2145392 Gas Turbine

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Gas turbines, like other heat engines, achieve conversion of heat energy of a fuel into mechanical energy by carrying out a sequence of processes, i.e. a cycle, on its working fluid. Typically a parcel of this fluid is first compressed and then heated either by burning a fuel in the fluid or by bringing the fluid into contact with an external source of heat energy. The hot high pressure flow then expands back to atmospheric pressure and in doing so provides both sufficient work to drive the original compression process and residual work to drive an external load.

Unlike the petrol or diesel engine however in a gas turbine these processes do not take place within the same compartment but in separate compartments or components, i.e., a compressor, a combustion chamber, (or heat exchanger) and a turbine. A consequence of this type of arrangement is that, under a steady rotational speed of the component, i.e., pressure, temperature, velocity, are steady. Additionally as a parcel of fluid passes from one component to another component it continually displaces a parcel of fluid in front of it and it is itself replaced behind by the next parcel. The gas turbine is therefore characterized by steady flow processes as opposed to the essentially non-flow processes of reciprocating machinery.

Motivation

Gas turbines are becoming increasingly used as power plants for a wide variety of applications around the world. Originally they were developed solely for aircraft propulsion where their inherent low specific weight (i.e. mass/unit power) made them essential for high speed flight. For this particular purpose they have been developed to a high degree of efficiency both thermodynamically and mechanically.

Due partly to the impetus from the aircraft engine field and also to other significant operational advantages, industrial gas turbines have been and are being developed for such diverse applications as electrical power peak lopping stations, fire fighting pump sets, natural gas pumping and compressor units, factory power and process heating plants, heavy lorry propulsion, rail and ship propulsion.

Objective

To study the performance of a gas turbine unit.

Problem statements

The specific problem statements are as follows.

The first experiment is for the specified gas generator turbine speed (or specified gas flow rate). Find the output power from the power turbine and the efficiency of the power turbine and the gas turbine unit for the adjustable range of the power turbine operating speeds.

The second experiment is to adjust the speed of gas generator turbine. For the adjustable range of the gas generator turbine operating speeds, find the compressor delivery pressure, air mass flow rate, fuel flow, power output and specific fuel consumption at a specified power turbine speed (or specified gas generator turbine and power turbine speed ratio).

Approach

General

Under the specified experimental conditions, measures the fuel flow, measures the air flow, measures the temperature, measures the pressure, measures the speed and measures the power output.

Brief Description and Diagram of Apparatus (For details, see Appendix).

The experiment apparatus is basically a Two Shaft Gas Turbine Unit as shown in Fig. 1. The two shaft gas turbine unit employs a centrifugal compressor and a radial turbine (gas generator turbine), arranged back to back on a common shaft which together with a gas-fueled combustion chamber operating on liquid petroleum gas (LPG), form the gas generator. Gases from the gas generator turbine pass to the power turbine which is a radial machine of larger size and thence to exhaust. The power turbine is loaded by a dynamometer system to absorb the power output. Starting is effected by an electrically driven auxiliary air blower, incorporated within the unit and delivering into the eye of the compressor, which accelerates the compressor/turbine initially and assists it until self-sustaining speed is reached after light-up. There is a lubrication system for both the compressor/turbine and the power turbine incorporating an electrically driven pump, filter, automatically oil cooler and reservoir.

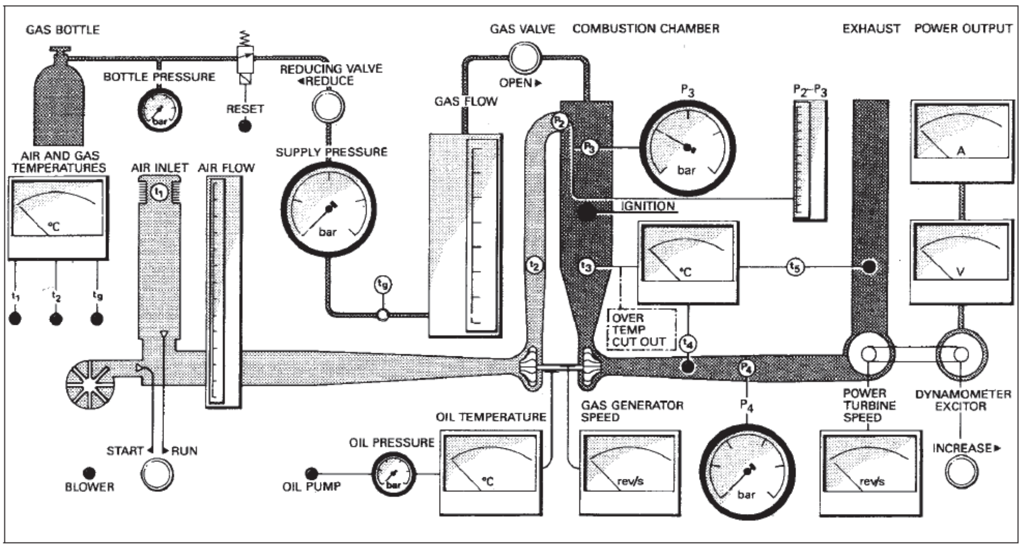


Figure 1 Flow diagram of the gas turbine unit.

Operating Instructions

General

The Cussons Gas Turbine Unit is designed to permit analysis of the performance characteristics of the gas generator, power turbine and combustion chamber using the instrumentation displayed on the front panel. Operation over a wide range of speed and load is possible which, together with the facility for varying the speed ratio between the gas generator and the power turbine, means that a test programmed on the Two Shaft Gas Turbine system can be carried out. By carefully controlling the speed ratio of the gas generator and power turbine to a constant value, a coupled power turbine can be simulated, whereas if the power turbine speed is held constant, then the gas generator simulates a single spool turbo jet.

Starting

1. Connect the cooling water supply and drain.
2. Connect the gas bottle.
3. Connect the electrical supply and start the exhaust fan blower.
4. Set the air inlet control to the start position.
5. Close the gas valve and open the valve on the gas bottle.
6. Set the dynamometer excitation to maximum.
7. Start the oil pump.
8. Press the reset button.
9. Start the blower.
10. Set the gas pressure to 2.0 bar with the reducing valve.
11. Press the ignition button and hold it in whilst opening the gas valve to give a gas flow of 0.5 g/s.
12. If ignition, as shown by an increase in T_3, does not occur within 5 seconds of gas flow commencing, close the gas valve to allow unburned gas to clear the system before continuing from item 11.
13. Release the ignition button.
14. Open the gas valve slowly to give a gas generator speed of 1000 rev/s taking care to keep combustion chamber temperature below 900°C (this operation may take some minutes depending on the oil temperature).
15. Turn the air inlet control to the run position.

16. Switch off the blower.

Operating Limitations

1. During the test program the following limits must not be exceeded:

   Gas generator speed 2000 rev/s
   Power turbine speed 600 rev/s
   Gas generator turbine inlet temperature 900°C

2. Set the gas pressure to 1.5 bar before making fuel flow readings.

3. The gas turbine unit has certain safety features built into it. If the combustion chamber temperature T_3 is allowed to exceed 900°C due to over fuelling, or if the oil pressure falls below 1.5 bar, then the gas supply will be shut of by means of a solenoid valve. To re-start the turbine after operation of the solenoid valve, follow starting instructions 4-17.

Stopping

1. Close the valve on the bottle.

2. Close the gas valve.

3. Once the turbines have stopped reset the air inlet control to the start position.

4. Re-start the blower.

5. When T_4 has dropped below 80°C and the oil temperature drops below 40°C:

   i) Switch off the blower.
   ii) Switch off the oil pump.
   iii) Turn off the gas supply.
   iv) Turn off the water supply.
   v) Turn off and disconnect the electrical supply.

Notes on Operating Instructions

Starting

When ignition initially occurs, a slight 'pop' is heard, and a sharp rise of combustion chamber temperature (T_3) takes place. If the gas valve is then opened too quickly, T_3 will rise above 950°C and the over temperature protection will operate. Should this occur, close the gas valve, press the 'reset' button and restart the turbine according to the starting procedures described earlier. Whilst accelerating T_3 should be kept below 850°C by 'slowly' opening the gas valve as the turbine speed increases. When the gas generator speed reaches 1000 rps, leave the gas valve in this position and turn the air inlet control switch to the run position and switch off the blower.

Operation

When varying the load on the power turbine, sudden large movements of the dynamometer exciter control should be avoided, so that high transient belt loads (which may cause the belt to jump the pulleys and cause damage) can be avoided. It is convenient when taking a set of readings to first set the fuel flow at the desired level by adjustment of the fuel control valve, and then (if required) trimming the reducing valve to give a fuel supply pressure of 1.5 bar.

Stopping

When the turbine has been stopped and the system is being cooled by operating the blower, it is essential to leave the blower running until the temperature of T_4 has dropped to less than 80°C and the oil temperature to less than 40°C.

Experimental Procedures

Exp 1. Run and maintain the gas generator turbine at a speed about 1200 rps and vary the speed of the power turbine from 100 to 550 rps (i.e. 100, 200, 250, 300, 350, 400, 450, 500, 550 rps).

Exp 2. Run and maintain the power turbine at a speed about 550 rps and vary the speed of the gas generator turbine from 1000 to 1400 rps (i.e. 1000,1050, 1100, 1150, 1200, 1300, 1400 rps).

Experimental Results

Exp 1: 1.1 Plot output power vs power turbine speed for a specified gas generator turbine speed.

1.2 Plot efficiency of the power turbine vs power turbine speed for a specified gas generator turbine speed.

1.3 Plot efficiency of the gas turbine unit vs power turbine speed for a specified gas generator speed.
(Note: in this case, the efficiency of the gas turbine unit is defined as the ratio of the output power from the power turbine to the power input from the external source (fuel) to the gas turbine unit.)

Exp 2: 2.1 Plot compressor delivery pressure vs gas generator turbine speed.

2.2 Plot fuel flow vs gas generator turbine speed.

2.3 Plot power output vs gas generator turbine speed.

2.4 Plot specific fuel consumption vs gas generator turbine speed.

Discuss all graphs in details. (i.e. how each parameter varied with other parameters?, what does each graph tell you?)

Note: Part of the information described in this lab sheet comes from detail specifications from the Cussons technology P9005 Two Shaft Gas Turbine Unit

References and Recommended Readings

1. Frost, T.H., A First Course in Gas Turbine Technology, published by G Cussons Limited, England.
2. Johnson W. R., The handbook of Fluid Dynamics, CRC Press, 1998.
3. Turns, S.R. Thermal Fluid Sciences An Integrated Approach, Cambridge University Press, 2006.

Example of lab data sheet

FUEL FLOW			AIR FLOW		OIL	PRESSURES			TEMPERATURES					SPEEDS		POWER OUTPUT			
M_f gram/sec	T_g °C	P_g bar	g/sec	P-RP mm H_2O	T_{oil} °C	P_3 bar	P_4 bar	P_2-P_3 mm Hg	T_1 °C	T_2 °C	T_3 °C	T_4 °C	T_5 °C	G.G rev/sec	P.T rev/sec	Voltage V	Current A	Correct Factor	Power WATTS

T3 OVER TEMPERATURE SETTING	°C	PITOT - REVERSE PITOT CONSTANT	DATE TEST COMPLETED
WATER THERMOSTAT SETTING	°C	AIR FLOW CALIBRATION EQUATION:-	TEST ENGINEERS SIGNATURE
BELT TENSIONING RAM PRESSURE	bar	M_{air} = {h} $^{0.5}$	TEST SUPERVISORS SIGNATURE
Remarks			

Appendix

1. Fundamental concepts

Figure A1 shows the simplified line diagram of a simple gas turbine which comprises of a compressor, a combustion chamber, and a turbine. The air is fed from the atmosphere to the compressor. The high pressure air from the compressor is mixed with the fuel and combust in the combustion chamber. The hot gas from the combustion chamber is expanded in the turbine driving the compressor and external load. The gas is then exhausted back to the atmosphere.

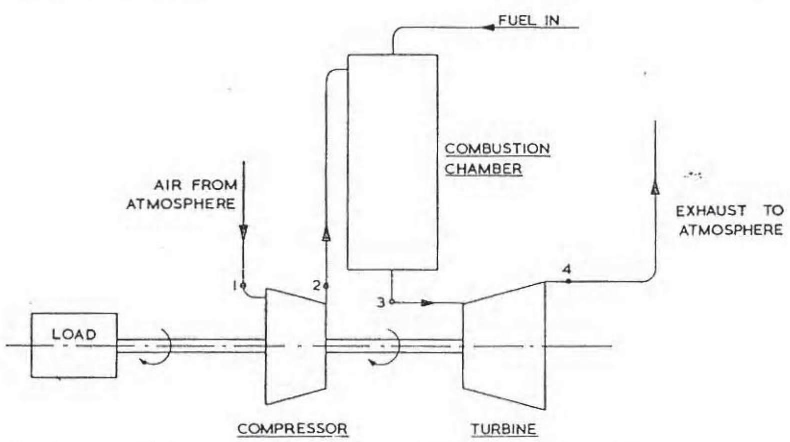


Figure A1 Simplified Line Diagram of a Simple Gas Turbine.

1.1 Basic equation

When considered the energy flow at each component of the gas turbine unit (compressor, combustion chamber and turbine), the energy balance for a steady fluid flow in each component can be written as

$$-\frac{\delta W}{dt}_{shaft} = -\frac{\delta Q}{dt} - \dot{m}\left(u_i + \frac{p_i}{\rho_i} + \frac{V_i^2}{2} + gz_i\right) + \dot{m}\left(u_o + \frac{p_o}{\rho_o} + \frac{V_o^2}{2} + gz_o\right) \quad (1)$$

Subscript *i* refers to inlet and subscript *o* refers to outlet.

Since $h = u + \frac{p}{\rho}$

Therefore, for $z_i = z_o$

$$-\frac{\delta W}{dt}_{shaft} = -\frac{\delta Q}{dt} - \dot{m}\left(h_i + \frac{V_i^2}{2}\right) + \dot{m}\left(h_o + \frac{V_o^2}{2}\right) \quad (2)$$

Where h_i is the inlet enthalpy and h_o is the outlet enthalpy.

$$-\frac{\delta W}{dt}_{shaft} = -\frac{\delta Q}{dt} + \dot{m}\left[\left(h_o + \frac{V_o^2}{2}\right) - \left(h_i + \frac{V_i^2}{2}\right)\right] \tag{3}$$

For ideal gas; $h = c_p T$

$$-\frac{\delta W}{dt}_{shaft} = -\frac{\delta Q}{dt} + \dot{m}\left[\left(c_p T_o + \frac{V_o^2}{2}\right) - \left(c_p T_i + \frac{V_i^2}{2}\right)\right] \tag{4}$$

$$-\frac{\delta W}{dt}_{shaft} = -\frac{\delta Q}{dt} + \dot{m}c_p\left[T_{0o} - T_{0i}\right] \tag{5}$$

Where T_{0k} is the stagnation temperature at *k*.

For compressor (from figure 1) with the adiabatic process, equation 5 can be written as

$$-\frac{\delta W}{dt}_{shaft-compressor} = \dot{m}c_p\left[T_{02} - T_{01}\right] \tag{6}$$

Where T_{01} is the stagnation temperature at compressor inlet.

T_{02} is the stagnation temperature at compressor outlet.

For combustion chamber, equation 5 can be written as

$$\frac{\delta Q}{dt}_{combustion} = \dot{m}c_p\left[T_{03} - T_{02}\right] \tag{7}$$

Where T_{02} is the stagnation temperature at combustion chamber inlet.

T_{03} is the stagnation temperature at combustion chamber outlet.

For turbine with the adiabatic process, equation 5 can be written as

$$-\frac{\delta W}{dt}_{shaft-turbine} = \dot{m}c_p\left[T_{04} - T_{03}\right] \tag{8}$$

Where T_{03} is the stagnation temperature at turbine inlet.

T_{04} is the stagnation temperature at turbine outlet.

1.2 Ideal cycle

The working cycle for gas turbine unit is called Brayton cycle. The Brayton cycle under the isentropic (reversible adiabatic process) is shown in figure A2.

1-2: adiabatic and reversible (isentropic) compression,

2-3: constant pressure heat addition,

3-4: adiabatic and reversible (isentropic) expansion and

4-1: constant pressure heat rejection

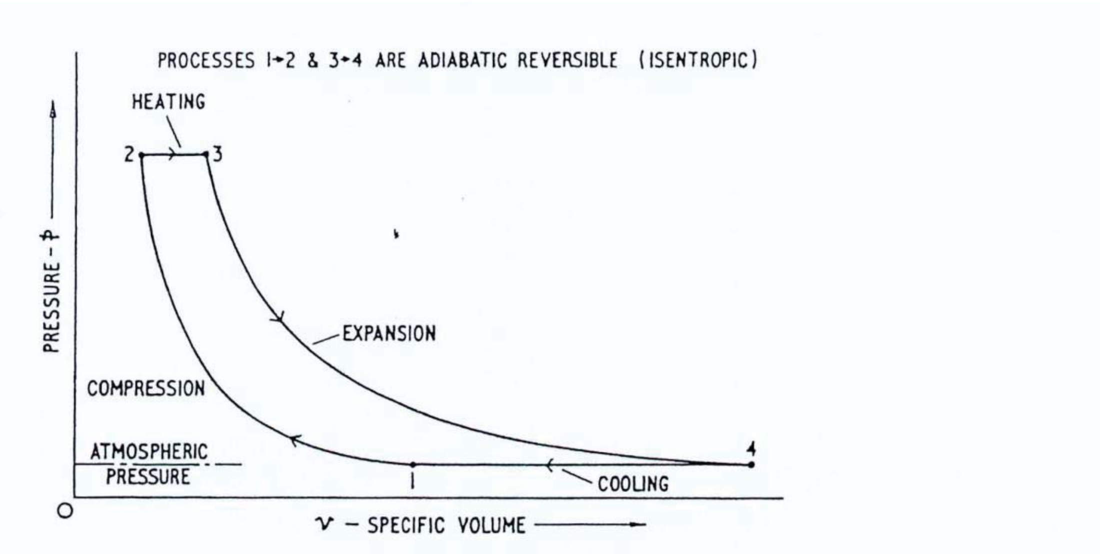


Figure A2 P-V Diagram for an ideal Gas Turbine Cycle.

The power added to the fluid which generated from the compressor, when neglecting changes in kinetic and potential energies across the compressor, can be written as

$$\dot{w}_c = \dot{m}c_p(T_2 - T_1) \quad (9)$$

The rate of heat added to the fluid from the combustion process in the combustion chamber, when neglecting changes in kinetic and potential energies across the combustion chamber, can be written as

$$\dot{Q} = \dot{m}c_p(T_3 - T_2) \quad (10)$$

The power input to the turbine, when neglecting changes in kinetic and potential energies across the turbine, can be written as

$$\dot{w}_t = \dot{m}c_p(T_3 - T_4) \quad (11)$$

Heat rejection at process 4-1 when neglecting changes in kinetic and potential energies across the heat rejection device, can be written as

$$\dot{Q}_{reject} = \dot{m}c_p(T_4 - T_1) \tag{12}$$

1.3 The calculation for the experimental results of the Gas Turbine Unit

For the purpose of understanding the gross behavior of the gas turbine performance, certain assumptions have been made to simplify the mathematical model of the system. The assumptions are: steady flow process, c_p average between the inlet and outlet condition, neglecting changes in kinetic and potential energies across the considered component, neglecting the fuel flow rate when considering the combusted gas flow rate.

$$P_{alternator} = VI \tag{13}$$

$$P_{output} = P_{alternator} / eff \tag{14}$$

$$\dot{w}_{power\,turb} = \dot{m}c_{p,avg,4-5}(T_4 - T_5) \tag{15}$$

$$\dot{Q}_{input} = \dot{m}_f c_V \tag{16}$$

$$\dot{Q}_{comb} = \dot{m}c_{p,avg,3-2}(T_3 - T_2) \tag{17}$$

$$\eta_{power\,turb} = \frac{P_{output}}{\dot{w}_{power\,turb}} \times 100 \tag{17}$$

$$\eta_{gas\,turb} = \frac{P_{output}}{\dot{Q}_{input}} \times 100 \tag{18}$$

$$sfc = \frac{\dot{m}_f}{P_{output}} \tag{19}$$

$$\dot{m} = k\sqrt{\Delta h} \quad \text{g/sec} \tag{20}$$

Where $P_{alternator}$ = power output from the alternator (Watt).

P_{output} = power output from the power turbine to drive the alternator (Watt).

eff = efficiency of the drive, alternator and rectify circuit which value can be read from figure A4.

V = measured voltage (Volt).

I = measured current (Ampere).

$\dot{w}_{power\ turb}$ = power that added to the power turbine (Watt).

$\dot{Q}_{input}$ = input heat rate to the system (to the combustion chamber) (Watt).

$\dot{Q}_{comb}$ = added heat from the combustion process in the combustion chamber (Watt).

sfc = specific fuel consumption (kg/(s-Watt)) or (g/(s-Watt)).

$\eta_{power\ turb}$ = efficiency of the power turbine (%).

$\eta_{gas\ turb}$ = efficiency of the gas turbine unit (%) (excluding the loss on the alternator unit).

$\dot{m}$ = gas flow rate (kg/s) or (g/s).

$\dot{m}_f$ = fuel flow rate (kg/s) or (g/s).

c_V = calorific heat value (kJ/kg) or (kJ/g).

c_p = specific heat at constant pressure (J/(kg-K)).

T_2 = gas generator compressor exit temperature or combustion chamber inlet temperature (K)

T_3 = combustion chamber outlet temperature (K)

T_4 = power turbine inlet temperature (K)

T_3 = power turbine outlet temperature (K)

k = calibration constant = 11.47 (determined by Cussons and engraved on the unit).

Δh = differential pressure reading on the manometer (mmH_2O).

Note: Calorific heat value for liquefied petroleum gas (LPG) is 50000 kJ/kg.

2. Detail of the Apparatus

The two shaft gas turbine unit is a self contained equipment with a gas generator, power turbine, loading unit, instrumentation and controls housed on a castor mounted framework.

2.1 Gas Generator

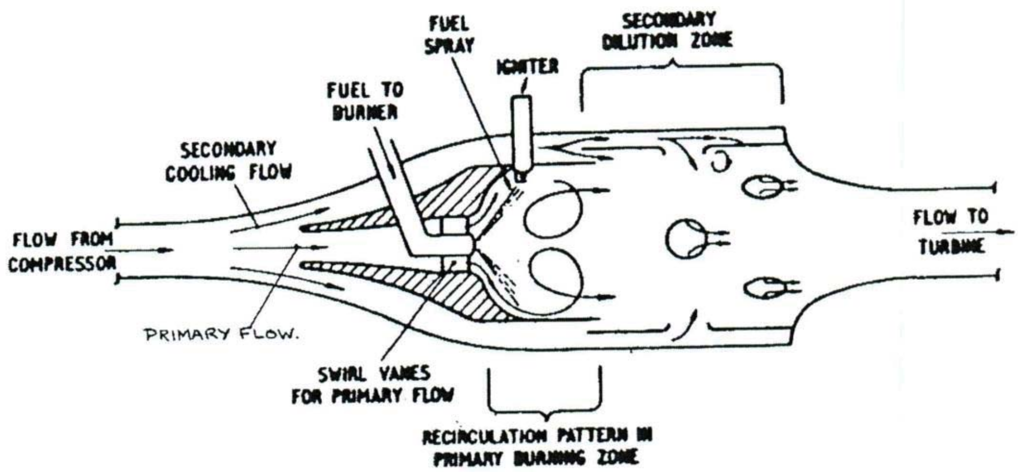
The single shaft generator comprises of a centrifugal compressor, a tubular combustion chamber and a radial turbine. The compressor and gas generator turbine are close coupled with the shaft located in a central housing by hydrodynamic bearings.

2.2.1 Compressor

The compressor is a single sided centrifugal type with a multi-bladed aluminum alloy impeller.

2.2.2 Combustion Chamber

The single vertical combustion chamber is of conventional design, incorporating a flame tube with central fuel injector for gaseous fuels. The combustion chamber is shown in figure A3. The flame tube divides the incoming air flow into 'primary' and 'secondary' air, with a stabilized combustion zone and tertiary dilution air. A spark igniter is mounted in the side of the combustion chamber for starting purposes. To allow a compressor air bleed to be taken from the chamber an air valve is incorporated in the top of the combustion chamber outer casing.



Flow Patterns in a Single Circular Combustion Chamber.

Figure A3 Inner Combustion Chamber Details.

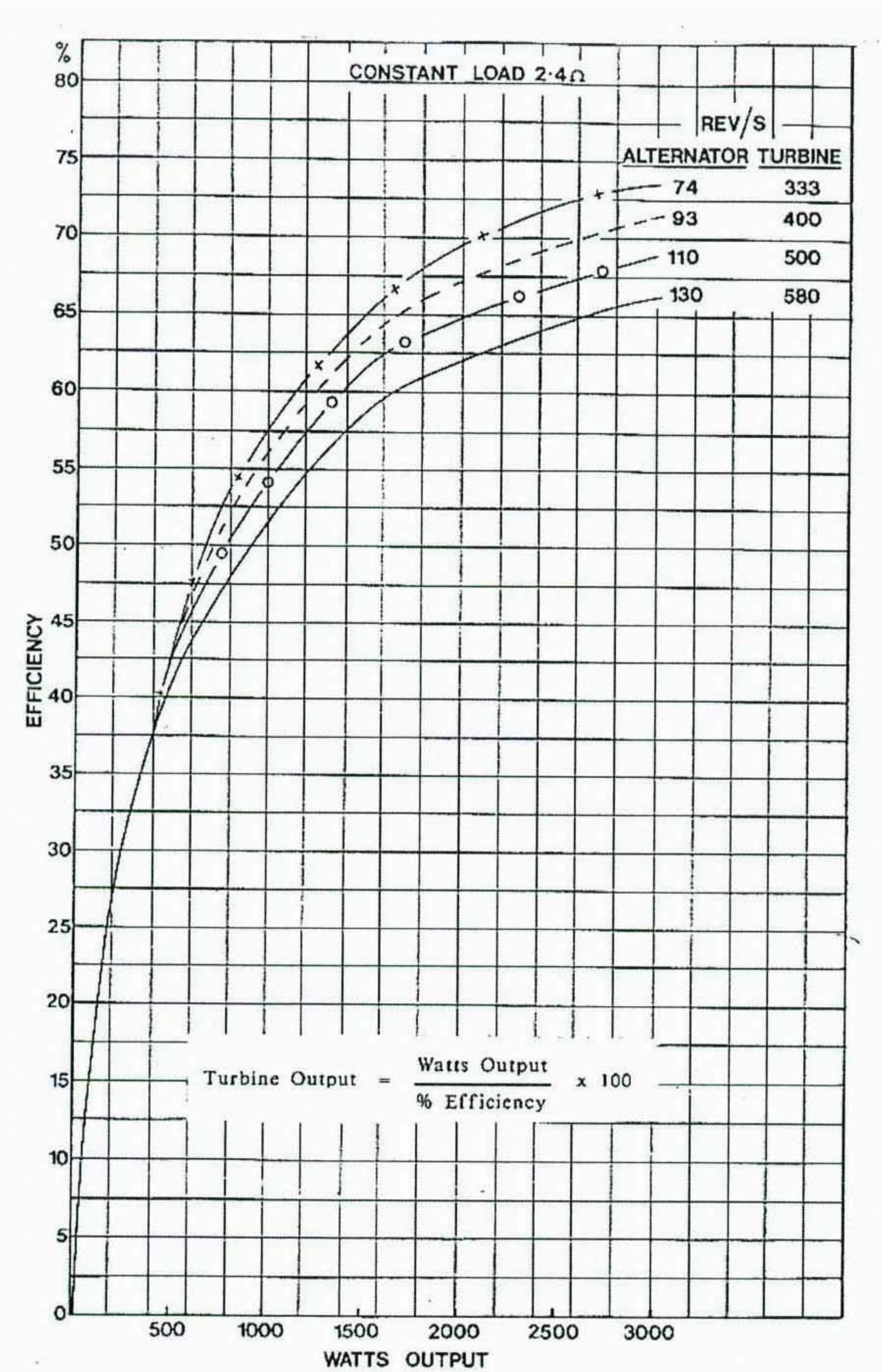


Figure A4 AC 7 Alternator Calibration.

2.7 Lubrication System

The gas generator compressor-turbine and the power turbine bearings are lubricated by a continuous circulation lubricating system. The system comprises an oil tank, separately driven gear pump, oil filter and a water cooled oil cooler. The pump draws oil from the tank and passes it through the full flow oil filter and oil cooler, directly to the main bearings from which free flowing drain pipes lead back to the oil tank. The system is protected by an oil pressure switch to shut down the gas turbine in the event of low oil pressure. A small oil bleed from the main pressure supply pipe is taken to supply the belt tensioning hydraulic ram. The recommended lubricant is Burmah Castrol "Assurnn T + 10" which is a low viscosity monograde mineral based detergent oil with an anti-oxidant additive formulated for use with turbocharged Diesel engines. The normal operating pressure of the lubrication system is 4 to 4.5 bar on starting from cold with the pressure dropping towards 2 bar as the working temperature in the oil tank rises. The oil cooler ensures that the temperature of the oil fed to the bearings is maintained at approx. 80°C

2.8 Instrumentation.

Instrumentation for both operational and experimental measurement is integrated into the colored schematic diagram on the instrument and control panel.

2.8.1 Temperature.

From serial number 206 all seven temperatures are measured using type K NiCr/NiA1 thermocouples, whereas previous models used diodes for low temperatures and thermocouples for high temperatures. The seven temperature channels are:

T_1 Air inlet temperature

T_2 Gas generator compressor exit temperature

T_3 Gas generators turbine inlet temperature

T_4 Power turbine inlet temperature

T_5 Power turbine exit temperature

T_g Gas (fuel) temperature

T_o Oil (lubricant) temperature

All the thermocouples are connected via a cold junction compensation unit and break-out unit to Cussons eight channel thermocouple printed circuit board CBA 219. For each channel there are two independent outputs, one is for the front panel instrumentation while the other is a 0-10V dc analogue output available for input to a data logger, computer input or chart recorder. Three front panel analogue temperature indicators are provided. The three high temperatures T_3, T_4 and T_5 are connected to a 1000°C meter, via cascaded push buttons to read T_4 and T_5. With neither button depressed the meter reads T_3. Similarly T_1, T_2 and T_g are connected to a 120°C meter which normally reads T_2 unless either the T_1 or T_g button is pressed. The oil thermocouple is permanently connected to the 120°C oil meter

2.8.2 Pressure

Conventional Bourdon tube pressure gauges are used to measure all pressures other than the combustion chamber pressure loss (p2 – p3) which is obtained from a differential mercury manometer. Snubbers are fitted in the P_2, P_3 and P_4 pressure lines.

2.8.3 Air Flow Rate

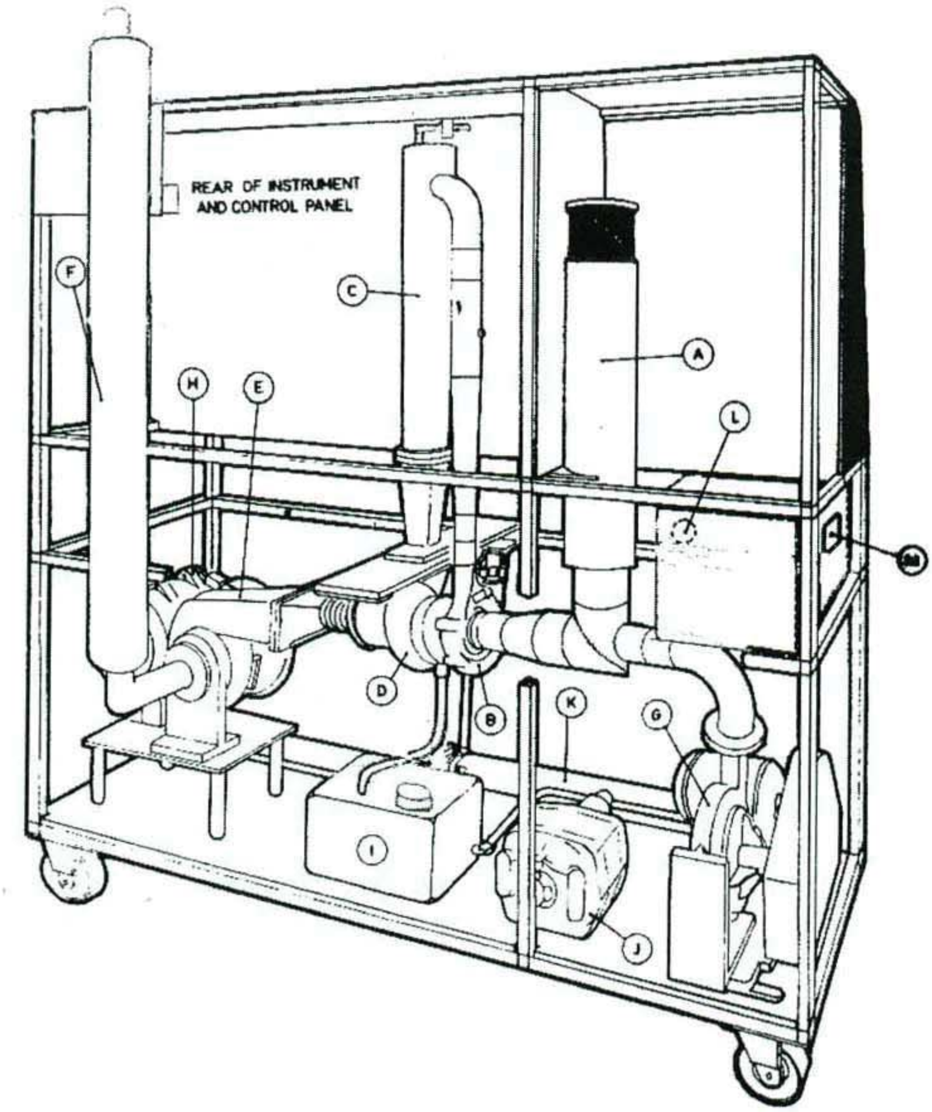
The air flow is measured at the inlet to the gas generator compressor by a pitot-reverse pitot tube connected to a differential manometer on the front panel. The air mass flow rate is given by:

$$\dot{m} = k\sqrt{\Delta h} \quad \text{g/sec}$$

where k = calibration constant (determined by Cussons and engraved on the unit)

Δh = differential pressure mmH_2O

The pitot-reverse pitot method is used as it is not sensitive as a pitot-static tube to flow pattern distortion effects.

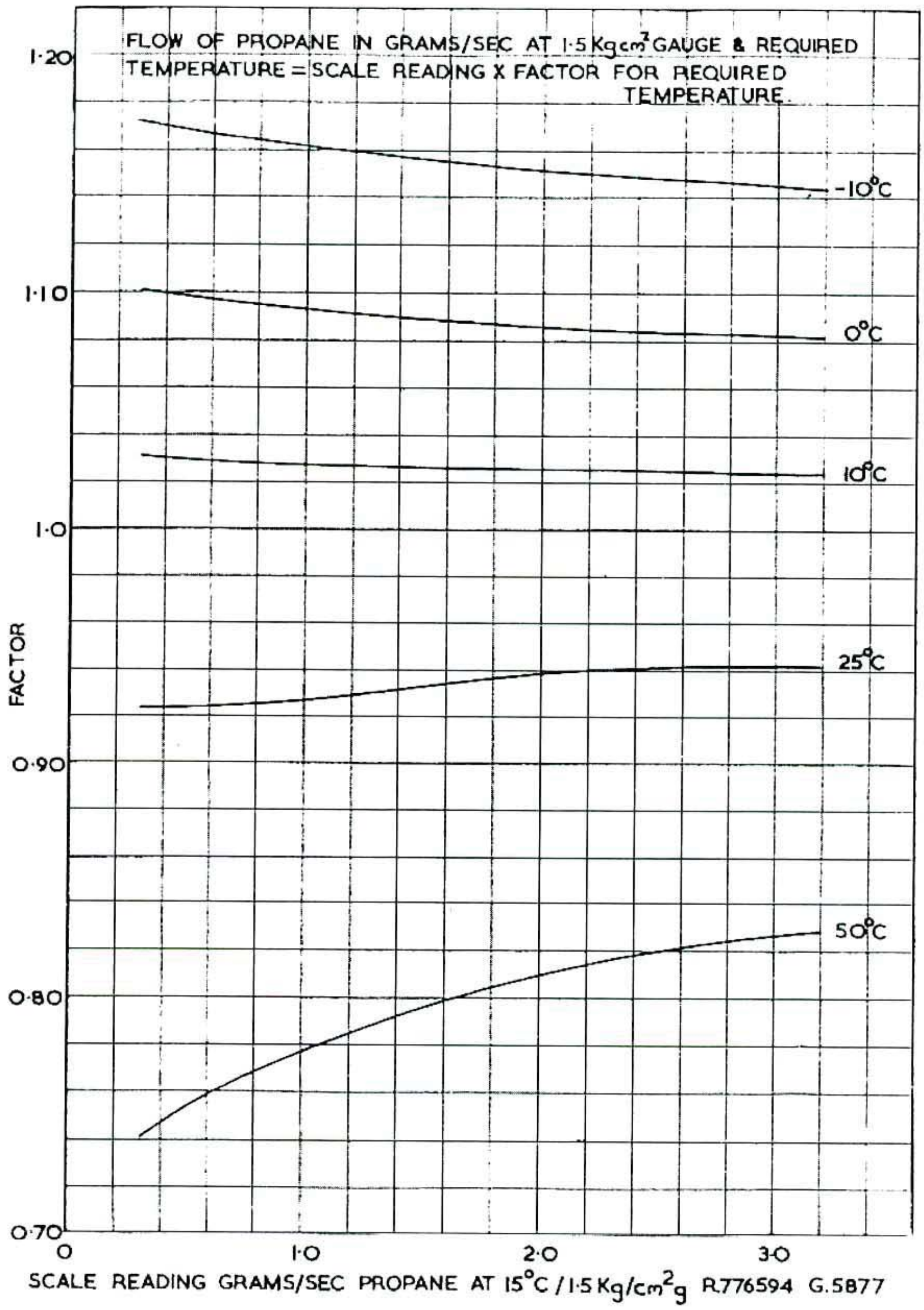


A - INLET AIR SILENCER
B - COMPRESSOR
C - COMBUSTION CHAMBER
D - GAS GENERATOR TURBINE
E - POWER TURBINE
F - EXHAUST SILENCER
G - STARTING AIR COMPRESSOR
H - DYNAMOMETER
I - OIL RESERVOIR
J - OIL PUMP
K - OIL COOLER
L - MAINS ELECTRICAL INPUT
M - OVER-TEMPERATURE CUT OUT

Figure A5 Rear view of Gas Turbine Unit.

2.8.4 Fuel Flow Rate

A conventional tapered tube and float flow meter calibrated for gaseous propane at 1.5 bar g and 15°C, is used to measure the fuel flow rate. Readings will need to be corrected for other temperatures by using figure A6.



CORRECTION FACTOR CURVES FOR FUEL FLOWMETER

REF. R768146-55 WHEN USED WITH PROPANE

AT 1.5 bar GAUGE AND VARIOUS TEMPERATURES

Figure A6 Correction factor curves for fuel flowmeter when using propane.

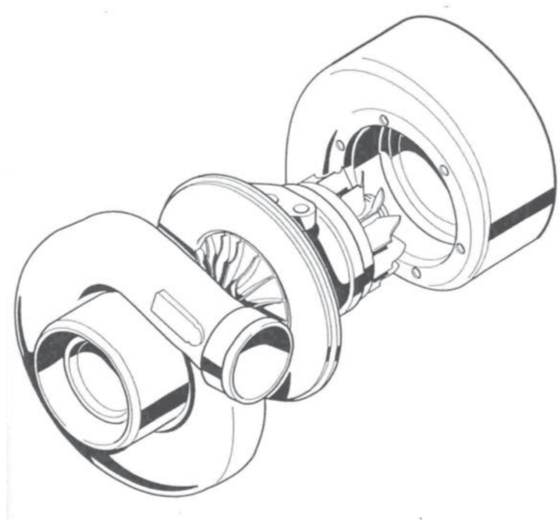


Figure A10 Compressor and gas generator turbine unit.

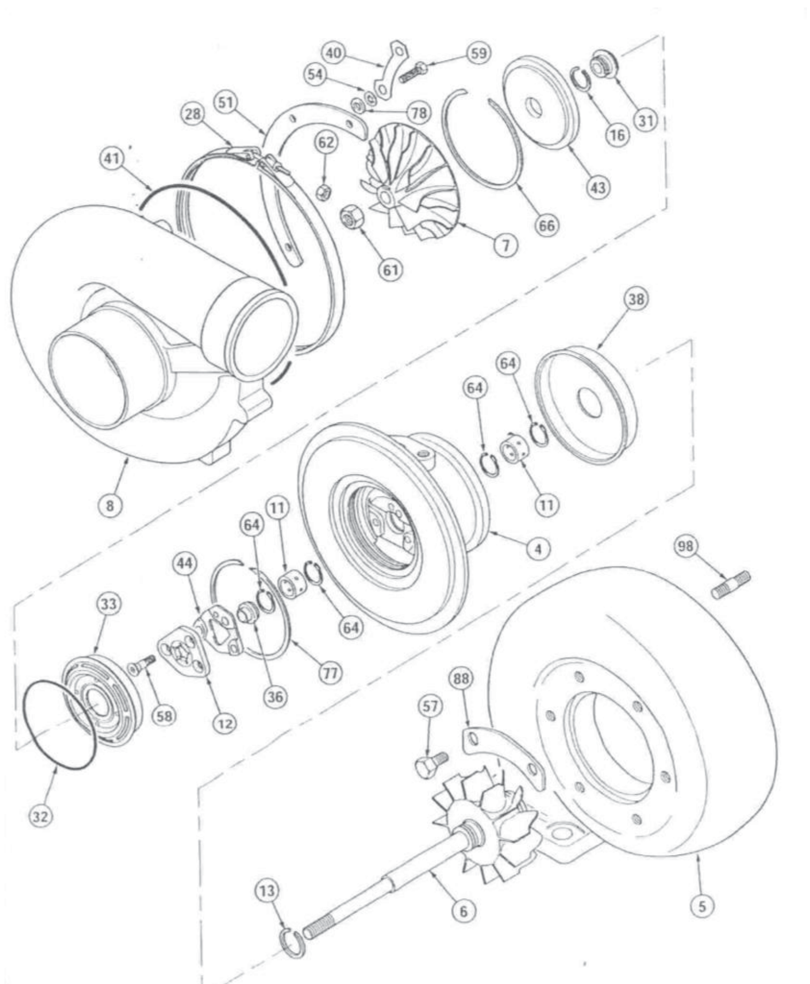


Figure A11 Exploded view of a compressor and gas generator turbine unit.

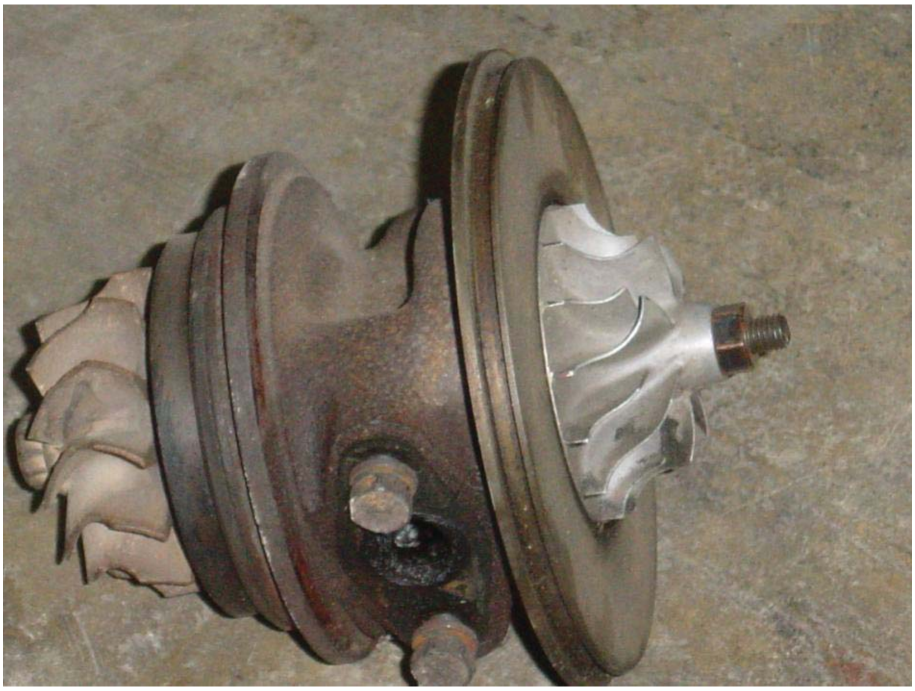


Figure A12 Example of a compressor and gas generator turbine unit.

Figure A13 The radial flow compressor.

Table A1 Thermo-Physical Properties of Air (100-1000 K at 1 atm) [3]

T (K)	ρ (kg/m^3)	c_p (kJ/kg·K)	μ (μPa·s)	ν (m^2/s)	k (W/m·K)	α (m^2/s)	Pr
100	3.6043	1.0356	7.1551	1.985E-06	0.010116	2.710E-06	0.73245
120	2.9772	1.0211	8.4995	2.855E-06	0.011996	3.946E-06	0.72349
140	2.5403	1.0142	9.7899	3.854E-06	0.013802	5.357E-06	0.71940
160	2.2169	1.0105	11.029	4.975E-06	0.015540	6.936E-06	0.71723
180	1.9674	1.0084	12.221	6.212E-06	0.017213	8.677E-06	0.71593
200	1.7688	1.0071	13.370	7.559E-06	0.018829	1.057E-05	0.71508
220	1.6068	1.0063	14.479	9.011E-06	0.020392	1.261E-05	0.71449
240	1.4721	1.0059	15.552	1.056E-05	0.021908	1.480E-05	0.71407
260	1.3584	1.0058	16.592	1.221E-05	0.023381	1.711E-05	0.71376
280	1.2610	1.0061	17.601	1.396E-05	0.024817	1.956E-05	0.71354
300	1.1767	1.0066	18.582	1.579E-05	0.026220	2.214E-05	0.71339
320	1.1030	1.0075	19.536	1.771E-05	0.027594	2.483E-05	0.71330
340	1.0380	1.0087	20.465	1.972E-05	0.028944	2.764E-05	0.71324
360	0.98022	1.0103	21.372	2.180E-05	0.030272	3.057E-05	0.71323
380	0.92856	1.0122	22.256	2.397E-05	0.031583	3.361E-05	0.71326
400	0.88208	1.0144	23.121	2.621E-05	0.032880	3.675E-05	0.71331
420	0.84004	1.0169	23.966	2.853E-05	0.034164	3.999E-05	0.71340
440	0.80183	1.0198	24.794	3.092E-05	0.035437	4.334E-05	0.71352
460	0.76695	1.0230	25.605	3.339E-05	0.036702	4.678E-05	0.71366
480	0.73497	1.0264	26.400	3.592E-05	0.037960	5.032E-05	0.71384
500	0.70556	1.0301	27.180	3.852E-05	0.039212	5.395E-05	0.71403
520	0.67842	1.0340	27.946	4.119E-05	0.040458	5.767E-05	0.71425
540	0.65329	1.0382	28.698	4.393E-05	0.041699	6.148E-05	0.71449
560	0.62995	1.0424	29.438	4.673E-05	0.042935	6.538E-05	0.71475
580	0.60823	1.0469	30.166	4.960E-05	0.044167	6.936E-05	0.71503
600	0.58795	1.0514	30.883	5.253E-05	0.045395	7.343E-05	0.71532
620	0.56898	1.0561	31.589	5.552E-05	0.046618	7.758E-05	0.71562
640	0.55120	1.0608	32.284	5.857E-05	0.047837	8.181E-05	0.71593
660	0.53450	1.0656	32.970	6.168E-05	0.049050	8.612E-05	0.71626
680	0.51878	1.0704	33.646	6.486E-05	0.050259	9.051E-05	0.71659
700	0.50396	1.0752	34.313	6.809E-05	0.051462	9.497E-05	0.71693
720	0.48996	1.0800	34.972	7.138E-05	0.052659	9.951E-05	0.71727
740	0.47672	1.0848	35.623	7.473E-05	0.053851	1.041E-04	0.71761
760	0.46417	1.0896	36.266	7.813E-05	0.055036	1.088E-04	0.71796
780	0.45227	1.0943	36.901	8.159E-05	0.056215	1.136E-04	0.71831
800	0.44097	1.0989	37.529	8.511E-05	0.057388	1.184E-04	0.71866
820	0.43022	1.1035	38.151	8.868E-05	0.058553	1.233E-04	0.71901
840	0.41997	1.1081	38.765	9.230E-05	0.059712	1.283E-04	0.71936
860	0.41021	1.1125	39.374	9.599E-05	0.060863	1.334E-04	0.71971
880	0.40089	1.1169	39.976	9.972E-05	0.062007	1.385E-04	0.72006
900	0.39198	1.1212	40.573	1.035E-04	0.063143	1.437E-04	0.72041
920	0.38346	1.1254	41.164	1.074E-04	0.064271	1.489E-04	0.72075
940	0.37530	1.1295	41.749	1.112E-04	0.065392	1.543E-04	0.72109
960	0.36749	1.1335	42.329	1.152E-04	0.066505	1.597E-04	0.72143
980	0.35999	1.1374	42.904	1.192E-04	0.067610	1.651E-04	0.72176
1000	0.35279	1.1412	43.474	1.232E-04	0.068708	1.707E-04	0.72210

*Values generated from NIST Database 23: REFPROP Version 7.0 (August 2002).

Table A1 Thermo-Physical Properties of Air (100-1000 K at 1 atm) (cont.) [3]

T (K)	ρ (kg/m^3)	c_p (kJ/kg·K)	μ (μPa·s)	ν (m^2/s)	k (W/m·K)	α (m^2/s)	Pr
1000	0.35281	1.1412	43.474	1.23E-04	0.068708	6.871E-06	0.72210
1100	0.32074	1.1590	46.258	1.44E-04	0.074077	7.408E-06	0.72372
1200	0.29402	1.1745	48.941	1.66E-04	0.079254	7.925E-06	0.72530
1300	0.27141	1.1881	51.539	1.90E-04	0.084248	8.425E-06	0.72683
1400	0.25202	1.1999	54.063	2.15E-04	0.089070	8.907E-06	0.72835
1500	0.23523	1.2103	56.524	2.40E-04	0.093733	9.373E-06	0.72986
1600	0.22053	1.2194	58.930	2.67E-04	0.098251	9.825E-06	0.73138
1700	0.20756	1.2274	61.286	2.95E-04	0.10263	1.026E-05	0.73293
1800	0.19603	1.2345	63.600	3.24E-04	0.10690	1.069E-05	0.73451
1900	0.18571	1.2409	65.877	3.55E-04	0.11105	1.111E-05	0.73614
2000	0.17643	1.2466	68.119	3.86E-04	0.11509	1.151E-05	0.73781
2100	0.16803	1.2517	70.332	4.19E-04	0.11904	1.190E-05	0.73954
2200	0.16039	1.2564	72.518	4.52E-04	0.12290	1.229E-05	0.74134
2300	0.15342	1.2607	74.681	4.87E-04	0.12668	1.267E-05	0.74320

*Values generated from NIST Database 23: REFPROP Version 7.0 (August 2002).