3.4714	0.4526	2.2093
2.64	0.5005	7.9645	2.2797	3.4937	0.4452	2.2461
2.66	0.4988	8.0882	2.3006	3.5157	0.4379	2.2835
2.68	0.4972	8.2128	2.3217	3.5374	0.4307	2.3218
2.70	0.4956	8.3383	2.3429	3.5590	0.4236	2.3608
2.72	0.4941	8.4648	2.3642	3.5803	0.4166	2.4005
2.74	0.4926	8.5922	2.3858	3.6015	0.4097	2.4411
2.76	0.4911	8.7205	2.4074	3.6224	0.4028	2.4825
2.78	0.4896	8.8498	2.4292	3.6431	0.3961	2.5246
2.80	0.4882	8.9800	2.4512	3.6636	0.3895	2.5676
2.82	0.4868	9.1111	2.4733	3.6838	0.3829	2.6115
2.84	0.4854	9.2432	2.4955	3.7039	0.3765	2.6561
2.86	0.4840	9.3762	2.5179	3.7238	0.3701	2.7017
2.88	0.4827	9.5101	2.5405	3.7434	0.3639	2.7481
2.90	0.4814	9.6450	2.5632	3.7629	0.3577	2.7954
2.92	0.4801	9.7808	2.5861	3.7821	0.3517	2.8436
2.94	0.4788	9.9175	2.6091	3.8012	0.3457	2.8927
2.96	0.4776	10.0552	2.6322	3.8200	0.3398	2.9427
2.98	0.4764	10.1938	2.6555	3.8387	0.3340	2.9937
3.00	0.4752	10.3333	2.6790	3.8571	0.3283	3.0456

M_1	M_2	p_2/p_1	T_2/T_1	ρ_2/ρ_1	p_{o2}/p_{o1}	A_2^*/A_1^*
3.00	0.4752	10.3333	2.6790	3.8571	0.3283	3.0456
3.02	0.4740	10.4738	2.7026	3.8754	0.3227	3.0985
3.04	0.4729	10.6152	2.7264	3.8935	0.3172	3.1523
3.06	0.4717	10.7575	2.7503	3.9114	0.3118	3.2072
3.08	0.4706	10.9008	2.7744	3.9291	0.3065	3.2630
3.10	0.4695	11.0450	2.7986	3.9466	0.3012	3.3199
3.12	0.4685	11.1901	2.8230	3.9639	0.2960	3.3778
3.14	0.4674	11.3362	2.8475	3.9811	0.2910	3.4368
3.16	0.4664	11.4832	2.8722	3.9981	0.2860	3.4969
3.18	0.4654	11.6311	2.8970	4.0149	0.2811	3.5580
3.20	0.4643	11.7800	2.9220	4.0315	0.2762	3.6202
3.22	0.4634	11.9298	2.9471	4.0479	0.2715	3.6835
3.24	0.4624	12.0805	2.9724	4.0642	0.2668	3.7480
3.26	0.4614	12.2322	2.9979	4.0803	0.2622	3.8136
3.28	0.4605	12.3848	3.0234	4.0963	0.2577	3.8803
3.30	0.4596	12.5383	3.0492	4.1120	0.2533	3.9483
3.32	0.4587	12.6928	3.0751	4.1276	0.2489	4.0174
3.34	0.4578	12.8482	3.1011	4.1431	0.2446	4.0877
3.36	0.4569	13.0045	3.1273	4.1583	0.2404	4.1593
3.38	0.4560	13.1618	3.1537	4.1734	0.2363	4.2321
3.40	0.4552	13.3200	3.1802	4.1884	0.2322	4.3062
3.42	0.4544	13.4791	3.2069	4.2032	0.2282	4.3815
3.44	0.4535	13.6392	3.2337	4.2179	0.2243	4.4581
3.46	0.4527	13.8002	3.2607	4.2323	0.2205	4.5361
3.48	0.4519	13.9621	3.2878	4.2467	0.2167	4.6154
3.50	0.4512	14.1250	3.3151	4.2609	0.2129	4.6960
3.52	0.4504	14.2888	3.3425	4.2749	0.2093	4.7780
3.54	0.4496	14.4535	3.3701	4.2888	0.2057	4.8614
3.56	0.4489	14.6192	3.3978	4.3026	0.2022	4.9461
3.58	0.4481	14.7858	3.4257	4.3162	0.1987	5.0324
3.60	0.4474	14.9533	3.4537	4.3296	0.1953	5.1200
3.62	0.4467	15.1218	3.4819	4.3429	0.1920	5.2091
3.64	0.4460	15.2912	3.5103	4.3561	0.1887	5.2997
3.66	0.4453	15.4615	3.5388	4.3692	0.1855	5.3918
3.68	0.4446	15.6328	3.5674	4.3821	0.1823	5.4854
3.70	0.4439	15.8050	3.5962	4.3949	0.1792	5.5806
3.72	0.4433	15.9781	3.6252	4.4075	0.1761	5.6773
3.74	0.4426	16.1522	3.6543	4.4200	0.1731	5.7756
3.76	0.4420	16.3272	3.6836	4.4324	0.1702	5.8755
3.78	0.4414	16.5031	3.7130	4.4447	0.1673	5.9770
3.80	0.4407	16.6800	3.7426	4.4568	0.1645	6.0801
3.82	0.4401	16.8578	3.7723	4.4688	0.1617	6.1849
3.84	0.4395	17.0365	3.8022	4.4807	0.1589	6.2915
3.86	0.4389	17.2162	3.8323	4.4924	0.1563	6.3997
3.88	0.4383	17.3968	3.8625	4.5041	0.1536	6.5096
3.90	0.4377	17.5783	3.8928	4.5156	0.1510	6.6213
3.92	0.4372	17.7608	3.9233	4.5270	0.1485	6.7348
3.94	0.4366	17.9442	3.9540	4.5383	0.1460	6.8501
3.96	0.4360	18.1285	3.9848	4.5494	0.1435	6.9672
3.98	0.4355	18.3138	4.0158	4.5605	0.1411	7.0861
4.00	0.4350	18.5000	4.0469	4.5714	0.1388	7.2069

Normal Shock Table for $\gamma = 1.4$
 For oblique shocks tabulated values are M_{n1} , M_{n2}

M_1	M_2	p_2/p_1	T_2/T_1	ρ_2/ρ_1	p_{o2}/p_{o1}	A_2^*/A_1^*
4.00	0.4350	18.5000	4.0469	4.5714	0.1388	7.2069
4.05	0.4336	18.9696	4.1254	4.5983	0.1330	7.5172
4.10	0.4324	19.4450	4.2048	4.6245	0.1276	7.8397
4.15	0.4311	19.9263	4.2852	4.6500	0.1223	8.1747
4.20	0.4299	20.4133	4.3666	4.6749	0.1173	8.5227
4.25	0.4288	20.9063	4.4489	4.6992	0.1126	8.8840
4.30	0.4277	21.4050	4.5322	4.7229	0.1080	9.2591
4.35	0.4266	21.9096	4.6165	4.7460	0.1036	9.6484
4.40	0.4255	22.4200	4.7017	4.7685	9.948 E-02	10.0522
4.45	0.4245	22.9363	4.7879	4.7904	9.550 E-02	10.4711
4.50	0.4236	23.4583	4.8751	4.8119	9.170 E-02	10.9054
4.55	0.4226	23.9862	4.9632	4.8328	8.806 E-02	11.3556
4.60	0.4217	24.5200	5.0523	4.8532	8.459 E-02	11.8222
4.65	0.4208	25.0596	5.1424	4.8731	8.126 E-02	12.3057
4.70	0.4199	25.6050	5.2334	4.8926	7.809 E-02	12.8065
4.75	0.4191	26.1563	5.3254	4.9116	7.505 E-02	13.3251
4.80	0.4183	26.7133	5.4184	4.9301	7.214 E-02	13.8620
4.85	0.4175	27.2762	5.5124	4.9482	6.936 E-02	14.4177
4.90	0.4167	27.8450	5.6073	4.9659	6.670 E-02	14.9928
4.95	0.4160	28.4196	5.7032	4.9831	6.415 E-02	15.5878
5.00	0.4152	29.0000	5.8000	5.0000	6.172 E-02	16.2032
5.10	0.4138	30.1783	5.9966	5.0326	5.715 E-02	17.4974
5.20	0.4125	31.3800	6.1971	5.0637	5.297 E-02	18.8801
5.30	0.4113	32.6050	6.4014	5.0934	4.913 E-02	20.3558
5.40	0.4101	33.8533	6.6097	5.1218	4.560 E-02	21.9296
5.50	0.4090	35.1250	6.8218	5.1489	4.236 E-02	23.6064
5.60	0.4079	36.4200	7.0378	5.1749	3.938 E-02	25.3915
5.70	0.4069	37.7383	7.2577	5.1998	3.664 E-02	27.2902
5.80	0.4059	39.0800	7.4814	5.2236	3.412 E-02	29.3083
5.90	0.4050	40.4450	7.7091	5.2464	3.179 E-02	31.4515
6.00	0.4042	41.8333	7.9406	5.2683	2.965 E-02	33.7257
6.20	0.4025	44.6800	8.4153	5.3094	2.584 E-02	38.6924
6.40	0.4011	47.6200	8.9055	5.3473	2.259 E-02	44.2603
6.60	0.3997	50.6533	9.4113	5.3822	1.981 E-02	50.4846
6.80	0.3985	53.7800	9.9326	5.4145	1.741 E-02	57.4238
7.00	0.3974	57.0000	10.4694	5.4444	1.535 E-02	65.1403
7.20	0.3963	60.3133	11.0218	5.4722	1.357 E-02	73.6997
7.40	0.3954	63.7200	11.5897	5.4980	1.202 E-02	83.1716
7.60	0.3945	67.2200	12.1732	5.5220	1.068 E-02	93.6294
7.80	0.3937	70.8133	12.7722	5.5443	9.510 E-03	105.1503
8.00	0.3929	74.5000	13.3867	5.5652	8.488 E-03	117.8157
8.20	0.3922	78.2800	14.0168	5.5847	7.592 E-03	131.7112
8.40	0.3915	82.1533	14.6625	5.6030	6.806 E-03	146.9266
8.60	0.3909	86.1200	15.3237	5.6201	6.114 E-03	163.5560
8.80	0.3903	90.1800	16.0004	5.6361	5.504 E-03	181.6981
9.00	0.3898	94.3333	16.6927	5.6512	4.964 E-03	201.4562
9.20	0.3893	98.5800	17.4006	5.6653	4.486 E-03	222.9381
9.40	0.3888	102.9200	18.1240	5.6787	4.061 E-03	246.2567
9.60	0.3884	107.3533	18.8629	5.6912	3.683 E-03	271.5295
9.80	0.3880	111.8800	19.6174	5.7031	3.346 E-03	298.8794
10.00	0.3876	116.5000	20.3875	5.7143	3.045 E-03	328.4339