### Appendix C Visual Basic Functions

The VBA functions described below are available in **four** Excel VBA modules (\*.bas files):

1. modGasProps
2. modJANAF
3. modGasTurbine
4. modGTFEPG

The first two modules contain the subroutines and the functions used for property calculations.

The third module contains the subroutines and the functions for combustion and gas turbine calculations.

The fourth module contains miscellaneous subroutines and functions.

In order to use them in your Excel spreadsheet calculations, please import these four modules into your project as they are. Do NOT mix and match subroutines or functions from different modules.

### Polytropic Compressor, COMPP

This function calculates compressor power (per unit mass flow rate) and discharge properties (pressure, temperature, enthalpy and entropy) using a user-provided polytropic efficiency, compressor pressure ratio and gas composition and suction properties (pressure and temperature). The function uses JANAF properties (see section C.5).

### Polytropic Expander, TURBP

This function calculates expander power (per unit mass flow rate) and discharge properties (pressure, temperature, enthalpy and entropy) using a user-provided polytropic efficiency, expander pressure ratio and gas composition and suction properties (pressure and temperature). The function uses JANAF properties.

### Cooled Turbine, GTURBC

This function represents a simple gas turbine model with “pseudo” compressor and cooled turbine stages. The methodology is described in Chapter 8.

Table C.3. GasTurbine inputs

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| 1 | Airflow | 768.37 | 961.06 | 1487.93 | Compressor inlet airflow, lb/s |
| 2 | Fuel Flow | 14.50 | 19.27 | 36.49 | Combustor fuel flow, lb/s |
| 3 | W/S Injection | 0 | 0 | 0 | Water or steam injection (not used) |
| 4 | Exh. Frame Blower | 0.0 | 0.0 | 0.0 | Exhaust frame blower flow, lb/s |
| 5 | c,p | 93.21% | 93.21% | 93.21% | Compressor polytropic efficiency (max.) |
| 6 | t,p | 92.45% | 93.44% | 94.62% | Turbine polytropic efficiency (max.) |
| 7 | TFUEL | 99.3 | 123.7 | 195.2 | Fuel temperature, F |
| 8 | PR | 14.07 | 16.63 | 22.73 | Compressor pressure ratio |
| 9 | TIT | 2,653.0 | 2,653.0 | 2,653.0 | Turbine inlet temperature (guess) |
| 10 | RIT | 2410.0 | 2410.0 | 2410.0 | S1B inlet (firing) temperature (guess) |
| 11 | sc | 0.00% | 0.00% | 0.00% | Heat transfer to cooling steam (fraction of HC) |
| 12 | cac | 0.00% | 0.00% | 0.00% | Heat transfer to cooling air coolant (fraction of HC) |
| 13 |  | 0.90 | 0.90 | 0.90 | See Eq. (1) in Ref. [8] |
| 14 | inf | 1.00 | 1.00 | 1.00 | See Eq. (1) in Ref. [8] |
| 15 | Tb | 1400.00 | 1500.00 | 1600.00 | See Eq. (1) in Ref. [8] |
| 16 | p,in | 4.00 | 4.00 | 4.00 | Inlet pressure loss, in. wc |
| 17 | p,exh | 6.50 | 6.50 | 6.50 | Exhaust pressure loss, in. wc |
| 18 | p,comb | 5.00% | 5.00% | 5.00% | Combustor pressure loss |
| 19 | PAMB | 14.696 | 14.696 | 14.696 | Ambient pressure, psia |
| 20 | TAMB | 59.0 | 59.0 | 59.0 | Ambient temperature, F |
| 21 | comb | 0.30% | 0.30% | 0.30% | Casing heat loss |
| 22 | mech | 0.22% | 0.16% | 0.26% | Shaft mechanical loss |
| 23 | gen | 98.60% | 98.40% | 98.80% | Generator efficiency |
| 24 | Overboard Leak | 0.00% | 0.00% | 0.00% | Leakage flow |
| 25 |  | 0.85 | 0.85 | 0.85 | Turbine PR / Compressor PR |
| 26 |  | 0.000 | 0.000 | 0.000 | Auxiliary load (fraction of generator output) |
| 27 | c | 0.095 | 0.095 | 0.090 | See Eq. (1) in Ref. [8] |
| 28 | hsteam | 460.00 | 460.00 | 460.00 | Injection steam/water enthalpy |
| 29 | Comp. Bleed Stg. # | 15 | 15 | 15 | Cooling air extraction pseudo stage |
| 30 | GT Class | E | F | HA |  |
| 31 | Wnch (estimate) | 0.1559 | 0.1623 | 0.0773 | Nonchargeable flow (fraction of inlet airflow) |
| 32 | Wch (estimate) | 0.1146 | 0.1146 | 0.1146 | Chargeable flow (fraction of inlet airflow) |
| 33 | Pseudo AeN |  |  |  | Turbine swallowing capacity |
| 34 | OFFD | 0 | 0 | 0 | Design/Off-Design switch |
| 35 | C\_ch |  |  |  | Chargeable flow C-factor (off-design) |
| 36 | C\_nch |  |  |  | Nonchargeable flow C-factor (off-design) |

Table C.3. GasTurbine outputs

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| 1 | W\_GT | 115,223 | 163,627 | 345,497 | Gas turbine generator output, kWe |
| 2 | Eff\_GT | 35.03% | 37.43% | 41.73% | LHV efficiency |
| 3 | HR\_GT | 9,742 | 9,115 | 8,176 | LHV heat rate, Btu/kWh |
| 4 | w\_sp | 149.96 | 170.26 | 232.20 | Specific work, Btu/lb |
| 5 | W1 | 768 | 961 | 1,488 | Inlet airflow, lb/s |
| 6 | WFUEL | 14.50 | 19.27 | 36.49 | Fuel flow, lb/s |
| 7 | W2 | 598 | 724 | 1,162 | Compressor discharge flow, lb/s |
| 8 | W3 | 612 | 744 | 1,198 | Turbine inlet flow, lb/s |
| 9 | W4 | 716 | 900 | 1,366 | S1B inlet flow, lb/s |
| 10 | W5 | 782.9 | 980.3 | 1,524.4 | Exhaust flow, lb/s |
| 11 | T2 | 703.1 | 762.6 | 881.1 | Compressor discharge temperature, F |
| 12 | T2c | 560 | 604 | 692 | Cooling air temperature, F |
| 13 | T3 | 2,372 | 2,553 | 2,912 | Turbine inlet temperature, F |
| 14 | T4 | 2,157 | 2,280 | 2,697 | S1B inlet (firing) temperature, F |
| 15 | T5 | 1,036.1 | 1,052.9 | 1,171.1 | Exhaust temperature |
| 16 | w\_ch | 8.66% | 8.39% | 10.67% | Chargeable flow (% of airflow) |
| 17 | w\_nch | 13.56% | 16.23% | 11.27% | Nonchargeable flow (% of airflow) |
| 18 | ETACP | 91.89% | 91.80% | 91.65% | Compressor polytropic efficiency |
| 19 | ETATP | 89.34% | 90.13% | 90.79% | Turbine polytropic efficiency |
| 20 | QSC\_FRAC | 0.0 | 0.0 | 0.0 | Heat transfer to cooling steam (fraction of HC) |
| 21 | QCAC\_FRAC | 0.0 | 0.0 | 0.0 | Heat transfer to cooling air coolant (fraction of HC) |
| 22 | S1N\_Pseudo\_AeN | 1.63374 | 1.30244 | 0.76302 | Turbine swallowing capacity |
| 23 | COMP\_PR | 14.066 | 16.629 | 22.728 | Compressor pressure ratio |
| 24 | MB\_ERROR | 0.0000 | 0.0000 | 0.0000 | Mass balance error |
| 25 | HB\_ERROR | 0.0000 | 0.0000 | 0.0000 | Heat balance error |
| 26 | C\_ch | 3.00238 | 3.23253 | 5.10162 | Chargeable flow C-factor (off-design) |
| 27 | C\_nch | 3.23118 | 4.19450 | 3.45617 | Nonchargeable flow C-factor (off-design) |
| 28 | T3(ISO-2314) | 2,047 | 2,169 | 2,532 | ISO-2314 TIT, F |
| 29 | Q5\_kW | 210,989 | 269,685 | 477,212 | Exhaust energy, kWth |
| 30 | E5\_kW | 110,518 | 142,113 | 261,656 | Exhaust exergy, kWth |

### Uncooled Turbine, GTURBUC

This function encapsulates Equations 8.1 and 8.6 to model a gas turbine without explicit HGP cooling calculations. The methodology is described in Chapter 8. Inputs are described in the code itself. The function returns the gas turbine efficiency, output and exhaust temperature.

### Gas Properties

Properties for air or combustion products, which are assumed to be ideal gas mixtures, are calculated using the approach described in section 4.7 (page 130) of J. B. Heywood’s “Internal Combustion Engine Fundamentals” [1]. Heywood used JANAF table thermodynamic data in the NASA equilibrium program described in the technical note TN D-7056 [2] to generate polynomial curve-fits for specific heat, enthalpy and entropy.

The main calling function is props.

Polynomial curve-fit coefficients are in the subroutine Get\_Coefs.

Species molecular weights are in the function MW\_JANAF.

Specific heat, enthalpy and entropy polynomials are in the functions Cp\_JANAF, h\_JANAF and s\_JANAF, respectively.

Argon is not available as a separate species (not listed in the table in Ref. [1]). In order to calculate properties for a specific gas mixture containing argon (usually less than 1 percent by volume), it is lumped with the nitrogen. The error should be negligible. In the compression work calculation example in Chapter 7 (see Table 7.3), it was shown that the Thermoflex model and the COMPP function (section C.1) using PROPS indeed returned identical results. On the other hand, in the turbine expansion work calculation example (see Table 7.4), the difference between Thermoflex model and the TURBP function (section C.2) using props was quite significant, i.e., 17°F in turbine exit temperature and about 1% for turbine specific work.

### Turbine Stage, TURB\_STG

This function represents a simple gas turbine stage aero-thermodynamic model incorporating the principles covered in Chapter 10. It has a 21-element input array, i.e., Table C.6.1 below

Table C.6.1 TURB\_STG input array

|  |  |  |  |
| --- | --- | --- | --- |
|  | **INPUTS** | **Value** | **Units** |
| 1 | RPM = vInputArray(1) | 3600 | rpm |
| 2 | psi = vInputArray(2) | 2.145 | - |
| 3 | phi = vInputArray(3) | 0.6 | - |
| 4 | alfa3 = vInputArray(4) | 20 | ° |
| 5 | mdot = vInputArray(5) | 350 | kg/s |
| 6 | T1tot = vInputArray(6) 'in K | 1630 | K |
| 7 | P1tot = vInputArray(7) 'in bar | 14.2 | bar |
| 8 | Stage\_PR = vInputArray(8) | 2.5 | - |
| 9 | Eff\_uc = vInputArray(9) | 0.925 | initial guess |
| 10 | Fwd\_ws\_purge\_frac = vInputArray(10) | 0.0055 | - |
| 11 | Aft\_ws\_purge\_frac = vInputArray(11) | 0.0055 | - |
| 12 | Fwd\_ws\_momloss\_frac = vInputArray(12) | 0.035 | - |
| 13 | Aft\_ws\_momloss\_frac = vInputArray(13) | 0.03 | - |
| 14 | mdot\_c\_st = vInputArray(14) | 25 | kg/s |
| 15 | Ttot\_c\_st = vInputArray(15) | 650 | K |
| 16 | mdot\_c\_rot = vInputArray(16) | 20 | kg/s |
| 17 | Ttot\_c\_rot = vInputArray(17) | 650 | K |
| 18 | Ttot\_c\_fws = vInputArray(18) | 650 | K |
| 19 | Ttot\_c\_aws = vInputArray(19) | 555 | K |
| 20 | u1 = vInputArray(20) | 150 | m/s |
| 21 | alfa1 = vInputArray(21) | 0 | ° |

and a 24-element output array, Table C.6.2 Note that the function is very basic and set up for only a single stage. It can be repeated for a multi-stage expansion path, either in an Excel spreadsheet or inside another (main) VBA code. The model does not include the cooling flow calculations (stator and rotor cooling flows are inputs). These calculations can be easily added either inside the function itself or outside the function as a separate VBA function (the more elegant solution).

TURB\_STG is essentially a “light” version of the GASCAN code encapsulated in the “Cooled Turbine Stage” icon of Thermoflow, Inc.’s Thermoflex heat balance simulation software. It incorporates all the salient aspects of a *free vortex* design and can be used for myriad purposes.

Table C.6.2 TURB\_STG output array

|  |  |  |  |
| --- | --- | --- | --- |
|  | **OUTPUTS** | **Value** | **Units** |
| 1 | vOutputArray(1, 0) = alfa2 | 72.7 | degs |
| 2 | vOutputArray(2, 0) = alfa3 | 20.0 | degs |
| 3 | vOutputArray(3, 0) = beta2 | 57.1 | degs |
| 4 | vOutputArray(4, 0) = beta3 | 63.8 | degs |
| 5 | vOutputArray(5, 0) = Va2 | 792.0 | m/s |
| 6 | vOutputArray(6, 0) = Va3 | 250.6 | m/s |
| 7 | vOutputArray(7, 0) = Vr2 | 433.3 | m/s |
| 8 | vOutputArray(8, 0) = T\_rr | 1,386 | K |
| 9 | vOutputArray(9, 0) = T2tot | 1,571 | K |
| 10 | vOutputArray(10, 0) = mdot\_2 | 377.1 | kg/s |
| 11 | vOutputArray(11, 0) = mdot\_3 | 399.2 | kg/s |
| 12 | vOutputArray(12, 0) = Deltah\_stage | 330,508 | J/kg |
| 13 | vOutputArray(13, 0) = T2st | 1,307 | K |
| 14 | vOutputArray(14, 0) = T3st | 1,269 | K |
| 15 | vOutputArray(15, 0) = T3st\_p | 1,178 | K |
| 16 | vOutputArray(16, 0) = T3tot | 1,296 | K |
| 17 | vOutputArray(17, 0) = Stage\_PR\_short | 2.34 | - |
| 18 | vOutputArray(18, 0) = r\_m | 1.04 | m/s |
| 19 | vOutputArray(19, 0) = ht\_ratio | 0.77 | - |
| 20 | vOutputArray(20, 0) = Stg\_Rxn | 0.15 | - |
| 21 | vOutputArray(21, 0) = Eff\_uc | 92.17% | - |
| 22 | vOutputArray(22, 0) = Eff\_c | -999.000 | - |
| 23 | vOutputArray(23, 0) = Eff\_poly | -999.000 | - |
| 24 | vOutputArray(24, 0) = Ma\_u | 0.55 | - |

For supercritical CO2, please use the TURB\_STGCO2, which is very similar to the TURB\_STG. The input array is slightly different as shown in Table C.6.3. The output array is the same.

Table C.6.3 TURB\_STGCO2 input array

|  |  |  |  |
| --- | --- | --- | --- |
|  | **INPUTS** | **Value** | **Units** |
| 1 | RPM = vInputArray(1) | 3600 | rpm |
| 2 | psi = vInputArray(2) | 1.443 | - |
| 3 | phi = vInputArray(3) | 0.4 | - |
| 4 | alfa3 = vInputArray(4) | 15 | ° |
| 5 | mdot = vInputArray(5) | 1000 | kg/s |
| 6 | T1tot = vInputArray(6) 'in K | 873.2 | K |
| 7 | P1tot = vInputArray(7) 'in bar | 232.9 | bar |
| 8 | Stage\_PR = vInputArray(8) | 1.25 | - |
| 9 | Eff\_uc = vInputArray(9) | 0.8 | initial guess |
| 10 | gamma | 1.205 | - |
| 11 | c\_p | 0.269 |  |
| 12 | Efficiency Debit (for calibration) | 0.020 |  |
| 13 | r\_m (initial guess) | 0.075 | m |
| 14 | mdot\_c\_st = vInputArray(14) | 0 | kg/s |
| 15 | Ttot\_c\_st = vInputArray(15) | 650 | K |
| 16 | mdot\_c\_rot = vInputArray(16) | 0.0 | kg/s |
| 17 | Ttot\_c\_rot = vInputArray(17) | 650 | K |
| 18 | Ttot\_c\_fws = vInputArray(18) | 650 | K |
| 19 | Ttot\_c\_aws = vInputArray(19) | 555 | K |
| 20 | u1 = vInputArray(20) | 107.9 | m/s |
| 21 | alfa1 = vInputArray(21) | 5 | ° |

### Number of Turbine Stages

This function encapsulates the calculations described in section 10.3.3.

### Combustion

This function carries out the chemical balance calculations to find turbine inlet and firing temperatures. It can be used as a standalone function (see section 12.7 in Chapter 12). It can also be called from another function or subroutine doing gas turbine cycle calculations such as GasTurbine in section C.9.

Its inputs are air mass flow rate, temperature and molar composition, fuel mass flow rate, temperature and molar composition, and diluent H2O injection flow.

Its outputs are combustion products temperature and molar composition.

This function uses the calculation methodology (including tables) in section 5.2 of ASME PTC 4.4-2008 “Gas Turbine Heat Recovery Steam Generators”. Those are encapsulated in several functions and subroutines.

### Cooled Turbine, GasTurbine

This is the VBA code for the cooled gas turbine model described in detail in section 8.3. The calculation philosophy as well as detailed description of input and output arrays are covered in section 8.3. Deatiled describtion of the model is available in the paper by Gülen ([2] in Chapter 5).

### Utility Functions

In this section, several useful VBA functions developed by the author to facilitate typical gas turbine calculations are listed. They are

1. Calculation of inverse cosine function (ARCCOS)
2. Calculation of inverse tangent function (ARCTAN)
3. Calculation of secant function (SECANT)
4. One-dimensional interpolation (INTP1)
5. Two-dimensional interpolation for table look-up (INTP2)
6. Smith chart look-up (Section 10.3.1) Eff\_Smith
7. Uncooled turbine stage efficiency (Section 10.5) Eff\_341
8. The term z in Equation 10.45 (section 10.3) I\_xx\_ovr\_y\_max

### References

1. Heywood, J.B., *Internal Combustion Engine Fundamentals*, (New York, NY, USA: Mc-Graw Hill, 1988).
2. Svehla, R. A., McBride, B. J., "Fortran IV Computer Program for Calculation of Thermodynamic and Transport Properties of Complex Chemical Systems," NASA technical note TND7056, 1973 (NTIS number N73-15954).