The University of Melbourne

School of Engineering

Semester 1 Assessment 2012

ENGR30001 – Fluid Mechanics & Thermodynamics

Exam Duration: 3 hours

This paper has FIFTEEN (15) pages consisting of EIGHT (8) questions.

Authorized material: Electronic calculators approved by the School of Engineering may be used. Three tables, one chart and a table of formulae are attached.

Instructions to Invigilators: Script books to be provided.

Instructions to Students: All questions are to be attempted. Full marks will be awarded for obtaining 100 marks of a potential 110 marks

THIS PAPER MUST NOT BE REMOVED FROM THE EXAMINATION ROOM

Question 1

i) Sketch a T - v diagram for H_20 showing the liquid, saturation and superheated regions and at least one isobar passing through each of these regions. Also indicate the critical point on the diagram. **(3 marks)**

ii) An open container of water, initially at sea-level, is transported up Mt Jackson, Colorado, where the atmospheric pressure is 70.11kPa. Has the H_20 boiling point temperature increased, decreased or remained the same during transport? **(1 mark)**

iii) Determine the saturation temperature for H_20 on Mt Jackson. **(1 mark)**

iv) A worker at an observatory on Mt Jackson needs to produce superheated steam. Using steam tables, calculate the heat energy (in Joules) required to raise the temperature of 0.5kg of dry saturated H_20 by 10°C above the saturation temperature. **(4 marks)**

v) What is the specific volume of H_20 at $T = 250°C$ and $p = 132.15$ kPa ? **(2 marks)**

(Total for Question 1 = 11 marks)

Question 2

i) Consider the compression of a hot gas by a piston in a leakproof cylinder. Is this system definitely open, closed or isolated? **(1 mark)**

ii) State the first law of thermodynamics and the non-flow energy equation **(2 marks)**

iii) Calculate the specific volume of air at a gauge pressure of 500 kPa and temperature of 25°C. $\overline{R} = 287$ J/(kg K) for air. Assume $p_{atm} = 101.3$ kPa. **(2 marks)**

(Question 2 continues on next page)

Question 2 (continued)

iv) Consider the flow of H_20 through a turbine. The process is adiabatic (no heat is transferred). The turbine inlet pressure is p_1 = 4 MPa, with T_1 = 400°C. The inlet velocity is V_1 = 30 m/s. The exit pressure, p_2 = 0.1 MPa with T_2 = 90°C and exit velocity of V_2 = 20 m/s. Using the steady flow energy equation, determine the specific work done by the turbine. **(5 marks)**

v) Determine the mass flow rate required for the turbine to produce 1 MW of power. **(1 mark)**

vi) In one or two sentences, explain why this turbine could not work in practice. **(1 mark)**

(Total for Question 2 = 12 marks)

Question 3

i) Sketch a p - v property diagram illustrating the Joule-Brayton Cycle. **(2 marks)**

ii) Sketch a $T-s$ diagram for the Joule-Brayton Cycle. You may need to make use of the equation to relate entropy to temperature and pressure:

$$s_2 - s_1 = C_p \ln\left(\frac{T_2}{T_1}\right) - \bar{R}\ln\left(\frac{p_2}{p_1}\right)$$

(Note: only a sketch is required – the equation above is only provided to help you qualitatively estimate the shape of the T-s curves for the processes in the cycle) **(2 marks)**

(Question 3 continues on next page)

Question 3 (continued)

iii) Show that the thermal efficiency of a Gas Turbine engine (using the Joule-Brayton cycle) is given by:

$$\eta = 1 - r_p^{\frac{1-\gamma}{\gamma}}$$

Note that for adiabatic compression or expansion:

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

(4 marks)

iv) What are the two main purposes of the turbine stage of a gas turbine engine in a helicopter (i.e., what does the turbine drive). **(2 marks)**

v) Consider two engines, a Gas Turbine (Joule-Brayton Cycle) and a Spark Ignition Internal Combustion engine (Otto cycle). If air can be supplied to these engines at p = 101.3kPa and T = 25°C (representing min. pressure and temperature), and after combustion T = 800°C and p = 3 MPa (max. temperature and pressure), determine which engine has the higher efficiency. $\overline{R}$ = 287 J/(kg K) and γ = 1.4 for air.

The efficiency of the Otto cycle is given by:

$$\eta = 1 - \frac{1}{r_v^{\gamma-1}},$$

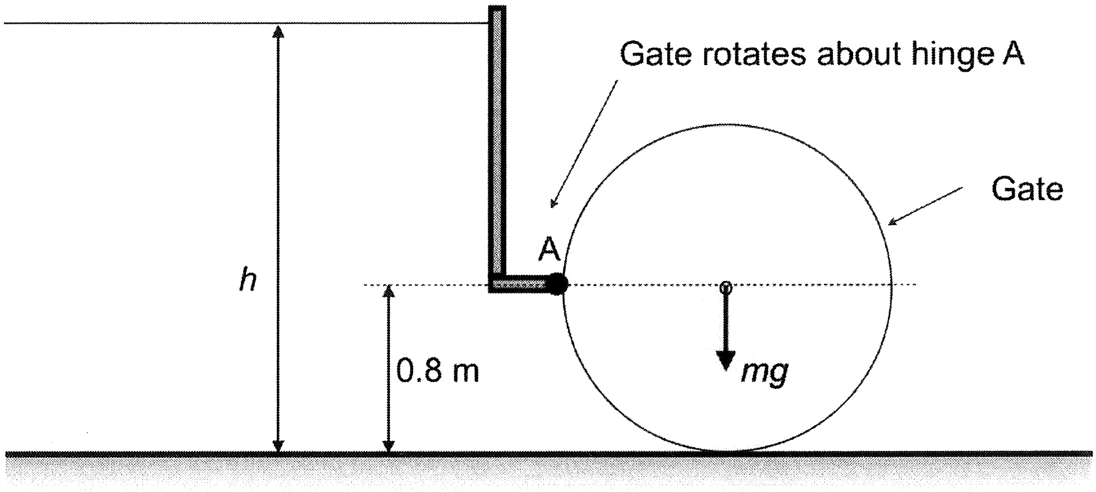
where r_v is the ratio between the maximum and minimum volumes during the cycle.

(2 marks)

(Total for Question 3 = 12 marks)

Question 4

A 1.0 m long solid cylinder hinged at point A is used as an automatic gate, as shown in the figure. When the water (of density 1000 kg/m^3) reaches the level of 5 m (h = 5 m), the gate opens by turning about the hinge at point A.



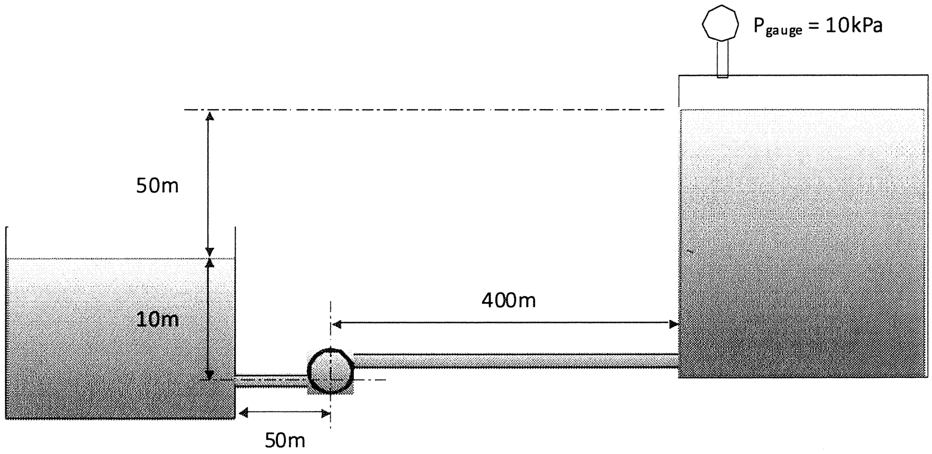
(a) Determine the net horizontal and vertical forces acting on the gate when the gate is just about to open. (Hint: you do *not* need to integrate along the curved surface to resolve these forces.) **(7 marks)**

(b) From this, determine the total hydrostatic force acting on the gate and its line of action when the gate is just about to open. **(3 marks)**

(c) Calculate the mass of the gate. (You may assume that the resultant hydrostatic force acts along a line that passes through the center of the circle.) **(5 marks)**

(Total for Question 4 = 15 marks)

Question 5



Water of density 1000 kg/m^3 is pumped between two large reservoirs through a pipe that has an internal diameter of 300 mm and a roughness length of 1.2 mm. The inlet tank is open to atmosphere (where P_{atm} = 101 kPa), while the discharge tank is sealed and is maintained at a pressure of 10kPa above atmospheric pressure. Loss coefficients for minor losses are as follows:

Minor Loss	Loss coefficient
Inlet loss	0.5
Exit loss	1.0

(a) Given that the pipe flow is in the fully rough regime, write an expression for the system head purely as a function of the volume flow rate Q. **(8 Marks)**

(b) The manufacturer of the pump provides details of the performance of the pump, where the pump head (in m) as a function of volume flow rate (in m^3/s) is given by

$$h_p = 150 - 25Q^2$$

Determine the volume flow rate at the operating point of the system. **(4 Marks)**

(Question 5 continues on next page)

Question 5 (continued)

(c) The required Net Positive Suction Head ($NPSH_R$) supplied by the pump manufacturer is 3 m. Determine whether the pump is within the permissible operating range at the operating point. The vapour pressure of water at the operating conditions is 2000 Pa. **(5 Marks)**

(d) If the mechanical efficiency of the pump is $\eta = 0.65$, determine the mechanical brake power supplied to the pump at the operating condition. **(3 Marks)**

(Total for Question 5 = 20 marks)

Question 6

The mechanical energy equation for horizontal, isothermal, ideal gas flow in a pipe of uniform cross-section is

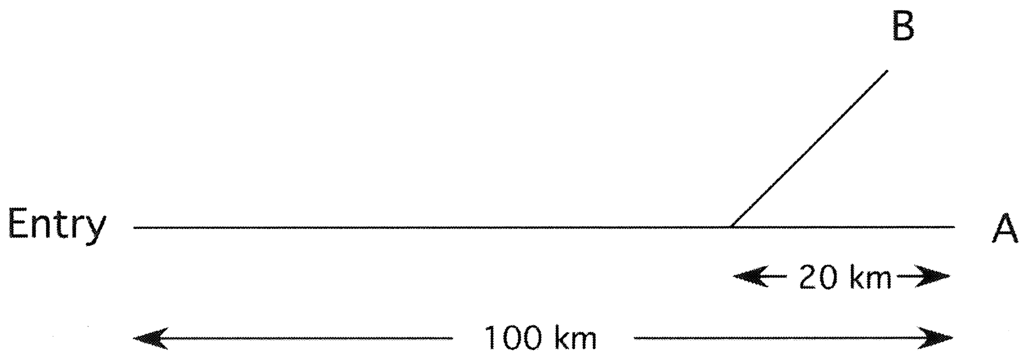
$$\frac{P_2^2 - P_1^2}{2(RT/M)} + \left(\frac{G}{A}\right)^2 \ln\left(\frac{P_1}{P_2}\right) + \frac{2fL}{D}\left(\frac{G}{A}\right)^2 = 0$$

where all symbols have their usual meaning. You may ignore the kinetic energy term when using this equation to calculate pressure. Otherwise, you should retain the kinetic energy term.

(Question 6 continues on next page)

Question 6 (continued)

Natural gas flows through a pipeline 100 km long and 25 cm in diameter to a receiving station A. At a point 20 km before A, a branch leads off from the main pipeline and runs to a receiving station B. The pressure at the beginning of the pipeline is 1000 kPa, the pressure at station A is 400 kPa, and the mass flow rate entering station A is 0.75 kg/s. The Fanning friction factor for all pipes is $f = 0.005$. Assume that the flow is isothermal at 30°C. Ignore energy losses at the branch point.



Gram molecular weight of natural gas	16
Gas constant R	8.314 J mol^{-1} K^{-1}

a) Calculate the velocity of the gas entering station A **(5 marks)**

b) Calculate the pressure where the pipe branches **(5 marks)**

c) Calculate the mass flow rate of gas entering the main pipeline **(4 marks)**

d) Calculate the mass flow rate of gas entering station B **(2 marks)**

(Total for Question 6 = 16 marks)

Question 7

(a) Define the modified Froude number for stirred tanks, stating the meaning of each symbol used. **(2 marks)**

(b) The Froude number can be interpreted as the ratio of which two forces? **(1 mark)**

(c) Under what conditions is the modified Froude number important in stirred tanks? **(1 mark)**

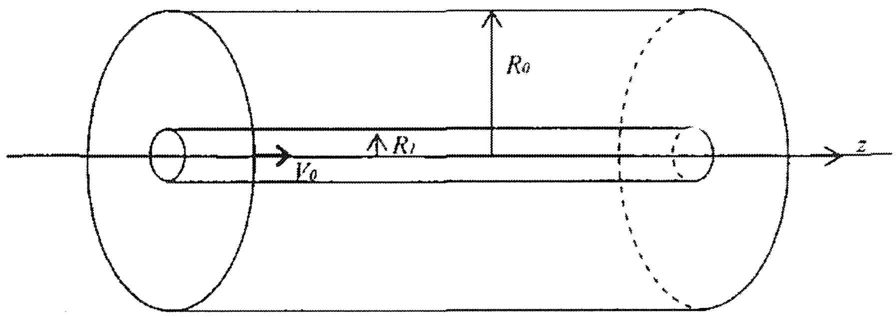
(d) Describe the type of flow produced in a stirred tank by using (i) a flat blade turbine and (ii) a propeller. Draw a sketch for each case to illustrate the flow pattern. **(4 marks)**

(Total for Question 7 = 8 marks)

QUESTION 8 IS ON THE NEXT PAGE

Question 8

An incompressible Newtonian fluid flows steadily between two infinitely long, concentric cylinders having radii R_0 and R_1 as shown in the diagram. The outer cylinder is fixed, but the inner cylinder moves with an axial velocity V_0. The fluid is also being driven in the z-direction due to a constant applied pressure gradient $\frac{\partial p}{\partial z} = -B$. The flow is steady and axially symmetric, with flow directed only in the z-direction.



a) Show that the axial velocity v_z is only a function of the radius r

(2 marks)

b) Find an expression for the velocity profile of the liquid in the annular region.

(6 marks)

c) Hence find an expression for the volumetric flow rate when $B = 0$.

(8 marks)

(Total for Question 8 = 16 marks)

(Total for paper = 110 marks)

Table 2, Temperature Saturation

Saturated Water & Steam

Temperatures from 1 to 120 °C

°C	kN/m^2	m^3/kg	m^3/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg K	kJ/kg K	kJ/kg K	°C
T	p	v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	T
1	0.657	0.001000	192.6	4.174	2376.9	4.174	2499.2	2503.4	0.0153	9.116	9.131	**1**
2	0.705	0.001000	179.9	8.386	2378.3	8.387	2496.8	2505.2	0.0306	9.074	9.105	**2**
4	0.813	0.001000	157.3	16.80	2381.1	16.80	2492.1	2508.9	0.0611	8.992	9.053	**4**
6	0.935	0.001000	137.8	25.21	2383.8	25.21	2487.4	2512.6	0.0913	8.910	9.001	**6**
8	1.072	0.001000	121.0	33.60	2386.6	33.60	2482.6	2516.2	0.1213	8.830	8.951	**8**
10	1.227	0.001000	106.4	41.99	2389.3	41.99	2477.9	2519.9	0.1510	8.751	8.902	**10**
12	1.401	0.001000	93.84	50.38	2392.1	50.38	2473.2	2523.6	0.1805	8.673	8.854	**12**
14	1.597	0.001001	82.90	58.75	2394.8	58.75	2468.5	2527.2	0.2098	8.596	8.806	**14**
16	1.817	0.001001	73.38	67.12	2397.6	67.13	2463.8	2530.9	0.2388	8.521	8.759	**16**
18	2.062	0.001001	65.09	75.49	2400.3	75.50	2459.0	2534.5	0.2677	8.446	8.713	**18**
20	2.337	0.001002	57.84	83.86	2403.0	83.86	2454.3	2538.2	0.2963	8.372	8.668	**20**
22	2.642	0.001002	51.49	92.22	2405.8	92.23	2449.6	2541.8	0.3247	8.299	8.624	**22**
24	2.982	0.001003	45.93	100.6	2408.5	100.6	2444.9	2545.5	0.3530	8.228	8.581	**24**
26	3.360	0.001003	41.03	108.9	2411.2	108.9	2440.2	2549.1	0.3810	8.157	8.538	**26**
28	3.778	0.001004	36.73	117.3	2414.0	117.3	2435.4	2552.7	0.4088	8.087	8.496	**28**
30	4.241	0.001004	32.93	125.7	2416.7	125.7	2430.7	2556.4	0.4365	8.018	8.455	**30**
32	4.753	0.001005	29.57	134.0	2419.4	134.0	2425.9	2560.0	0.4640	7.950	8.414	**32**
34	5.318	0.001006	26.60	142.4	2422.1	142.4	2421.2	2563.6	0.4913	7.883	8.374	**34**
36	5.940	0.001006	23.97	150.7	2424.8	150.7	2416.4	2567.2	0.5184	7.816	8.335	**36**
38	6.624	0.001007	21.63	159.1	2427.5	159.1	2411.7	2570.8	0.5453	7.751	8.296	**38**
40	7.375	0.001008	19.55	167.4	2430.2	167.5	2406.9	2574.4	0.5721	7.686	8.258	**40**
42	8.198	0.001009	17.69	175.8	2432.9	175.8	2402.1	2577.9	0.5987	7.622	8.221	**42**
44	9.100	0.001009	16.04	184.2	2435.6	184.2	2397.3	2581.5	0.6252	7.559	8.184	**44**
46	10.09	0.001010	14.56	192.5	2438.3	192.5	2392.5	2585.1	0.6514	7.497	8.148	**46**
48	11.16	0.001011	13.23	200.9	2440.9	200.9	2387.7	2588.6	0.6776	7.435	8.113	**48**
50	12.34	0.001012	12.05	209.2	2443.6	209.3	2382.9	2592.2	0.7035	7.374	8.078	**50**
52	13.61	0.001013	10.98	217.6	2446.2	217.6	2378.1	2595.7	0.7293	7.314	8.043	**52**
54	15.00	0.001014	10.02	226.0	2448.9	226.0	2373.2	2599.2	0.7550	7.254	8.009	**54**
56	16.51	0.001015	9.159	234.3	2451.5	234.4	2368.4	2602.7	0.7804	7.195	7.976	**56**
58	18.15	0.001016	8.381	242.7	2454.1	242.7	2363.5	2606.2	0.8058	7.137	7.943	**58**
60	19.92	0.001017	7.679	251.1	2456.8	251.1	2358.6	2609.7	0.8310	7.080	7.911	**60**
62	21.84	0.001018	7.044	259.4	2459.4	259.5	2353.7	2613.2	0.8560	7.023	7.879	**62**
64	23.91	0.001019	6.469	267.8	2462.0	267.8	2348.8	2616.6	0.8809	6.967	7.848	**64**
66	26.15	0.001020	5.948	276.2	2464.5	276.2	2343.9	2620.1	0.9057	6.911	7.817	**66**
68	28.56	0.001022	5.476	284.6	2467.1	284.6	2338.9	2623.5	0.9303	6.856	7.786	**68**
70	31.16	0.001023	5.046	292.9	2469.7	293.0	2334.0	2626.9	0.9548	6.802	7.756	**70**
72	33.96	0.001024	4.656	301.3	2472.2	301.4	2329.0	2630.3	0.9792	6.748	7.727	**72**
74	36.96	0.001025	4.300	309.7	2474.8	309.7	2324.0	2633.7	1.003	6.695	7.698	**74**
76	40.19	0.001027	3.976	318.1	2477.3	318.1	2318.9	2637.1	1.027	6.642	7.669	**76**
78	43.65	0.001028	3.680	326.5	2479.8	326.5	2313.9	2640.4	1.051	6.590	7.641	**78**
80	47.36	0.001029	3.409	334.9	2482.3	334.9	2308.8	2643.8	1.075	6.538	7.613	**80**
82	51.33	0.001031	3.162	343.3	2484.8	343.3	2303.8	2647.1	1.099	6.487	7.586	**82**
84	55.57	0.001032	2.935	351.7	2487.3	351.7	2298.6	2650.4	1.123	6.436	7.559	**84**
86	60.11	0.001033	2.727	360.1	2489.7	360.1	2293.5	2653.6	1.146	6.386	7.532	**86**
88	64.95	0.001035	2.536	368.5	2492.2	368.5	2288.4	2656.9	1.169	6.336	7.506	**88**
90	70.11	0.001036	2.361	376.9	2494.6	376.9	2283.2	2660.1	1.193	6.287	7.480	**90**
92	75.61	0.001038	2.200	385.3	2497.0	385.4	2278.0	2663.4	1.216	6.239	7.454	**92**
94	81.46	0.001039	2.052	393.7	2499.4	393.8	2272.8	2666.6	1.239	6.190	7.429	**94**
96	87.69	0.001041	1.915	402.1	2501.8	402.2	2267.5	2669.7	1.261	6.143	7.404	**96**
98	94.30	0.001042	1.789	410.5	2504.1	410.6	2262.2	2672.9	1.284	6.095	7.380	**98**
100	101.3	0.001044	1.673	419.0	2506.5	419.1	2256.9	2676.0	1.307	6.049	7.355	**100**
105	120.8	0.001048	1.419	440.0	2512.3	440.2	2243.6	2683.7	1.363	5.933	7.296	**105**
110	143.3	0.001052	1.210	461.2	2518.0	461.3	2230.0	2691.3	1.418	5.820	7.239	**110**
115	169.1	0.001056	1.036	482.3	2523.5	482.5	2216.2	2698.7	1.473	5.710	7.183	**115**
120	198.5	0.001061	0.892	503.5	2529.0	503.7	2202.2	2706.0	1.528	5.602	7.129	**120**

MN/m^2

°C T \ p	0.001	0.01	0.02	0.05	0.1	0.5	1	2	4	6	8	10	15	20	25	30	35	40	45	50	60	80	100	T
0	999.8	999.8	999.8	999.8	999.8	1000	1000	1001	1002	1003	1004	1005	1007	1010	1012	1014	1017	1019	1022	1024	1028	1037	1046	**0**
5	999.9	999.8	999.8	999.8	999.8	1000	1000	1001	1002	1003	1004	1005	1007	1009	1012	1014	1016	1019	1021	1023	1028	1036	1044	**5**
10	0.00766	999.8	999.8	999.8	999.8	1000	1000	1001	1002	1003	1004	1004	1007	1009	1011	1014	1016	1018	1020	1022	1027	1035	1043	**10**
20	0.00739	998.3	998.3	998.3	998.3	998.5	998.7	999.2	1000	1001	1002	1003	1005	1007	1009	1012	1014	1016	1018	1020	1024	1032	1040	**20**
25	0.00727	997.0	997.0	997.0	997.0	997.2	997.4	997.9	998.8	999.7	1001	1001	1004	1006	1008	1010	1012	1014	1016	1018	1022	1030	1038	**25**
30	0.00715	995.7	995.7	995.7	995.8	995.9	996.2	996.6	997.5	998.4	999.2	1000	1002	1004	1007	1009	1011	1013	1015	1017	1021	1029	1036	**30**
40	0.00692	992.3	992.3	992.3	992.3	992.5	992.7	993.1	994.0	994.9	995.7	996.6	998.7	1001	1003	1005	1007	1009	1011	1013	1017	1025	1032	**40**
50	0.00671	0.0673	988.0	988.0	988.1	988.2	988.5	988.9	989.8	990.6	991.5	992.4	994.5	996.6	998.7	1001	1003	1005	1007	1009	1013	1020	1027	**50**
60	0.00651	0.0652	981.9	983.2	983.2	983.4	983.6	984.0	984.9	985.8	986.6	987.5	989.6	991.8	993.8	995.9	997.9	999.9	1002	1004	1008	1015	1023	**60**
70	0.00632	0.0633	0.1269	977.7	977.7	977.9	978.1	978.5	979.4	980.3	981.2	982.1	984.2	986.4	988.5	990.6	992.6	994.7	996.7	998.6	1003	1010	1017	**70**
80	0.00614	0.0615	0.1232	971.6	971.7	971.8	972.1	972.5	973.4	974.3	975.2	976.1	978.3	980.5	982.7	984.8	986.9	988.9	990.9	993.0	996.9	1005	1012	**80**
90	0.00597	0.0598	0.1197	0.301	965.1	965.3	965.5	966.0	966.9	967.9	968.8	969.7	972.0	974.2	976.4	978.5	980.7	982.8	984.8	986.9	990.9	998.7	1006	**90**
100	0.00581	0.0582	0.1165	0.293	0.590	958.3	958.6	959.0	960.0	960.9	961.9	962.8	965.1	967.4	969.7	971.9	974.1	976.2	978.3	980.4	984.5	992.5	1000	**100**
125	0.00544	0.0545	0.1091	0.274	0.550	938.8	939.1	939.6	940.6	941.7	942.7	943.7	946.2	948.7	951.1	953.5	955.9	958.2	960.4	962.7	967.0	975.5	983.5	**125**
150	0.00512	0.0512	0.1026	0.257	0.516	916.8	917.1	917.7	918.8	920.0	921.1	922.2	925.0	927.7	930.4	933.0	935.6	938.1	940.5	943.0	947.7	956.7	965.3	**150**
175	0.00484	0.0484	0.0968	0.243	0.487	2.504	892.1	892.8	894.1	895.4	896.7	898.0	901.1	904.2	907.2	910.1	912.9	915.7	918.4	921.1	926.3	936.2	945.5	**175**
200	0.00458	0.0458	0.0917	0.230	0.460	2.353	4.856	865.0	866.6	868.1	869.6	871.1	874.7	878.2	881.6	884.9	888.1	891.3	894.3	897.3	903.1	914.0	924.1	**200**
225	0.00435	0.0435	0.0871	0.218	0.437	2.223	4.554	9.643	835.1	837.0	838.8	840.6	844.9	849.0	853.0	856.9	860.6	864.3	867.8	871.2	877.7	889.9	901.1	**225**
250	0.00414	0.0414	0.0829	0.207	0.416	2.108	4.296	8.973	799.2	801.5	803.8	806.1	811.4	816.5	821.3	826.0	830.4	834.7	838.8	842.7	850.3	864.1	876.6	**250**
275	0.00395	0.0395	0.0791	0.198	0.396	2.006	4.073	8.429	18.34	759.3	762.2	765.2	772.3	778.9	785.1	790.9	796.4	801.6	806.6	811.3	820.2	836.2	850.4	**275**
300	0.00378	0.0378	0.0756	0.189	0.379	1.914	3.876	7.968	17.00	27.67	41.21	715.4	725.7	735.0	743.3	751.0	758.1	764.7	770.9	776.7	787.5	806.4	822.7	**300**
325	0.00362	0.0362	0.0725	0.181	0.363	1.830	3.700	7.569	15.94	25.42	36.54	50.40	663.6	679.0	691.8	703.0	712.9	721.8	729.9	737.5	751.0	773.9	792.9	**325**
350	0.00348	0.0348	0.0696	0.174	0.348	1.754	3.541	7.217	15.05	23.68	33.39	44.60	87.24	600.1	625.0	643.5	658.6	671.4	682.6	692.6	710.0	738.1	760.6	**350**
375	0.00334	0.0334	0.0669	0.167	0.335	1.685	3.396	6.902	14.29	22.29	31.04	40.76	72.04	132.0	488.7	555.4	586.5	608.5	625.9	640.4	664.2	699.7	726.5	**375**
400	0.00322	0.0322	0.0644	0.161	0.322	1.620	3.263	6.617	13.63	21.11	29.15	37.87	63.85	100.5	166.3	353.3	473.8	523.8	555.1	578.3	612.6	658.8	691.4	**400**
425	0.00310	0.0310	0.0621	0.155	0.311	1.561	3.141	6.357	13.04	20.09	27.57	35.55	58.37	87.21	127.0	189.3	292.3	390.6	455.0	497.2	551.1	613.6	653.9	**425**
450	0.00300	0.0300	0.0599	0.150	0.300	1.506	3.028	6.119	12.51	19.19	26.22	33.62	54.20	78.70	109.0	148.5	201.8	272.1	343.2	401.3	479.9	564.3	613.9	**450**
475	0.00290	0.0290	0.0579	0.145	0.290	1.455	2.923	5.900	12.02	18.39	25.03	31.97	50.87	72.54	97.92	128.3	165.4	210.5	262.9	315.9	403.9	510.8	571.2	**475**
500	0.00280	0.0280	0.0561	0.140	0.280	1.407	2.825	5.696	11.58	17.67	23.98	30.53	48.09	67.70	89.86	115.2	144.4	178.1	216.2	257.6	338.8	457.0	528.2	**500**
550	0.00263	0.0263	0.0527	0.132	0.263	1.320	2.649	5.331	10.80	16.41	22.17	28.09	43.65	60.43	78.61	98.37	119.9	143.2	168.5	195.6	253.3	361.8	445.3	**550**
600	0.00248	0.0248	0.0496	0.124	0.248	1.244	2.494	5.012	10.13	15.34	20.66	26.10	40.19	55.06	70.79	87.44	105.0	123.6	143.2	163.6	206.8	295.9	374.8	**600**
650	0.00235	0.0235	0.0469	0.117	0.235	1.176	2.356	4.731	9.537	14.42	19.38	24.41	37.36	50.83	64.87	79.48	94.68	110.5	126.8	143.7	178.7	251.6	322.0	**650**
700	0.00223	0.0223	0.0445	0.111	0.223	1.115	2.233	4.481	9.017	13.61	18.26	22.96	34.98	47.37	60.13	73.28	86.80	100.7	115.0	129.5	159.5	221.3	282.8	**700**
750	0.00212	0.0212	0.0424	0.106	0.212	1.060	2.123	4.256	8.555	12.89	17.28	21.70	32.94	44.45	56.21	68.24	80.52	93.04	105.8	118.8	145.2	199.3	253.0	**750**
800	0.00202	0.0202	0.0404	0.101	0.202	1.011	2.023	4.054	8.140	12.26	16.41	20.58	31.17	41.94	52.89	64.03	75.33	86.80	98.42	110.2	134.0	182.5	230.4	**800**
T_{sat}	6.98	45.83	60.09	81.35	99.63	151.8	179.9	212.4	250.3	275.5	295.0	311.0	342.1	365.7										
ρ_f	999.9	989.9	983.1	970.8	958.4	915.0	887.0	849.9	798.7	758.3	722.4	688.4	603.2	490.9										
ρ_g	0.00774	0.0681	0.1307	0.309	0.590	2.669	5.147	10.05	20.10	30.83	42.51	55.43	96.71	170.2										

Density of Water & Steam kg/m^3

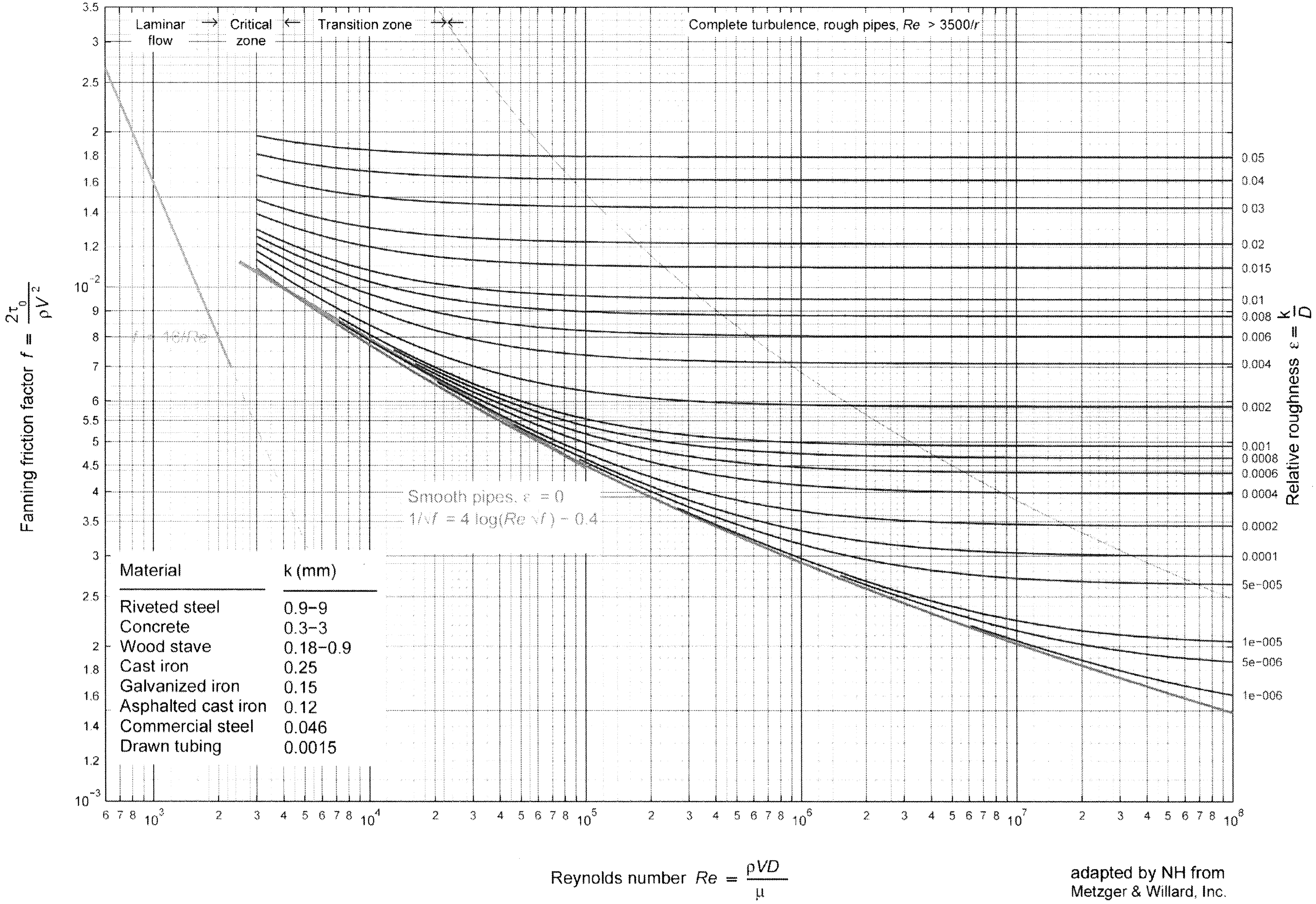
Table 6, Density

°C T \ p (MN/m²)	0.001	0.01	0.02	0.05	0.1	0.5	1	2	4	6	8	10	15	20	25	30	35	40	45	50	60	80	100	T
0	0.042	0.042	0.043	0.043	0.044	0.054	0.065	0.088	0.131	0.173	0.213	0.250	0.336	0.409	0.469	0.517	0.553	0.577	0.590	0.592	0.571	0.454	0.324	0
5	21.02	21.02	21.02	21.02	21.02	21.02	21.02	21.02	21.01	21.01	21.01	21.00	20.98	20.95	20.91	20.86	20.81	20.74	20.67	20.58	20.40	19.96	19.50	5
10	2389	41.99	41.99	41.99	41.99	41.98	41.97	41.95	41.90	41.85	41.80	41.75	41.62	41.49	41.35	41.21	41.06	40.90	40.74	40.57	40.22	39.47	38.68	10
20	2403	83.86	83.86	83.86	83.85	83.83	83.80	83.74	83.62	83.50	83.38	83.26	82.96	82.66	82.36	82.06	81.77	81.47	81.17	80.87	80.27	79.05	77.83	20
25	2410	104.8	104.8	104.8	104.8	104.7	104.7	104.6	104.5	104.3	104.2	104.0	103.6	103.3	102.9	102.5	102.2	101.8	101.4	101.1	100.4	98.96	97.56	25
30	2417	125.7	125.7	125.7	125.7	125.6	125.6	125.5	125.3	125.1	124.9	124.7	124.3	123.9	123.4	123.0	122.6	122.1	121.7	121.3	120.5	118.9	117.3	30
40	2431	167.4	167.4	167.4	167.4	167.4	167.3	167.2	167.0	166.7	166.5	166.2	165.7	165.1	164.5	164.0	163.4	162.9	162.3	161.8	160.8	158.8	156.9	40
50	2445	2444	209.2	209.2	209.2	209.2	209.1	208.9	208.6	208.3	208.1	207.8	207.0	206.3	205.7	205.0	204.3	203.7	203.0	202.4	201.1	198.8	196.5	50
60	2460	2458	251.1	251.1	251.1	251.0	250.9	250.7	250.4	250.0	249.7	249.3	248.5	247.6	246.8	246.0	245.2	244.5	243.7	243.0	241.5	238.8	236.2	60
70	2474	2473	2471	292.9	292.9	292.8	292.7	292.5	292.1	291.7	291.3	290.9	289.9	289.0	288.0	287.1	286.2	285.3	284.5	283.6	282.0	278.8	275.9	70
80	2488	2487	2486	334.9	334.9	334.8	334.6	334.4	333.9	333.5	333.0	332.6	331.5	330.4	329.3	328.3	327.2	326.2	325.3	324.3	322.4	318.9	315.6	80
90	2502	2501	2500	2497	376.9	376.8	376.6	376.4	375.8	375.3	374.8	374.3	373.1	371.8	370.6	369.5	368.3	367.2	366.1	365.0	362.9	359.0	355.3	90
100	2516	2516	2515	2512	2507	418.8	418.7	418.4	417.8	417.2	416.7	416.1	414.7	413.4	412.1	410.8	409.5	408.2	407.0	405.8	403.5	399.1	395.1	100
125	2552	2552	2551	2549	2545	524.7	524.5	524.1	523.4	522.6	521.9	521.2	519.4	517.7	516.0	514.4	512.8	511.2	509.6	508.1	505.2	499.7	494.6	125
150	2588	2588	2587	2586	2583	631.6	631.4	630.9	630.0	629.1	628.2	627.3	625.0	622.9	620.8	618.7	616.8	614.8	612.9	611.0	607.4	600.7	594.4	150
175	2625	2625	2624	2623	2620	2601	740.1	739.5	738.3	737.1	736.0	734.9	732.1	729.4	726.8	724.3	721.8	719.4	717.1	714.8	710.4	702.2	694.6	175
200	2662	2661	2661	2660	2658	2643	2621	850.2	848.8	847.3	845.9	844.4	841.0	837.7	834.4	831.3	828.3	825.3	822.5	819.7	814.3	804.4	795.3	200
225	2699	2699	2698	2697	2696	2684	2667	2627	962.5	960.6	958.8	957.0	952.6	948.4	944.3	940.4	936.6	933.0	929.5	926.1	919.5	907.5	896.7	225
250	2736	2736	2736	2735	2734	2724	2710	2679	1081	1078	1076	1073	1068	1062	1057	1052	1047	1043	1038	1034	1026	1012	998.9	250
275	2774	2774	2774	2773	2772	2764	2753	2728	2668	1203	1200	1196	1188	1181	1174	1168	1162	1156	1150	1145	1135	1118	1102	275
300	2812	2812	2812	2811	2811	2803	2794	2774	2727	2668	2593	1329	1318	1307	1298	1289	1281	1273	1266	1259	1247	1225	1207	300
325	2851	2851	2851	2850	2849	2843	2835	2818	2780	2734	2680	2612	1464	1447	1432	1419	1407	1397	1387	1378	1362	1335	1313	325
350	2890	2890	2890	2889	2889	2883	2876	2862	2829	2792	2750	2702	2523	1614	1585	1563	1545	1530	1516	1504	1483	1447	1419	350
375	2929	2929	2929	2929	2928	2923	2917	2904	2876	2846	2811	2773	2652	2442	1814	1739	1703	1677	1656	1639	1610	1567	1534	375
400	2969	2969	2969	2969	2968	2964	2958	2946	2922	2896	2867	2836	2744	2622	2432	2077	1919	1858	1820	1791	1749	1693	1653	400
425	3009	3009	3009	3009	3008	3004	2999	2989	2967	2944	2919	2893	2818	2727	2611	2455	2254	2107	2022	1968	1900	1822	1771	425
450	3050	3050	3050	3049	3049	3045	3041	3031	3011	2991	2969	2946	2883	2810	2725	2623	2503	2369	2253	2169	2062	1952	1888	450
475	3091	3091	3091	3091	3090	3087	3082	3073	3056	3037	3018	2997	2942	2881	2812	2735	2648	2552	2453	2363	2231	2086	2006	475
500	3132	3132	3132	3132	3132	3128	3124	3116	3100	3083	3065	3047	2999	2946	2888	2825	2756	2682	2605	2529	2393	2222	2127	500
550	3217	3217	3217	3216	3216	3213	3210	3202	3188	3174	3159	3144	3105	3063	3019	2972	2923	2872	2819	2765	2659	2487	2369	550
600	3303	3303	3303	3302	3302	3300	3296	3290	3278	3265	3252	3239	3207	3172	3137	3100	3062	3023	2983	2943	2861	2710	2591	600
650	3390	3390	3390	3390	3390	3388	3385	3379	3368	3357	3346	3335	3307	3278	3248	3218	3186	3155	3123	3091	3027	2902	2795	650
700	3480	3480	3480	3480	3479	3477	3475	3470	3460	3451	3441	3431	3407	3382	3356	3330	3304	3278	3251	3224	3171	3067	2971	700
750	3571	3571	3571	3571	3570	3569	3567	3562	3554	3545	3537	3528	3507	3485	3463	3441	3418	3396	3373	3350	3304	3215	3131	750
800	3663	3663	3663	3663	3663	3662	3660	3656	3649	3641	3634	3626	3607	3588	3569	3550	3530	3511	3491	3471	3432	3354	3280	800
T_{sat}	6.98	45.83	60.09	81.35	99.63	151.8	179.9	212.4	250.3	275.5	295.0	311.0	342.1	365.7										
u_f	29.33	191.8	251.4	340.5	417.4	639.6	761.5	906.2	1082	1206	1306	1394	1586	1786										
u_g	2385	2438	2457	2484	2506	2560	2582	2598	2601	2590	2572	2547	2460	2301										

Specific Internal Energy of Water & Steam kJ/kg

Table 7, Internal Energy

Moody Diagram



Material	k (mm)
Riveted steel	0.9–9
Concrete	0.3–3
Wood stave	0.18–0.9
Cast iron	0.25
Galvanized iron	0.15
Asphalted cast iron	0.12
Commercial steel	0.046
Drawn tubing	0.0015

adapted by NH from
Metzger & Willard, Inc.

Continuity and Navier-Stokes equations for incompressible homogeneous fluids in Cartesian, cylindrical, and spherical coordinates

Cartesian	Cylindrical	Spherical
Continuity equation		
$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0$	$\frac{1}{r}\frac{\partial(rv_r)}{\partial r}+\frac{1}{r}\left(\frac{\partial v_\theta}{\partial \theta}\right)+\frac{\partial v_z}{\partial z}=0$	$\frac{1}{r^2}\frac{\partial(r^2v_r)}{\partial r}+\frac{1}{r\sin\theta}\frac{\partial(v_\theta\sin\theta)}{\partial\theta}+\frac{1}{r\sin\theta}\frac{\partial v_\phi}{\partial\phi}=0$
Navier-Stokes equation		
$\rho\left(\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_x}{\partial y}+v_z\frac{\partial v_x}{\partial z}\right)$ $=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_x}{\partial y^2}+\frac{\partial^2 v_x}{\partial z^2}\right)$	$\rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial\theta}-\frac{v_\theta^2}{r}+v_z\frac{\partial v_r}{\partial z}\right)$ $=-\frac{\partial p}{\partial r}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv_r)\right)+\frac{1}{r^2}\frac{\partial^2 v_r}{\partial\theta^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial\theta}+\frac{\partial^2 v_r}{\partial z^2}\right]$	$\rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial\theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_r}{\partial\phi}-\frac{v_\theta^2+v_\phi^2}{r}\right)$ $=-\frac{\partial p}{\partial r}+\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_r}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial v_r}{\partial\theta}\right)\right.$ $\left.+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_r}{\partial\phi^2}-\frac{2v_r}{r^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial\theta}-\frac{2v_\theta\cot\theta}{r^2}-\frac{2}{r^2\sin\theta}\frac{\partial v_\phi}{\partial\phi}\right]$
$\rho\left(\frac{\partial v_y}{\partial t}+v_x\frac{\partial v_y}{\partial x}+v_y\frac{\partial v_y}{\partial y}+v_z\frac{\partial v_y}{\partial z}\right)$ $=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v_y}{\partial x^2}+\frac{\partial^2 v_y}{\partial y^2}+\frac{\partial^2 v_y}{\partial z^2}\right)$	$\rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial\theta}+\frac{v_rv_\theta}{r}+v_z\frac{\partial v_\theta}{\partial z}\right)$ $=-\frac{1}{r}\frac{\partial p}{\partial\theta}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv_\theta)\right)+\frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial\theta^2}+\frac{2}{r^2}\frac{\partial v_r}{\partial\theta}+\frac{\partial^2 v_\theta}{\partial z^2}\right]$	$\rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial\theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_\theta}{\partial\phi}+\frac{v_rv_\theta}{r}-\frac{v_\phi^2\cot\theta}{r}\right)$ $=-\frac{1}{r}\frac{\partial p}{\partial\theta}+\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_\theta}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial v_\theta}{\partial\theta}\right)\right.$ $\left.+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_\theta}{\partial\phi^2}+\frac{2}{r^2}\frac{\partial v_r}{\partial\theta}-\frac{v_\theta}{r^2\sin^2\theta}-\frac{2\cos\theta}{r^2\sin^2\theta}\frac{\partial v_\phi}{\partial\phi}\right]$
$\rho\left(\frac{\partial v_z}{\partial t}+v_x\frac{\partial v_z}{\partial x}+v_y\frac{\partial v_z}{\partial y}+v_z\frac{\partial v_z}{\partial z}\right)$ $=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 v_z}{\partial x^2}+\frac{\partial^2 v_z}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right)$	$\rho\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial\theta}+v_z\frac{\partial v_z}{\partial z}\right)$ $=-\frac{\partial p}{\partial z}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_z}{\partial\theta^2}+\frac{\partial^2 v_z}{\partial z^2}\right]$	$\rho\left(\frac{\partial v_\phi}{\partial t}+v_r\frac{\partial v_\phi}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\phi}{\partial\theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial v_\phi}{\partial\phi}+\frac{v_rv_\phi}{r}+\frac{v_\theta v_\phi\cot\theta}{r}\right)$ $=-\frac{1}{r\sin\theta}\frac{\partial p}{\partial\phi}+\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_\phi}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial v_\phi}{\partial\theta}\right)\right.$ $\left.+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_\phi}{\partial\phi^2}-\frac{v_\phi}{r^2\sin^2\theta}+\frac{2}{r^2\sin\theta}\frac{\partial v_r}{\partial\phi}+\frac{2\cos\theta}{r^2\sin^2\theta}\frac{\partial v_\theta}{\partial\phi}\right]$