Computer Program for Stirling Engine Performance Calculations

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National Aeronautics and Space Administration
Lewis Research Center

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The attached tables VII, VIII, and IX should be included in the report.
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I. ABSTRACT

To support the development of the Stirling engine as a possible alternative to the automobile spark-ignition engine, the thermodynamic characteristics of the Stirling engine were analyzed and modeled on a computer. The computer model is documented. The documentation includes a user's manual, symbols list, a test case, comparison of model predictions with test results, and a description of the analytical equations used in the model.

II. INTRODUCTION

The Stirling engine is being developed as a possible alternative to the spark-ignition engine under the Department of Energy's Stirling Engine Highway Vehicle Systems Program. NASA Lewis Research Center has project management responsibility for the program.

A Stirling engine performance model has been developed at Lewis to support both the project management activities and the Stirling engine test program at Lewis. An early version of the model, published in reference 1, assumed fixed heater and cooler tube temperatures. The model was then expanded to include the coolant side of the cooler and used to make predictions for comparison with the single cylinder GPU-3 Stirling engine test results (ref. 2). More recently, variable specific heats, appendix gap pumping losses and adiabatic connecting ducts have been included in the model, and it has been used to simulate one of United Stirling of Sweden's P-40 (approx. 40 kW) engines. This engine, which has four cylinders and double-acting pistons, is now being tested at Lewis. Some of the test results are reported in reference 3; this reference also compares a few of the P-40 model predictions with some of the test results. Additional test results and a description of the test facility are reported in reference 4.

This model predicts engine performance for a given set of engine operating conditions (i.e., mean pressure, boundary temperatures, and engine speed). One of the four engine working spaces is modeled, and the resultant power is multiplied by four (controls models such as the one documented in reference 5 require modeling all four working spaces). The working space model includes two pistons, the piston swept volumes - the expansion and compression spaces, three heat exchangers - heater, regenerator and cooler, and four connecting ducts. The pistons are positioned as functions of time according to the specified frequency. The working space is divided into appropriately sized control volumes for analysis. Flow resistances and heat transfer coefficients are calculated for each control volume at each time step over the engine cycle. Within each gas volume the continuity and energy equations are integrated with respect to time; a simplified momentum equation (pressure drop is a
function of a friction factor and flow rate) and an equation of state are also used in the calculations.

This report documents the current version of the Lewis Stirling engine performance model. A user's manual, symbols list, a test case and comparison of model predictions with test results for the P-40 engine are included in the documentation.

III. MODEL DESCRIPTION

The United Stirling P-40 engine, for which the test case and other model predictions were generated, is shown schematically in figure 1. The model simulates the thermodynamics of one of the four engine working spaces. The engine parts whose dimensions define the working spaces of the engine are:

1. the four pistons and four cylinders, connected in a square-four arrangement, as shown in the lower right corner schematic of Figure 1.

2. the circular array of heater tubes, the heater head, which connect the hot ends of the cylinders (expansion spaces) and the regenerators.

3. the eight regenerators (two per cylinder).

4. the eight coolers (two per cylinder) which connect the regenerators with the cold ends of the cylinders (compression spaces).

5. the four transition regions or connecting ducts per working space (expansion space-heater, heater regenerator, etc.).

The hot expansion volume over one piston (part of the blackened area in the lower right corner schematic of fig. 1) is connected via one quadrant of the circular heater tube array, two regenerators and two coolers to the cold compression space volume beneath an adjacent piston; this constitutes one of the four working spaces. The model, assuming the four working spaces contribute equal amounts of power, multiplies the power predicted for the one simulated working space by four.

The simulated working space was divided into control volumes as shown in Figure 2 for the test case. The model provides for one control volume each for the expansion space, compression space and the four connecting ducts (or, optionally, the connecting duct volumes may be lumped with the adjacent control volumes - thus neglecting the loss due to the adiabatic nature of the control volumes). For the test case, 3 heater, 5 regenerator, and 3 cooler control volumes were used. However, the heater and cooler may be divided into any number of equal sized control volumes. The regenerator may be divided into any odd number of equal-sized control volumes (the regenerator matrix temperature convergence method has been checked out only for an odd number). In addition, two (optional) isothermal appendix gap control volumes, one adjacent to the expansion space and one adjacent to the compression space, are available to evaluate appendix gap pumping losses. For all predictions discussed in this report, the 17 non-isothermal plus two isothermal appendix gap control volumes shown in Figure 2 were used in the model.

The basic computer model equations are applied to each of the control volumes. The temperatures, masses, heat transfer coefficients, flow rates,
etc. for each of the control volumes and interfaces (except the appendix gap volumes and interfaces) are represented by dimensioned variable names in the computer model. The numbering procedure used for control volume and interface variable names is defined in figure 2. The circled numbers in figure 2 correspond to control volume variables. The numbers with solid arrows correspond to interface variables. Appendix gap interfaces are labeled with numbers 0 and 17, respectively (dashed arrows); however, appendix gap volume and interface variables are represented by unique nondimensioned names in the computer model.

The model has recently been generalized to allow changing the number of heater, regenerator or cooler control volumes by resetting the appropriate parameters. Preliminary results of changing the number of control volumes are summarized in table I. It is seen that increasing the number of control volumes increases the value of the predicted power. It also increases the value of regenerator effectiveness and the required computer time (regenerator effectiveness, as used in this model, is defined in table IX).

Increasing the number of control volumes should increase the accuracy of the model, since variables which change continuously along the working space are being approximated by lumped parameters which change discontinuously from one control volume to another. However, increasing the number of control volumes costs additional computing time. Also the model already overpredicts power and efficiency for the P-40 engine with the control volume configuration of figure 2. Additional runs are needed to define how the number of control volumes affects the trade-off between computing time and accuracy. For the purpose of this documentation the 17 nonisothermal plus 2 isothermal control volumes, as shown in figure 2, were used.

The required engine operating conditions which must be input to the model are - heater tube outside wall temperatures (the combustor is not modeled), expansion and compression space inside wall temperatures, cooling water inlet temperature, cooling water flow rate, engine speed, and mean pressure. The cooler tube inside wall temperature is solved for by iteration but is constant for any one cycle. The only wall temperatures which are allowed to vary during a cycle are the regenerator matrix temperatures; a technique for speeding up the convergence of these temperatures was used to get a solution in a reasonable amount of computing time. Cylinder and regenerator housing temperatures for conduction calculations can either be inputs or can be calculated from heater and cooler input temperatures.

Losses due to imperfect heat transfer and appendix gap pumping losses are an integral part of the cycle calculations. The appendix gap pumping calculations assume isothermal appendix gaps as in reference 6. A cold appendix gap is included for the sake of generality; however, its volume is very small and its effect is negligible for the P-40 engine. Heat conduction and piston shuttle losses are calculated and are accounted for in the efficiency calculations.

The pressure drop and heat transfer calculations are based on correlations taken from Kays and London (ref. 7). The pressure drop calculations are based on a simplified momentum equation which neglects gas inertia.
Pressure drop calculations are also decoupled from the basic thermodynamic calculations for the working space to neglect pressure wave dynamics. A more rigorous modeling of pressure drop, accounting for pressure wave dynamics, would require a much smaller time step for stable calculations (with the explicit, one iteration per step, numerical integration used in this model).

In the early version of the model reported in reference 1, one pass, consisting of about 25 engine cycles, was made through the cycle calculations. In the model documented here two separate passes, using 25 engine cycles each, are usually made through the cycle calculations. The optional second pass was added to improve the modeling of the effect of pressure drop on engine performance.

Calculated power loss due to pressure drop is about the same whether one or two passes are made. However, in the second pass calculations, the effect of pressure drop on heat transfer to and from the engine is more accurately modeled; the net effect on predicted performance is to increase the basic power (power before pressure drop loss) and efficiency of the engine. More details of the method used to account for the effect of pressure drop on engine performance are discussed in appendix E.

For hydrogen at design P-40 conditions the effect of the second pass is to increase predicted brake power by about 1.2 kW (3.5 percent). For helium at design P-40 conditions a more significant increase, about 1.9 kW (9.7 percent) is found. As indicated above, the significant change is in the basic power (before pressure drop loss) and heat transfer; the power loss due to pressure drop is essentially unchanged. Since the model overpredicted power with one pass, the above changes increase the errors in predicted power. The shape of the revised predicted curve (power as function of speed at constant pressure) does however approximate more closely the shape of the experimental curve.

Real or ideal gas equations of state can be used for pure hydrogen or helium working gas. Only the ideal gas equation of state can be used for a mixture of hydrogen and carbon dioxide. Working gas thermal conductivity, viscosity and specific heats are functions of gas temperature.

Current computing time for the model is about 2.5 minutes for 50 cycles on an IBM 370 or 3 seconds per cycle. This is based on 500 iterations per engine cycle or a time step of 3X10^-5 seconds when the engine frequency is 66.7 Hz (4000 rpm). (1000 iterations per cycle were required to give satisfactory accuracy when trapezoidal integration was used for the work integration as in the model of ref. 1; it was shown there that when the number of iterations per cycle was reduced from 1000 to 200, the error in the prediction of both power and efficiency approached 10 percent; numerical stability was, however, maintained. It was then found that by switching to the more accurate Simpson rule integration, the number of iterations required for good accuracy decreased from 1000 to 500.)

The analytical model upon which the computer program is based is discussed in appendix A. The working gas temperature differential equation used in the model is derived in appendix B. The method used to numerically integrate the decoupled gas temperature differential equation is explained in appendix C. The calculation of expansion and compression space heat transfer coefficients is discussed in appendix D. The simplifications made in the general form of
the one dimensional conservation of momentum equation and the decoupled pressure drop calculations are discussed in appendix E. The symbols used in the FORTRAN source programs and the input and output datasets are defined in appendix F. Predictions of the model are compared with P-40 engine data in appendix G.

IV. USERS' MANUAL

A. Overall Simulation Structure

The overall simulation structure is shown in figure 3. The computer model consists of a main program, MAIN, and five subroutines - ROMBC, HEATX, XDEL, CNDCT, and CYCL.

In program MAIN, a data statement specifies the number of heater, regenerator, and cooler control volumes and the number of time steps per cycle. Dimensions for all control volume variables are specified in MAIN; instructions for setting the dimensions are given in comment statements in MAIN. MAIN communicates only with subroutine ROMBC.

ROMBC reads in the basic engine parameters and uses them to calculate control volume geometry; it also reads in engine operating conditions, option switches (indexes), and multiplying factors. ROMBC initializes variables and steps time and crank angle; at each new crank angle it recalculates the variable volumes and calls subroutine HEATX to update the working space heat and mass transfer calculations. ROMBC also integrates to determine work, stores working space variables for plotting, and averages working space variables over the cycle; instantaneous values of working space variable are also written out during each cycle (optional). Regenerator matrix temperature corrections, to speed up convergence, and cooler tube temperature corrections are made in ROMBC at the end of specified cycles. Subroutine CYCL is called at the end of each engine cycle to make summary calculations for the cycle. When predictions are completed for one set of operating conditions and ROMBC does not succeed in reading in a new set of input data, execution returns to MAIN for program termination.

Subroutine HEATX updates pressure, heat transfer, gas temperatures, regenerator matrix temperatures, gas flow rates and sums heat transfers over the cycle for use in energy balance and efficiency calculations. HEATX also calls subroutine XDEL to make a new calculation of engine pressure drop loss and subroutine CNDCT to calculate heat conduction losses.

Subroutine XDEL calculates pressure drop for tube and wire screen friction, tube 45, 90, and 180 degree turns, flow path contractions and expansions; subroutine calling arguments specify the type of pressure drop to be calculated and the flow geometry.

Subroutine CNDCT calculates conduction losses through the cylinder housing, piston and the regenerator housing and also shuttle losses.

Once per cycle, subroutine CYCL calculates the net heat into the engine by adding conduction, shuttle losses, etc., to the heat transferred into the working space over the previous cycle. Mechanical friction loss is calculat-
ed. Then net heat out is calculated by adding conduction, shuttle, appendix gap pumping and mechanical friction losses to the heat transferred out of the working space over the previous cycle. CYCL writes out summary results at the end of each engine cycle (optional). After the last engine cycle, CYCL calculates auxiliary losses and brake power and efficiency; it then outputs an overall summary of operating conditions and performance results.

The input data is read into ROMBC. The output data is written from either CYCL or ROMBC. The form of the input and output data will be discussed in the following two sections.

B. Program Setup

Array dimensions for all control volume variables are specified in the main program, MAIN. Several indexes which affect the choice of these dimensions are set in a data statement in MAIN; NH, NR, and NC specify the number of control volumes allotted to the heater, regenerator and cooler, respectively. The index, ISCD, is set equal to 1 to use separate control volumes for the following connecting ducts: expansion space-heater, heater-regenerator, regenerator-cooler, and cooler-compression space. If ISCD = 0 then the connecting duct volumes are lumped with adjacent control volumes. The index, NITPC, specifies the number of time steps per engine cycle (normally = 500).

The engine geometry is defined by reading the engine parameters into subroutine ROMBC. For the test case, the P-40 engine parameters shown in table II were read into ROMBC via NAMELIST/ENGINE/. For convenience, the engine parameters of table II are defined in table III. To set the model up for another engine would require changing these engine parameters, the variable volume equations in subroutine ROMBC, and the mechanical and auxiliary loss equations in subroutine CYCL; the function definition, WINT, used in the work integration in ROMBC, would also need changing to be consistent with new variable volume equations. Also, the calls to the pressure drop subroutine XDEL from subroutine HEATX should be checked to see if the types of pressure drop calculations specified are appropriate for the new engine.

The model option switches and multiplying factors and the engine operating conditions are also defined by reading the appropriate parameters into ROMBC. For the test case these parameters, as shown in table IV, were read in via NAMELIST/STRNLNG/ and NAMELIST/INDATA/. The parameters of table IV are defined in tables V and VI.

Multiple runs for a given engine can be made by adding sets of input data (table IV data), sequentially. After a run is complete the program tries to read a new set of input data; if another set of data is not found, the run terminates.

The model options and multiplying factors shown in table V are discussed below:

The parameter REALGS is set equal to 1 to use a real gas equation of state or equal to 0 to use an ideal gas equation. FACT1 and FACT2 are empirical factors used in the procedure for speeding up convergence of regenerator matrix temperatures. The current values, 0.4 and 10, respectively, have yielded
satisfactory results for all simulations attempted. The index, NOCYC, specifies the number of engine cycles to be calculated per pass; this is usually set at 25. However, there have been cases when a particular combination of operating conditions and engine parameters required as many as 40 cycles to get satisfactory convergence. (Convergence indicators are the percent errors in the engine and regenerator energy balances. These will be discussed later under Output – Test Case.) NSTRT specifies the cycle number at which the regenerator matrix and cooler temperature convergence procedures are turned on; this is usually set equal to one. The index, NOEND, specifies the cycle number at which the regenerator matrix and cooler temperature convergence procedures are turned off; this index is set at five less than NOCYC. For the last five cycles, the matrix energy equation alone determines regenerator matrix temperatures. This constitutes a check to see if the convergence procedure arrived at a temperature profile consistent with the basic matrix energy equation. (If it did not, then the percent error in the regenerator energy balance will increase during the last five cycles.) The index, MWGAS, = 2 to use hydrogen working gas or = 4 to use helium. RHCFAC, HHCFAC, and CHCFAC are multiplying factors for regenerator, heater and cooler heat transfer coefficients, respectively, for use in sensitivity studies. Set index IPCV = 0 to make a second pass through the calculations or = 1 to eliminate the second pass. The first pass calculations include a correction of engine power and an approximate correction of heat into and out of the engine for the effect of pressure drop; the second pass provides a more accurate calculation of the effect of pressure drop on heat transfer and power. FMULT and FMULTR are overall pressure drop and regenerator pressure drop multiplying factors, respectively. Set index IMIX = 1 to use a mixture of hydrogen and carbon dioxide as the working gas; the mixture is defined by the volume fraction of hydrogen, VH2, which is set next after IMIX, as shown in table V. If IMIX = 1, then REALGS should be set equal to 0 and MWGAS should be set equal to 2. IMIX = 0 for pure hydrogen or helium. Set index IPUMP = 1 to include the piston-cylinder "appendix" gap pumping loss; IPUMP = 0 omits the pumping loss calculation. Set index ICOND = 1 to calculate cylinder and regenerator housing temperatures for conduction calculations from input hot end temperatures (TM(1) and TM(4)) and the coolant inlet temperature (TH20IN). If ICOND = 0, then the specified input values of cylinder and regenerator housing temperatures are used. The remaining indexes in table V are discussed in the next section, Output Options.

The pressure drop subroutine, XDEL, is set up to calculate pressure drop due to tube friction, wire mesh friction, expansions, contractions, and 45, 90, and 180 degree turns. The desired option is specified by setting the subroutine calling argument, K, to the appropriate value of KTYPE as defined in comment statements in subroutine XDEL (KTYPE, in comment statements = K).

C. Output Options

The last five entries in table V define the output options. Three different sets of output data are available as shown in tables VII to IX. Table VII has been used primarily for debugging purposes and its shortened form, table VIII, has been used very little since the output of table IX was added.

If the index, IOUT (in table V), is set equal to 1, then the value of the index, JIP, determines whether the data of table VII or VIII is output. If JIP = 0, then summary data for each cycle, as shown in table VII is output.
If JIP = 1, the shortened form, table VIII, is output (Symbols and units used in these two tables are defined in the symbols list in appendix F). If IOUT = 0, then neither of these two tables is produced.

At the beginning of table VII, the input parameters and some of the calculated control volume parameters are output in NAMELIST write format. The remaining portion of the table contains summary data for each cycle.

For example, during the first cycle, variables are written out at TIME = 0.0, the beginning of the cycle, and TIME = 0.0150 secs., the end of the cycle. The number of time steps between these variable printouts is specified by the index, IPRINT (table V); thus with 500 time steps per cycle, IPRINT = 500 yields the two lines of printout shown for all except the last 5 cycles (per pass). For the last 5 cycles the number of time steps between variable printouts is changed to IPRINT/25 (= 20 for the test case); variations over the cycle of gas temperatures, pressures, Reynolds Numbers and gas flow rates are shown in these expanded printouts for the last 5 cycles; the last cycle in table VII shows flowrates at intervals of 20 time steps (or 25 printouts per cycle).

Most of the quantities in table VII that are determined by summing or averaging over each time step in a given cycle (such as QIN, heat in per cylinder per cycle, and QOUT, heat out per cylinder per cycle) are also printed out with definitions in table IX. There are some additional working space variable average and maximum values available in the output of table VII (and not in IX) that may be of interest. On the bottom half of the last page of table VII are average gas and metal temperatures (TGACYC, TMCYC), average and maximum heat transfer coefficients (HACYC, HMX), and, average and maximum heat fluxes (QOAAVG, QOAMX); these values are shown for expansion and compression spaces, connecting ducts, and the hot and cold end control volumes for each heat exchanger. Expansion space values are at the extreme left and compression space values are at the extreme right. Near the bottom of the page, brake power per cylinder, AUXPWR, and brake efficiency, AUXEFF, are found; these can be checked against the corresponding values in table IX for consistency.

The index, ITMPS (table V), can be set equal to 1 to print variable temperatures at each time step for debugging purposes. The index, MAPLOT, = 1 to store cycle variables for plotting or = 0 to skip the storage procedure; the particular variables to be stored are specified in the FORTRAN coding of subroutine ROMBC.

Table IX, the Final Summary Printout, is written out after the final cycle for each set of input data; no provision is made for switching off this output. Table IX includes a summary of the engine operating conditions and predicted performance. The predicted performance includes an engine energy balance. For example the brake power plus total heat rate from the engine should equal the heat rate to the engine for a perfect energy balance. The values printed out in table IX show that the energy balance error for the test case, on a 4 cylinder basis, is:
\[
\left( \frac{\text{BRAKE TOTAL HEAT RATE}}{\text{POWER FROM ENGINE}} \right) \times 100 = \left( \frac{37.239 \text{ kw} + 102.100 \text{ kw}}{138.931 \text{ kw}} - 1 \right) \times 100 = 0.294 \text{ percent}
\]

Brake and indicated engine efficiencies are also shown. Table IX also shows heat flows into and out of the engine separated into various parts. Regenerator heat flows, percent error in regenerator energy balance and two measures of regenerator effectiveness are shown; the two measures of regenerator effectiveness are defined in the table (The two most important criteria in determining whether the simulation has converged satisfactorily to a solution are the percent error in the engine energy balance and the percent error in the regenerator energy balance). Overall pressure drop is shown separated into parts by component. Maximum and minimum pressures and pressure ratios are shown for expansion and compression spaces.

D. Program Execution

Table X shows which Read/Write FORTRAN statement unit numbers, in subroutines ROMBC and CYCL, were linked with the test case input and output data. For example, item 1 in table X indicates that a read statement in subroutine ROMBC used unit number 4 to read in the input data of table II.

The P-40 simulation test case was initiated by using system commands to:

1. Link the READ unit #'s with the appropriate sets of input data as shown in table X.

2. Link the WRITE unit #'s with the desired locations for the tables of output data.

3. Execute the main program, MAIN.

V. OUTPUT--TEST CASE

A sample run was made using the input data shown in tables II and IV. The engine parameters specified in table II, the variable volume equations in subroutine ROMBC, and the mechanical and auxiliary loss equations in subroutine CYCL set the model up to simulate the United Stirling P-40 engine. The operating conditions specified in table IV correspond to a NASA Lewis P-40 experimental run which approximated the design operating conditions of the engine (15 MPa (2175 lbf/in²), 66.78 Hz (4000 rpm)). The effective outside heater tube temperature was estimated to be 930 K (1672° R); the cooling water inlet temperature was 323 K (580° R), and the cooling water flow rate was 0.860 liter/sec (13.6 gal/min).

The previously discussed tables of output data (VII to IX) were generated using the above test case operating conditions. Table IX shows that brake power and efficiency predicted for the P-40 at the specified operating conditions are 37.2 kW and 0.268, respectively. This efficiency does not ac-
count for external heat system (combustor) losses. Predicted heat flows, pressure drop losses and pressure ratios are also shown in table IX.

The index, MAPLOT, was set equal to 1 (table IV) for the test case to store the cycle variables for plotting. A separate plotting program (not documented in this report) using the IBM 370 graphics package was used to read in the stored data and make plots. The results are shown in figures 4 to 9. Expansion and compression space pressures are shown as a function of crank angle in figure 4. Expansion and compression space volumes are shown in figure 5. Expansion and compression space gas temperatures are shown in figures 6(a) and (b), respectively. They are also shown plotted to the same scale in figure 6(c). Gas flow rates out of the expansion space and into the compression space are shown in figure 7; flow is assumed positive from the expansion space toward the compression space (flow rates are also calculated at each interface between control volumes). Overall engine pressure drop (expansion space pressure minus compression space pressure) is shown in figure 8. P-V diagrams for expansion and compression space are shown superimposed in figure 9.

VI. CONCLUDING REMARKS

Testing of the United Stirling P-40 engine at NASA-Lewis has provided engine performance data for comparison with the predictions of this model. A comparison of a small portion of this data with predictions of this model is discussed in appendix G.

There are several possibly significant losses which have not been included in the model and so have not been evaluated for the P-40 engine. Papers by Kangil Lee (refs. 8 and 9) suggest that cyclic heat transfer or hysteresis loss due to heat exchange between working gas and cylinder walls may be significant for engines as small as the GPU-3. Also, no attempt has been made to evaluate losses due to non-uniform flow distribution or regenerator matrix "by-pass flow" (that is, flow near the regenerator housing that does not exchange heat effectively with the matrix and thus degrades the effectiveness of the regenerator)

The model's qualitative ability to predict variations in the state of the working gas over the cycle and to predict performance trends has been useful in helping to understand operation of the engine, to plan the experimental program, and to study sensitivity to various engine and working gas parameters. The model was recently used to generate a performance map for a 37 kW (50 hp) scaled down version of a United Stirling 67 kW (90 hp) engine design. The performance map was then input to a vehicle driving cycle code which was used to predict the fuel economy of a 37 kW Stirling engine powered vehicle.

Predictions made with helium working gas tend to result in regenerator effectivenesses that appear too high unless an adjustment is made in the slope of the temperature variation across the regenerator control volumes. A typical adjustment made for helium gas is to multiply the quantity, DTGASL, in subroutine HEATX by 0.95 (the model is set up to make this adjustment automatically when helium working gas is specified).
With relatively minor modification the model should be able to simulate Stirling cycle refrigerators or heat pumps. For the refrigerator application it would be necessary to define the working gas properties over a lower range of operating temperatures.
APPENDIX A: Analytical Model

A rigorous simulation of the gas dynamics in the working space of a Stirling engine would require solution of a set of partial differential equations. The simulation problem can be simplified by assuming the flow is essentially one-dimensional and dividing the working space into control volumes; a set of ordinary differential equations is then solved for each of the control volumes; this is the approach is used here.

Each of the control volumes shown in figure 2 is a special case of the generalized control volume shown in figure 10. The generalized control volume includes mass flow across two surfaces, heat transfer across one surface, and work interchange between gas and piston. Only the expansion and compression space control volumes are variable.

The basic equations used to model the thermodynamics of the gas in each control volume are conservation of energy, mass, momentum and an equation of state. These equations are used to determine temperature, pressure and mass distributions within the working space at a particular time.

The energy, mass and state equations, as written for the generalized control volume shown in figure 10, are as follows, where three formulations of the equations of state are shown:

Conservation of energy (for negligible change in kinetic energy across the control volume):

\[
\frac{d}{dt} (MC_v T) = hA(T_w - T) + (C_{pi} W_i T_i - C_{po} W_o T_o) - P \frac{dV}{dt}
\]  

(1)

Conservation of mass:

\[
\frac{dM}{dt} = W_i - W_o
\]  

(2)

Equation of state:

\[
PV = MRT \text{ for ideal gas}
\]

\[
PV = MR[T + 0.02358 P] \text{ for hydrogen-real gas}
\]  

(3)
PV = MR[T + 0.01613 P] for helium-real gas

where

A = heat-transfer area of control volume
Cp, Cv = heat capacities at constant pressure and volume
h = heat-transfer coefficient
M = mass of gas in volume
P = pressure
R = gas constant
T = bulk or average temperature of gas in volume
Ti, To = temperatures of gas flowing across surfaces i and o, respectively (in fig. 10)
Tw = temperature of metal wall adjacent to heat-transfer area, A
t = time
V = volume
Wi, Wo = flow rate across surfaces i and o, respectively

(The real-gas equations of state were developed from data in ref. 10)

Several assumptions are inherent in the use of these equations:

(1) Flow is one dimensional.

(2) Heat conduction through the gas and the regenerator matrix along the flow axis is neglected. The thermal conductivity of the regenerator matrix is assumed to be infinite in calculating the overall gas-to-matrix heat-transfer coefficient.

(3) Kinetic energy can be neglected in the energy equation.

(4) The time derivative term in the momentum equation is neglected (see appendix E).

In appendix B it is shown that equations (1) and (2) and the ideal-gas equation of state can be used to derive the following differential equation:

\[ \frac{dT}{dt} = \frac{hA(T_w - T) + (W_o - W_i)C_p T + (C_{p_i} W_i T_i - C_{p_o} W_o T_o) + V \frac{dP}{dt} - MT \frac{dC_p}{dt}}{MC_p} \] (4)

The same result is obtained if either of the real-gas equations of state are used in the derivation. This equation says that the bulk or average gas temperature of a control volume is a function of the following four processes:

(1) Heat transfer across the boundary from the wall

(2) Gas flow across the boundary

(3) Changes in pressure level
(4) Changes in working gas specific heat

Equation (4) can be solved for the temperature derivative to get:

\[
\frac{dT}{dt} = \frac{hA}{M C_p} (T_w - T) + \frac{(W_o - W_i)}{M} T + \frac{(C_{p_i} W_i T_i - C_{p_o} W_o T_o)}{M C_p} + \frac{V}{M C_p} \frac{dP}{dt} - \frac{T}{C_p} \frac{dC_p}{dt}
\]  (5)

The approach used in numerically integrating equation (5) (suggested by Jefferies, ref. 1) was to decouple the four processes that contribute to the temperature change and solve for the temperature change due to each process separately. This approach allows a trade-off between computing time and accuracy of solution with little concern for numerical instabilities. The approach is suggested by representation of equation (5) in the following form:

\[
\frac{dT}{dt} = \text{due to heat transfer} + \frac{dT}{dt} = \text{due to mixing} + \frac{dT}{dt} = \text{due to pressure change} + \frac{dT}{dt} = \text{due to change in specific heat}
\]

where

\[
\frac{dT}{dt} = \text{due to change in specific heat} = -\frac{T}{C_p} \frac{dC_p}{dt}
\]  (5a)

\[
\frac{dT}{dt} = \text{due to change in pressure} = \frac{V}{M C_p} \frac{dP}{dt}
\]  (5b)

\[
\frac{dT}{dt} = \text{due to mixing} = \frac{(W_o - W_i)}{M} T + \frac{(C_{p_i} W_i T_i - C_{p_o} W_o T_o)}{M C_p}
\]  (5c)

\[
\frac{dT}{dt} = \text{due to heat transfer} = \frac{hA}{M C_p} (T_w - T)
\]  (5d)

In appendix C it is shown that equations (5a), (b), and (d) can be integrated in closed form and that equation (5c) can be numerically integrated. When the results of appendix C are modified slightly to show just how they are used in the model, the resulting expressions are:
where the superscripts \( t \) and \( t+\Delta t \) denote values of the variables at times \( t \) and \( t+\Delta t \). The subscript \( S \) denotes the value of the temperature after it has been updated for the effect of change in the specific heat. The subscript \( SP \) denotes the value of the temperature after it has been updated for the effect of change in specific heat and pressure. The subscript \( SPM \) denotes the value of the temperature after it has been updated for the effects of change in specific heat, pressure, and mixing. No subscript (as on the left side of eq. (5d')) denotes the value of the temperature after it has been updated for all four effects—change in specific heat, pressure, mixing, and heat transfer to or from the metal.

**Discussion of Equations in Order of Calculation Procedure**

The equations considered so far have been derived and discussed with reference to the generalized control volume of figure 10. In the computer model these equations are applied to each of the control volumes shown in figure 2. Thus temperatures, masses, heat-transfer coefficients, flow rates, etc., are all subscripted with an index for the non-isothermal control volumes. The index varies from 1 to \( NCV \) for variables that are averages for the control volumes and from 1 to \( NCV-1 \) for variables defined at the interfaces between control volumes (as shown in fig. 2). The equations discussed in this section include these indexes. The discussion of the equations follows the steps shown in the outline of calculation procedure in figure 11.

**Update Time and Crank Angle, ROMBC (Step 1, Fig. 11):**

Time is an independent variable input to the computer model. The assumption of constant frequency means that both crank angle and time are updated by fixed steps at the beginning of each iteration. There are \( NITPC (= 500, \) usually) fixed time and crank angle steps per engine cycle.
Compression and Expansion Space Volumes, ROMBC (Step 2, Fig. 11):

Equations for expansion and compression space volumes as a function of crankshaft angle are as follows:

\[ V_e = A_p \left[ r(1. - \cos \alpha) + L \left( 1. - \sqrt{1. - \left( \frac{r}{L} \sin \alpha \right)^2} \right) \right] + V_e, \text{ clearance} \quad (6) \]

\[ V_c = A_{pr} \left[ r \left( 1. - \cos \left( \alpha + \frac{\pi}{2} \right) \right) - L \left( 1. - \sqrt{1. - \left( \frac{r}{L} \sin \left( \alpha + \frac{\pi}{2} \right) \right)^2} \right) \right] \]

\[ + V_c \text{ clearance}, \quad (7) \]

where \( V_e, \text{ clearance} \) includes the hot appendix gap volume and \( V_c, \text{ clearance} \) includes the cold appendix gap volume - only if the appendix gap pumping losses are not calculated (that is, only if the index, IPUMP = 0)

where

\( V_e \) expansion-space volume
\( V_c \) compression-space volume
\( A_p \) piston cross-sectional area
\( A_{pr} \) piston minus piston rod cross-sectional area
\( r \) crank radius
\( L \) piston rod length
\( \alpha \) crank angle

Thermal Conductivity and Viscosity Equations (Step 3):

The equations used in subroutine ROMBC to calculate gas thermal conductivity and viscosity (for hydrogen, helium and carbon dioxide) assume both quantities vary linearly with temperature. The equations are derived from data in reference 11. The mixture equations used to determine the conductivity and viscosity for a mixture of hydrogen and carbon dioxide are based on information in references 12 and 13.

Pressure (Step 4):

The pressure \( P \) is calculated by

\[ p^{t+\Delta t} = R \sum_{I=1}^{NCV} \frac{M_{I}^{t+\Delta t}}{\sum_{I=1}^{NCV} V_{I}^{t+\Delta t + \Delta t}} \quad \text{if IPUMP} = 0 \]
if IPUMP = 1

\[
\frac{M_{\text{hgp}} T_{\text{hgp}}}{V_{\text{hgp}} F_{\text{hgp}}^t} + \sum_{i=1}^{NCV} \left( \frac{M_{\text{i}}^t}{M_{\text{i}}} t + t \right) + \frac{M_{\text{cgp}} T_{\text{cgp}}}{V_{\text{cgp}} F_{\text{cgp}}^t} \quad \text{if IPUMP = 1}
\]

where

\(P\) pressure at center of regenerator

\(R\) gas constant

\(M\) control volume mass

\(T\) control volume average temperature

\(V\) control volume

\(F\) ratio of pressure in control volume to pressure at center of regenerator

\(I\) index denoting which of control volumes 1 through NCV is under consideration

\(hgp\) subscript denoting isothermal hot gap control volume

\(cgp\) subscript denoting isothermal cold gap control volume

Equations (8) are obtained by first writing the ideal-gas equation for the Ith control volume

\[P_I V_I = (F_I P) V_I = M_I R T_I\]

where

\(P_I\) pressure in Ith control volume

then summing over each of the control volumes under consideration and solving for \(P\), the pressure at the center of the regenerator.

Equations (8) indicate that if appendix gap pumping losses are included in the model (by setting IPUMP = 1), then the summation is over each of the 1 through NCV plus the two isothermal appendix gap control volumes. If appendix gap pumping losses are not included (IPUMP = 0) then the appendix gap volumes are lumped with expansion and compression space clearance volumes and the summation is only over the 1 through NCV control volumes. The appendix gap pumping loss model used is based on the one in reference 6.

If the real-gas equation of state for hydrogen is used and the same procedure is followed, the result is:
Equations (8) and (9) are both included in the model. Also an equivalent real-gas equation for helium is included. An index, REALGS (table IV), specifies whether a real or ideal equation is to be used.

The variable, $F$, represents an array of pressure ratios with different values for each control volume at each time step over an engine cycle. $F$ is used above to evaluate the effect of the decoupled pressure drop calculations on pressure level at the center of the regenerator. $F$ is defined as follows:

During the first pass through the calculations (NOCVC cycles), each element of $F = 1$. At the end of the first pass, pressure drop information for each control volume at each time step is stored in $F$; each element represents the ratio of pressure at a particular control volume and increment of time to pressure at the center of the regenerator. Thus the array appears as:

$$F_{i,k} = \begin{bmatrix}
F_{1,1} & F_{1,2} & \cdots & F_{1,NRC-1} & 1 & F_{1,NRC+1} & \cdots & F_{1,NCV} \\
F_{2,1} & F_{2,2} & \cdots & F_{2,NCR-1} & 1 & F_{2,NRC+1} & \cdots & F_{2,NCV} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\
F_{FNITPC,1} & F_{FNITPC,2} & \cdots & F_{FNITPC,NRC-1} & 1 & F_{FNITPC,NRC+1} & \cdots & F_{FNITPC,NCV}
\end{bmatrix}$$

(rows (time increases) \hspace{1cm} \begin{array}{c}
NITPC \\
\text{NITPC}
\end{array} \hspace{1cm} \begin{array}{c}
NCV \text{ columns}
\end{array}$$
where
\[ NCV = 17 \]
\[ NRC = 9 \]

time steps per engine cycle, \( \text{NITPC} = 500 \) for the sample runs.

This array of pressure drop information is used in the second pass (NOCYC additional cycles).

The second pass, using the array \( F \), was incorporated to get a more accurate evaluation of the effect of the decoupled pressure drop on the thermodynamic calculations. The method is discussed in more detail in appendix E.

**Update Gas Specific Heats (Step 5):**

The equations used to calculate gas specific heats in subroutine HEATX assume a quadratic variation with temperature (except for helium whose specific heat is essentially constant over the temperature range of interest). The equations are derived from data in reference 11.

**Update Temperatures for Effect of Change in Specific Heat (Step 6):**

Introducing the control volume index, \( I \), into equation (5a'), the form of the equation used to correct gas temperatures for the effect of changes in specific heat is:

\[
T_{I,s}^{t+\Delta t} = T_{I,s}^{t} \frac{C_{p,I}^{t}}{C_{p,I}^{t+\Delta t}}
\]

(10)

**Update Temperatures for Effect of Change in Pressure (Step 7):**

\[
T_{I,sp}^{t+\Delta t} = T_{I,s}^{t} \left( \frac{p_{I,t+\Delta t}}{p_{I,t}} \right) \]

(11)

This equation is commonly used to relate temperature and pressure for an adiabatic fixed-mass process.

**Mass Distribution (Step 8):**

On the first pass through the calculations the mass distribution is determined by assuming that the mass redistributes itself in accordance with the
new volumes and temperatures in such a way that pressure is uniform throughout the working space. The pressure, $P$, throughout the working space is derived from the perfect-gas law as follows:

The perfect-gas law for the $i$th control volume can be written

$$M_i = \frac{F_i PV_i}{RT_i}$$

Summing over the NCV control volumes (and the two isothermal appendix gaps control volumes if $IPUMP = 1$)

$$M_{TOTAL} = \sum_{i=1}^{NCV} M_i = \frac{P}{R} \sum_{i=1}^{NCV} \frac{F_i V_i}{T_i}$$

if $IPUMP = 0$

$$= M_{hgp} + \sum_{i=1}^{NCV} (M_i) + M_{cgp} = \frac{P}{R} \left[ \frac{F_i V_{hgp}}{T_{hgp}} + \sum_{i=1}^{NCV} \left( \frac{F_i V_i}{T_i} \right) + \frac{F_{NCV} V_{cgp}}{T_{cgp}} \right]$$

if $IPUMP = 1$

Solving for $P/R$ for the case, $IPUMP = 0$, gives

$$\frac{P}{R} = \frac{M_{total}}{\sum_{i=1}^{NCV} \frac{F_i V_i}{T_i}} \quad IPUMP = 0$$

Now substituting for $P/R$ into the perfect-gas equation for the $i$th control volume gives

$$M_i = \frac{M_{total}}{\sum_{i=1}^{NCV} \frac{F_i V_i}{T_i}} \quad IPUMP = 0$$

The form of this equation used in the model to calculate the working gas mass in each of the NCV control volumes is:
The preceding equation calculates the new mass distribution for the case of a perfect gas. The following equation, which can be derived in the same manner, is used to approximate the real properties of hydrogen for the case of no appendix gap pumping loss:

\[
M_{I}^{t+\Delta t} = \frac{F_{I}^{t+\Delta t} V_{I}^{t+\Delta t}}{T_{I,sp}^{t+\Delta t}} \sum_{I=1}^{NCV} \left[ \frac{F_{I}^{t+\Delta t} V_{I}^{t+\Delta t}}{T_{I,sp}^{t+\Delta t}} \right] \quad (13)
\]

A similar equation that approximates the real properties of helium is included in the model.

When appendix gap pumping losses are included (IPUMP = 1) then the summations used in deriving the equivalents of equations (12) and (13) are over the 1 through NCV plus the two isothermal appendix gap control volumes.

**Flow Rates (Step 9):**

Once the new mass distribution is known, the new flow rates are calculated from the old and new mass distributions according to

\[
W_{0} = \frac{M_{o}^{t} - M_{o}^{t+\Delta t}}{\Delta t} \quad \text{if IPUMP} = 1
\]

and

\[
(14)
\]
where

\[ W_I = \frac{M^t_I - M^{t+\Delta t}_I}{\Delta t} + W_{I-1} \]

or

\[ I = 1, NCV \text{ if } IPUMP = 1 \]

\[ I = 1, NCV - 1 \text{ if } IPUMP = 0 \]

Mo = mass in hot appendix gap if IPUMP = 1 (not used if IPUMP = 0)

Wo = FHGP, flow from hot gap to expansion space, if IPUMP = 1 (not used if IPUMP = 0)

W_{NCV} = FCGP, flow to cold gap from compression space, if IPUMP = 1 (not used if IPUMP = 0)

\( W_I \) = is the flow rate at the Ith interface between control volumes.

Update Temperatures in Each Control Volume for Effect of Gas Flow Between Control Volumes (Step 10):

The following equation (modification of eq. (5c'1)) was used to update temperature for the mixing effect following gas flow between control volumes:

\[
T^{t+\Delta t}_I = \frac{M^t_I}{M^{t+\Delta t}_I} T^{t+\Delta t}_{I,sp} + \frac{C_{pI} W_I t^{t+\Delta t}_I \theta_{I-1} - C_{pI} W_I t^{t+\Delta t}_I \theta_{I-1}}{M^{t+\Delta t}_I C_{pI}} \ (15)
\]

where the temperature \( T^{t+\Delta t}_{I,sp} \) has already been updated for specific heat change and pressure change.

The temperature of the fluid flowing across the interface has been given a new variable name, \( \theta_I \), to better distinguish it from the average control volume temperature, \( T_I \), and to keep the subscripts as simple as possible. The procedure used to update the temperature, \( \theta_I \), for each interface is now defined.

The temperature of the fluid flowing across a control volume boundary is just the bulk temperature of the control volume from which the fluid came - for flow from the expansion space, heater, cooler, or compression space control volumes or hot and cold appendix gap volumes. This is a reasonable assumption for these volumes since the actual temperature gradient across each is expected to be relatively small. In a five-control-volume regenerator, however, the temperature gradient is not small. One option would be to increase the number of control volumes in the regenerator. However, to save computing time, an alternative approach was used. It was assumed that a temperature gradient existed across each volume in the regenerator. The magnitude of the gradient was assumed to be equal to the corresponding regenerator metal gradient.
A schematic of a regenerator control volume is shown in figure 12(a). Flow across both interfaces is, for now, assumed to be in the direction shown (which is defined to be the positive flow direction). The cross-hatched area represents the portion of the fluid that will flow across interface I during the time step, $\Delta t$. The assumed temperature profile of the control volume is characterized in figure 12(b). The vertical dashed line in figure 12(b) defines the temperature at the left boundary of the fluid that will flow across interface I during $\Delta t$. If $T_I$ is defined as the average temperature of control volume I and $\Delta T_I$ equals one-half the change in temperature across the control volume, then $T_I - \Delta T_I$ is the temperature of the fluid at interface I and

$$T_I - \Delta T_I + \frac{W_I \Delta t}{M_I} 2 \Delta T_I$$

is the temperature of fluid at the vertical dashed line. (figure 2 shows the numbering methods used for the control volumes and the interfaces between control volumes).

The temperature of the fluid that flows across an interface during $\Delta t$ is assumed to be equal to the average temperature of that fluid before it crosses the interface. The average temperature of the fluid in the cross-hatched area of figure 12(a) is then

$$\frac{1}{2} \left[ \left( T_I - \Delta T_I + \frac{W_I \Delta t}{M_I} 2 \Delta T_I \right) + (T_I - \Delta T_I) \right] = T_I - \Delta T_I + \frac{W_I \Delta t}{M_I} \Delta T_I$$

Therefore, for the flow directions shown in figure 12(a), the updated temperatures of the fluid that crosses the interfaces during $\Delta t$ are

$$\theta^{t+\Delta t}_I = T_{I,SP} - \Delta T_I + \frac{W_I^{t+\Delta t} \Delta t}{M_I^{t}} \Delta T_I, \ W_I^{t+\Delta t} > 0$$

(16)

$$\theta^{t+\Delta t}_{I-1} = T_{I-1,SP} - \Delta T_{I-1} + \frac{W_{I-1}^{t+\Delta t} \Delta t}{M_{I-1}^{t}} \Delta T_{I-1}, \ W_{I-1}^{t+\Delta t} > 0$$

If the flow direction is reversed at both interfaces, then
Heat Transfer Coefficients (Step 11):

The heat transfer coefficient calculations for heater and cooler are derived from figure 7-1, page 123 of reference 7; heat transfer coefficient calculations for the regenerator are derived from figure 7-9, page 130 of the same reference. The assumption used in calculating heat transfer coefficients for the expansion and compression spaces are discussed in appendix D.

Update Temperature in Each Gas Control Volume for Effect of Heat Transfer Between Gas and Metal (and Determine Heat Transfer Between Gas and Metal) (Step 12):

This temperature update for control volumes 1 through NCV is accomplished by using the following equation (a modification of equation (5d')):

\[
T_{I}^{t+\Delta t} = T_{I,SPM}(T_{W,I} - T_{I,SPM}) \left[ 1 - e^{-\left(\frac{h_{I}^{t+\Delta t}A_{I}}{M_{I}^{t+\Delta t}C_{p_{I}}^{t+\Delta t}}\right)\Delta t} \right]
\]

where \( T_{W,I} \) is the wall temperature of the \( I \)th control volume. Note that, no matter how large the heat-transfer coefficient, the gas temperature cannot change more than the \( \Delta T \) between the wall and the gas. Thus this calculation cannot cause the solution to become unstable, but it can lead to significant inaccuracies if the time increment, \( \Delta t \) is made too large.

The heat transferred between gas and metal is then calculated from:

\[
Q_{I}^{t+\Delta t} = -(T_{I}^{t+\Delta t} - T_{I,SPM})M_{I}^{t+\Delta t}C_{p_{I}}^{t+\Delta t}
\]

so that heat transfer from gas to metal is defined to be positive.

The appendix gap control volumes are assumed to be isothermal. Three steps are used to calculate the heat transfer between the cylinder wall and the appendix gap working gas that would be required to maintain constant gap temperature.
For the hot appendix gap:

1. The change that would occur in appendix gap temperature due to pressure change if there were no heat exchange with the cylinder wall is:

\[ \Delta T_{hgp} = T_{hgp} \left( \frac{R}{C_{p_{hgp}}} \right) \left( p_t^{t+\Delta t} F_1^{t+\Delta t} \right) \]

where

- \( R \) is the gas constant.
- \( C_{p_{hgp}} \) is the specific heat at constant pressure.
- \( F_1 \) is used since there is assumed to be no pressure drop between the hot gap and the expansion space.

2. The net change that would occur in appendix gap temperature due to pressure change and mixing, if there were no heat exchange, is calculated by adding an additional "mixing" term to the above expression when there is flow from the expansion space to the appendix gap. That is:

\[ \Delta T_{hgp} = \Delta T_{hgp} + \left( \frac{M_{hgp}^{t+\Delta t} - M_{hgp}^t}{M_{hgp}^{t+\Delta t}} \right) C_{p_{hgp}}^{t+\Delta t} \left( T_{hgp} - W_{o} C_{p_{hgp}}^{t+\Delta t} T_{hgp}^{t+\Delta t} \right) \]

where

- \( hgp \) is a subscript denoting quantities within the hot gap control volume.
- \( hgp_I \) is a subscript denoting variable values at the flow interface between the expansion space and the appendix gap.

3. The rate of heat exchange with the cylinder wall required to maintain an isothermal appendix gap is then calculated to be:

\[ Q_{hgp} = \Delta T_{hgp} M_{hgp}^{t+\Delta t} C_{p_{hgp}} \]

A similar set of calculations is made for the cold appendix gap.

Regenerator Metal Temperature (Step 13):

The equation used to update the metal temperatures in the regenerator control volumes is
\[
M_I C \frac{dT_{w,I}}{dt} = Q_I \quad I=NR1,NRL \tag{19}
\]

where \(Q_I\) is the rate of heat transfer between gas and metal. This is integrated numerically by setting

\[
T_{w,I}^{t+\Delta t} = T_{w,I}^t + \frac{Q_{I}^{t+\Delta t}}{M_{I} C} \Delta t \tag{20}
\]

where

- \(M_I\) mass of metal in \(I\)th volume
- \(C\) thermal capacitance of metal
- \(\Delta t\) time increment

For most regenerators, the thermal capacitance of the metal is so much larger than the thermal capacitance of the adjacent gas volume that an excessive number of engine cycles (from the point of view of computing time) are required to reach steady state. Therefore, it is necessary to apply a correction to the metal temperatures after each cycle to speed up convergence. The method used is discussed in a later section.

Pressure-drop Calculations (Step 14):

Since the pressure-drop calculations have been decoupled from the heat and mass transfer calculations, pressure drop need not be re-calculated over every cycle. Pressure drops are re-calculated only every third cycle. Thus the indicated work calculation is corrected using the most recently calculated loss.

A general form of the conservation of momentum equation for one-dimensional flow is:

\[
\frac{\partial}{\partial t} (\rho v) = \frac{\partial}{\partial x} (\rho v^2) - \frac{\partial}{\partial x} \left( \frac{1}{2} \rho v^2 \right) - \frac{\partial p}{\partial x} \tag{21}
\]

Rate of Rate of Rate of Rate of
accumulation momentum momentum momentum
of momentum gain by gain by viscous gain due to
per unit convection per transport per pressure force
volume unit volume unit volume per unit volume
where

$\rho$  density
$v$  velocity of flow
$f$  friction factor
$D_h$  hydraulic diameter
$P$  pressure
$t$  time
$x$  distance

In appendix E it is shown that by combining the continuity and momentum equations and then neglecting the time derivative term in the resulting equation, the following equation results:

$$v dv + \frac{f v^2}{2 D_h} dx + \frac{dP}{\rho} = 0 \tag{22}$$

This equation can be integrated over a length $L$ for the special cases of adiabatic or isothermal flow processes (the two extremes). When the resulting adiabatic and isothermal expressions were applied to the P-40 heat exchangers (by setting index, $K$, appropriately in the call to subroutine XDEL from subroutine HEATX for heat exchanger pressure drop calculations), the contribution of the $vdv$ term was negligible for the two extremes. By neglecting the $vdv$ term, the expression for pressure drop is reduced to

$$\frac{f v^2}{2 D_h} dx + \frac{dP}{\rho} = 0 \tag{23}$$

or applying the differential equation (23) over a finite length $L$

$$\Delta P = \frac{f}{2 D_h} \frac{1}{\rho} v^2 L \tag{24}$$

where $\Delta P$ is the pressure drop over length $L$ (using the adiabatic or isothermal forms of the pressure drop equation with the $vdv$ term retained requires an iterative solution procedure which increases computing time by about 20 percent).

A modification of this equation can also be used to account for the effect of expansions and contractions in flow area. The form of the modified equation is:

$$\Delta P = K \frac{1}{2} \rho v^2 \tag{25}$$
It is applied at each area change in the flowpath between the expansion and compression spaces. At a particular point where an area change occurs, \( K \) is a function of the two areas and the direction of flow (since an expansion for one flow direction is a contraction when the flow reverses). The term, \( K \), is calculated in accordance with the procedure given in references 14 and 15. Values of \( K \) are also specified to account for pressure drop due to tube bends.

The types of pressure drop calculations that can be made in subroutine XDEL are specified by the calling argument, \( K \), and are defined in comment statements in the subroutine (KTYPE, in comment statements = \( K \)).

For the heater and cooler control volumes the friction factor, \( f \), is determined from equations based on figure 7-1, page 123 of reference 7. The friction factor for the regenerator is derived from figure 6.3-1, page 6-35 of reference 16.

With the pressure level, \( P \), known (assumed to be the pressure at the center of the regenerator) and the \( \Delta P \)'s across each of the control volumes calculated, the pressures needed in the work calculations, \( P_e \) and \( P_c \), can be calculated as follows:

\[
P_e = \sum_{I=2}^{NRC-1} \Delta P_I + \frac{\Delta P_{NRC}}{2} + P
\]

\[
P_c = P - \frac{\Delta P_{NRC}}{2} - \sum_{NRC+1}^{NCV-1} \Delta P_I
\]

Near the end of the first pass the pressure drop information for each control volume over a complete cycle is incorporated into the array of pressure ratios (discussed under step 4) for use in the second pass.

Heat Conduction From Hot End to Cold End of Engine and Shuttle Loss (Step 15):

Three separate paths were considered in the calculation of heat conduction losses from the hot end to the cold end of the engine:

(1) Through each of the regenerators

(2) Through the cylinder wall

(3) Through the wall of the piston from the hot space to the cold space

The effect of temperature on metal conductivity was accounted for.
The piston picks up heat from the cylinder at the hot end of its stroke and loses heat to the cylinder at the cold end of its stroke. This shuttle loss is calculated by using the following equation from reference 17:

\[
Q_{\text{shuttle}} = \frac{K\pi DS^2 \Delta T}{8CL}
\]

(26)

where

- \(K\) thermal conductivity of gas
- \(D\) piston diameter
- \(S\) stroke
- \(\Delta T\) temperature difference across displacer length
- \(C\) clearance between displacer and cylinder
- \(L\) displacer length

The conduction and shuttle losses are calculated once per cycle. The calculations could be made just once per run except that the conduction through the piston is assumed to depend on the average gas temperature (The conduction through the piston is sufficiently small for the P-40 that a once per run calculation would yield very little error.)

**Sum Up Heat Transfers Between Gas and Metal for Each Component (Step 16):**

The basic heat into the working space per cycle is the sum of the net heat transfer from metal to gas in the heater and expansion-space control volumes over the cycle. The basic heat out of the working space per cycle is the sum of the net heat transfer from the gas to the metal in cooler and compression-space control volumes per cycle. Since it is assumed that there are no losses from the regenerator matrix, the net heat transferred between gas and metal in the regenerator over a cycle should be zero. This net heat transfer in the regenerator over the cycle is the most convenient criterion for judging when convergence of regenerator metal temperatures has been achieved.

The net heat into the engine is the basic heat (as defined above) plus conduction and shuttle losses. The net heat out of the engine is the basic heat out plus conduction, shuttle, appendix gap losses, mechanical losses and auxiliary power losses. Conduction, shuttle, appendix gap and mechanical losses (and any heat transfer out via the compression space) are assumed to pass into the cooling water but not through the cooler tubes (there are cooling water flow passages in contact with the cylinder). It is arbitrarily assumed that the auxiliary power requirement does not increase the heat load on the cooling water but is dissipated via convection and radiation to the surroundings.
Work Calculations (Step 17):

The indicated work, neglecting pressure drop loss, is calculated according to:

\[ W = \int P(dV_e + dV_c) \]  

The indicated work, accounting for pressure drop loss, is calculated according to:

\[ W = \int (P_e dV_e + P_c dV_c) \]  

From the volume equations for the P-40 engine, (6) and (7) it is found that

\[ dV_e = A_p r \sin \alpha \left[ 1 + \frac{\frac{r}{L} \cos \alpha}{\sqrt{1 - \left(\frac{r}{L} \sin \alpha \right)^2}} \right] d\alpha \]

\[ dV_c = -A_{pr} r \sin \left(\alpha + \frac{\pi}{2}\right) \left[ 1 + \frac{\frac{r}{L} \cos \left(\alpha + \frac{\pi}{2}\right)}{\sqrt{1 - \left(\frac{r}{L} \sin \left(\alpha + \frac{\pi}{2}\right)\right)^2}} \right] d\alpha \]

or, defining

\[ F(P,A,\phi) = PAR \sin \phi \left[ 1 + \frac{\frac{r}{L} \cos \phi}{\sqrt{1 - \left(\frac{r}{L} \sin \phi \right)^2}} \right] \]

then

\[ W = \int (P_e dV_e + P_c dV_c) \]

\[ = \int \left[ F(P_e, A_p, \alpha) + F\left(P_c, A_{pr}, \alpha + \frac{\pi}{2}\right) \right] d\alpha \]

\[ = f(\alpha) d\alpha \]
The above integration over a cycle was accomplished numerically using Simpson's rule integration, that is:

\[
\int_{a_0}^{a_2} \left( p_e dV_e + p_c dV_c \right) = \int_{a_0}^{a_2} f(a) da = \frac{a_2^2 - a_0^2}{3} \left[ f(a_0) + 4f(a_1) + f(a_2) \right]
\]

A number of additional work calculations were made to separate the work loss due to pressure drop for each of the components and for the end effects.

The chart in table XI shows how the various pressure and work parameters were made equivalent to arrays to allow reducing the number of programming steps required for the calculations; this chart is included only as an aid in following the FORTRAN programming steps of subroutine ROMBC.

**Is Cycle Complete? (Step 18):**

The number of iterations made during the current engine cycle is checked to see if the cycle is complete. If the cycle is not complete, then the model loops back to step 1 and another iteration is begun.

**Convergence Method for Regenerator Metal Temperatures (Step 19):**

The correction to regenerator matrix temperatures between cycles to speed up convergence (suggested by Jefferies, ref. 1) is made as follows:

\[
\Delta T_I = \frac{\sum_{TIME=0}^{TIME=N\Delta t} \left( T_{w,I} - T_I \right) \left[ 1 - e^{-\left( \frac{h_I A_I}{M_I C_p} \right) \Delta t} \right]^{M_I}}{\sum_{TIME=0}^{TIME=N\Delta t} \left[ 1 - e^{-\left( \frac{h_I A_I}{M_I C_p} \right) \Delta t} \right]^{M_I}}
\]  

where

\( N \) number of iterations per cycle

\( \Delta T_I \) weighted average difference between wall and gas temperature over cycle for Ith regenerator control volume

\( T_I \) Ith gas temperature (instantaneous average over control volume)

\( T_{w,I} \) Ith wall temperature

Then let
\[ \Delta I = \Delta I_{i,\text{OLD}} \times \text{FACT}_1 + \Delta I \times \text{FACT}_2 \quad \text{I}=\text{NR1, NRL} \]

where \( \text{FACT}_1 = 0.4 \) and \( \text{FACT}_2 = 10.0 \) are the factors that were found to work best when the method was originally developed. (These factors were not re-optimized for the P-40 engine). The final step in the correction is:

\[
T_{w,\text{NR1,NEW}} = T_{w,\text{NR1,OLD}} - (R_{C1,1} \times \Delta T_{\text{NR1}} + R_{C1,2} \times \Delta T_{\text{NR1+1}} + \ldots + R_{C1,NR} \times \Delta T_{\text{NRL}})
\]

\[
T_{w,\text{NR1+1,NEW}} = T_{w,\text{NR1+1,OLD}} - (R_{C2,1} \times \Delta T_{\text{NR1}} + R_{C2,2} \times \Delta T_{\text{NR1+1}} + \ldots + R_{C2,NR} \times \Delta T_{\text{NRL}})
\]

\[
T_{w,\text{NRL,NEW}} = T_{w,\text{NRL,OLD}} - (R_{CNR,1} \times \Delta T_{\text{NR1}} + R_{CNR,2} \times \Delta T_{\text{NR1+1}} + \ldots + R_{CNR,NR} \times \Delta T_{\text{NRL}})
\]

where the coefficients \( R_{C_i,k} \) are calculated as follows:

For \( k \geq i \), \( R_{C_i,k} = \frac{(\text{NR} + 1 - k)\text{NR}}{\sum_{k=1}^{\text{NR}} k} \) \quad \text{if } i = 1

\[
= i \times R_{C_1,k} \quad \text{if } i \neq 1
\]

for \( k < i \), \( R_{C_i,k} = R_{C_k,i} \)

For \( \text{NR}=5 \) (that is, 5 regenerator control volumes) the coefficients generated by the above equations are:

\[
R_{C_i,k} = \begin{bmatrix}
5 & 4 & 1 & 2 & 1 \\
3 & 3 & 3 & 3 & 3 \\
4 & 8 & 4 & 2 & 3 \\
3 & 3 & 3 & 3 & 3 \\
1 & 2 & 3 & 2 & 1 \\
2 & 4 & 2 & 8 & 4 \\
3 & 3 & 3 & 3 & 3 \\
1 & 2 & 4 & 5 & 1 \\
3 & 3 & 1 & 3 & 3
\end{bmatrix}
\]
Calculated Indicated Power and Efficiency (Step 20):

Indicated efficiency is defined to be the indicated work divided by the net heat into the engine (per cycle).

Calculate Mechanical (Plus Leakage) Loss (Step 21):

The mechanical loss calculations for the engine are based on information obtained from United Stirling.

The mechanical loss per engine (4 cylinders) is assumed to be:

\[ M.L. = 12.8 \frac{N}{N_D} \left( \frac{P + 5}{20} \right) \]

where:

- \( M.L. \) mechanical loss/cylinder in KW
- \( N \) engine speed
- \( N_D \) design engine speed
- \( P \) mean pressure in MPa

This "mechanical loss" is also assumed to include loss due to leakage. A plot generated with this equation is shown in figure 13.

Calculate Auxiliary Losses and Brake Power and Efficiency (Step 22):

A plot of the auxiliary power requirement is shown in figure 14. The only auxiliary power requirement assumed to change significantly with the mean pressure level is that of the combustion blower. The auxiliary power requirement for mean pressures between 15 and 4 MPa is obtained by interpolating between the two curves. The lower curve is assumed to define the minimum auxiliary power requirement.

Brake power is defined to be indicated power minus mechanical friction and auxiliary losses. Brake efficiency is defined to be the brake power divided by the net heat rate into the engine. The net heat rate into the engine is defined to be the net heat transfer from metal to gas in the heater and expansion space plus conduction and shuttle losses.

Convergence Method for Cooler Tube Temperatures (Step 23):

The cooler tube temperature is a function of cooling water inlet temperature and flow rate, and the rate of heat out through the cooler. Since the rate of heat out through the cooler is a function of cooler tube temperature, an iterative procedure is required to solve for cooler tube temperature.

The cooler tube temperature is updated every third cycle during the same period that the regenerator matrix temperature convergence procedure is operative. The procedure used is outlined as follows:
\[ \mathbf{T}_{H_2O} = \mathbf{T}_{H_2O, IN} + \frac{Q_{H_2O, OUT}}{2C_{p,H_2O}W_{H_2O}} \]

where

\( \mathbf{T}_{H_2O} \)  
average coolant temperature

\( \mathbf{T}_{H_2O, IN} \)  
inlet coolant temperature

\( Q_{H_2O, OUT} \)  
rate of heat out through coolant

\( C_{p,H_2O} \)  
coolant specific heat

\( W_{H_2O} \)  
coolant flow rate

Calculate water side heat transfer coefficient using the following two steps to incorporate a fouling factor:

1. \( h_1 = \frac{12k_{H_2O}}{0.350N_{Re}^{0.55}N_{Pr}^{-0.333}} \)

2. \( h = \frac{1}{\frac{1}{h_1} + 1.8} \)

where

\( h \)  
heat transfer coefficient, incorporating a fouling factor

\( k_{H_2O} \)  
thermal conductivity of coolant

\( N_{Re} \)  
coolant Reynolds number

\( N_{Pr} \)  
coolant Prandtl number

\( D_0 \)  
cooler tube outside diameter
The fouling factor 1.8 has units sec-ft\(^2\)R/Btu (0.881 cm\(^2\)K/w)

Calculate water side and cooler tube thermal resistances:

\[
R_{H2O} = \frac{1}{hA_{HT}N_T}
\]

\[
R_{TUBE} = \frac{12 \log \frac{D_{OD}}{D_{ID}}}{2\pi L_e N_T k_{ss}}
\]

where

- \(A_{HT}\): water side heat transfer area per tube
- \(N_T\): no. of cooler tubes
- \(L_e\): effective heat transfer length of cooler tube
- \(D_{ID}, D_{OD}\): cooler tube inside and outside diameters, respectively
- \(k_{ss}\): cooler tube thermal conductivity

Then the cooler tube temperature is updated as follows:

\[
T_{NEW} = T_{H2O} + 1.287 \times 10^{-3} \dot{Q}_{H2O,OUT} \omega (R_{H2O} + R_{TUBE})
\]

\[
T_{NEW} = 0.5T_{NEW} + 0.5T_{OLD}
\]

where

- \(T_{NEW}\): new tube temperature
- \(T_{OLD}\): old tube temperature
- \(\dot{Q}_{H2O,OUT}\): rate of heat out through cooler
- \(\omega\): engine frequency

The compression space wall temperature, \(T_{MNCV}\), is then set as follows:

\[
T_{MNCV} = T_{H2O,IN} + 2(T_{H2O} - T_{H2O,IN})
\]

Have the Specified Number of Cycles (NOCYC) Been Completed? (Step 24):

A check is made to see if the specified number of cycles (NOCYC) has been completed. If not the model loops back to step 1. If, yes, then the proce-
dure continues to the next step, 25, provided the two pass option, IPCV = 0, was specified (If a one pass option was chosen, IPCV = 1, then the procedure jumps to step 27, skipping steps 25 and 26).

Is This the Second Pass Through NOCYC Cycles? (Step 25):

A check is made to see if the second pass was just completed. If not, the second pass is begun (step 26). If, yes, then the procedure continues to the final step, 27.

Second Pass Calculations (Step 26):

Time is reset to zero. The pressure drop information from the first pass is used in making working space thermodynamic calculations (instead of using a uniform pressure throughout the working space for these calculations) when the procedure loops back to step 1 and begins the second pass iterations.

Final Step (Step 27):

When the second pass is completed, if IPCV was set equal to 0, or the first pass is completed, if IPCV was set equal to 1, then the summary of predictions shown in table IX is written out. The model then attempts to read in a new set of operating conditions; if successful, the entire calculation procedure of figure 11 is repeated; when no new operating conditions are found, the simulation is terminated.
APPENDIX B
DERIVATION OF GAS TEMPERATURE DIFFERENTIAL EQUATIONS

The basic gas volume equations used in the derivation are:

\[
\frac{d}{dt} (MC_v T) = hA(T_w - T) + \left( C_p W_i T_i - C_p W_o T_o \right) - P \frac{dV}{dt} \quad (1)
\]

\[
\frac{dM}{dt} = W_i - W_o \quad (2)
\]

\[
PV = MRT \quad (3)
\]

Expanding the first term of equation (1) gives:

\[
MC_v \frac{dT}{dt} + C_v T \frac{dM}{dt} + MT \frac{dC_v}{dt} = hA(T_w - T) + \left( C_p W_i T_i - C_p W_o T_o \right) - P \frac{dV}{dt} \quad (B1)
\]

Differentiating equation (3) gives:

\[
MR \frac{dT}{dt} + RT \frac{dM}{dt} = P \frac{dV}{dt} + V \frac{dP}{dt} \quad (B2)
\]

Letting \( R = C_p - C_v \) in the first and second terms of equation (B2) and solving for

\[
C_v T \frac{dM}{dt}
\]

yields

\[
C_v T \frac{dM}{dt} = M(C_p - C_v) \frac{dT}{dt} + C_p T \frac{dM}{dt} - P \frac{dV}{dt} - V \frac{dP}{dt} \quad (B3)
\]

Substituting the right side of equation (B3) for the second term of equation (B1) yields:

\[
MC_v \frac{dT}{dt} + M(C_p - C_v) \frac{dT}{dt} + C_p T \frac{dM}{dt} - P \frac{dV}{dt} - V \frac{dP}{dt} + MT \frac{dC_v}{dt}
\]

\[
= hA(T_w - T) + \left( C_p W_i T_i - C_p W_o T_o \right) - P \frac{dV}{dt}
\]

or
Using equation (2) to substitute for $\frac{dM}{dt}$ in equation (B4) and also substituting

$$\frac{dC_v}{dt} = \frac{dC_p}{dt} \quad \text{in (B4)}$$

then solving for $MC_p \frac{dT}{dt}$ gives

$$MC_p \frac{dT}{dt} = hA(T_w - T) + (W_o - W_i)C_p T + (C_{p_i} W_i T_i - C_{p_o} W_o T_o) + V \frac{dp}{dt} - MT \frac{dC_p}{dt} \quad (4)$$

which is the equation used in the model to solve for gas temperature.
APPENDIX C
INTEGRATION OF DECOUPLED TEMPERATURE EQUATIONS

Temperature time derivative due to change in specific heat:

\[ \frac{dT}{dt} \text{ due to change in specific heat} = - \frac{1}{C_p} \frac{dC_p}{dt} \]  \hspace{1cm} (5a)

\[ \therefore \frac{dT}{T} = - \frac{dC_p}{C_p} \]

Integrating -

\[ \ln T|^{t+\Delta t}_t = - \ln C_p|^{t+\Delta t}_t \]

\[ \therefore \ln \frac{T^{t+\Delta t}}{T^t} = \ln \frac{C_p^t}{C_p^{t+\Delta t}} \]

\[ \therefore T^{t+\Delta t} = T^t \frac{C_p^t}{C_p^{t+\Delta t}} \]

Temperature timeDerivative Due to Pressure Change:

The equation

\[ \frac{dT}{dt} \text{ due to change in pressure} = \frac{V}{M C_p} \frac{dP}{dt} \]  \hspace{1cm} (5b)

can be integrated in closed form (if it is assumed that \( C_p \) is constant over the time increment) by solving the equation of state for \( V/M \) and substituting in equation (5b).

\[ PV = MRT \Rightarrow \frac{V}{M} = \frac{RT}{P} \]

Substituting
\[ \frac{dT}{dt} = \frac{RT}{\rho C_p} \frac{dP}{dt} \]

\[ \frac{dT}{T} = R \frac{dP}{\rho C_p P} \]

Assuming \( C_p \) is constant over \( \Delta t \) and integrating -

\[ \ln \frac{T^{t+\Delta t}}{T^t} = \frac{R}{\rho C_p} \ln \frac{P^{t+\Delta t}}{P^t} \]

\[ \therefore \frac{T^{t+\Delta t}}{T^t} = \left( \frac{P^{t+\Delta t}}{P^t} \right) \]

\[ \therefore T^{t+\Delta t} = T^t \left( \frac{p^{t+\Delta t}}{p^t} \right) \]

For the second pass it is assumed that \( P \) is the pressure in the center of the regenerator and a pressure ratio factor (ratio of pressure at the control volume of interest to pressure in the center of the regenerator) is introduced to better account for the influence of pressure drop on the heat transfer calculations. Introducing the array of pressure ratios, \( F \), into the above equation the result is:

\[ T^{t+\Delta t} = T^t \left( \frac{p^{t+\Delta t}}{p^t} \right) \]

(Each element of this array, \( F \), is set equal to 1 during the first pass.)

Temperature Time Derivative Due to Mixing:

\[ \frac{dT}{dt} \text{ due to mixing} = \frac{(W_o - W_i) C_p T + (C_{p_i} W_i T_i - C_{p_o} W_o T_o)}{MC_p} \quad (5C) \]
Using numerical integration let

\[ t^{t+\Delta t} = t^t + \frac{dT}{dT} \Delta t \]

\[ T^{t+\Delta t} = T^t + \frac{(W_0^{t+\Delta t} - W_i^{t+\Delta t})C_{p}\Delta t}{M^{t+\Delta t}} + \frac{(C_{p_i}^{t+\Delta t}W_i^{t+\Delta t}t^{t+\Delta t} - C_{p_o}^{t+\Delta t}W_0^{t+\Delta t}t^{t+\Delta t})}{M^{t+\Delta t}C_{p}^{t+\Delta t}} \Delta t \]

Substituting

\[ (W_0^{t+\Delta t} - W_i^{t+\Delta t}) = \frac{M^t - M^{t+\Delta t}}{\Delta t} \]

\[ T^{t+\Delta t} = \frac{M^t}{M^{t+\Delta t}} T^t + \frac{(C_{p_i}^{t+\Delta t}W_i^{t+\Delta t}t^{t+\Delta t} - C_{p_o}^{t+\Delta t}W_0^{t+\Delta t}t^{t+\Delta t})}{M^{t+\Delta t}C_{p}^{t+\Delta t}} \Delta t \]

Temperature Time Derivative Due to Heat Transfer:

\[ \frac{dT}{dt} \text{ due to heat transfer} = \frac{hA}{MC_p}(T_w - T) \Rightarrow \frac{dT}{T_w - T} = \frac{hA}{MC_p} dt \quad \text{(5d)} \]

Assume \( T_w \) is constant over the time step for the purpose of integrating the left side with respect to time. This is a reasonable assumption since \( T_w \) changes much more slowly than \( T \) due to the relatively large heat capacity of the metal. It was also assumed that \( h \) and \( M \) were constant over the time step to allow integration of the right side of the equation.

\[ -\ln(T_w - T) \begin{bmatrix} t^{t+\Delta t} \\ t \end{bmatrix} = \frac{hA}{MC_p} t \begin{bmatrix} t^{t+\Delta t} \\ t \end{bmatrix} \]

\[ \ln \left( \frac{(T_w - T)^{t+\Delta t}}{(T_w - T)^t} \right) = -\frac{hA}{MC_p} \Delta t \]

\[ \Rightarrow (T_w - T)^{t+\Delta t} = (T_w - T)^t e^{-\frac{hA}{MC_p} \Delta t} \]
This equation says that, as the time step is made larger, the gas temperature approaches the wall temperature asymptotically. Thus using large time steps cannot cause instabilities because of excessive change in gas temperature.
APPENDIX D

EXPANSION AND COMPRESSION SPACE HEAT TRANSFER COEFFICIENTS
EXPANSION SPACE

This analysis assumes perfect insulation between the combustion gas and
the expansion space wall. Heat transfer between the expansion space wall
and the working space gas is a combination of radiation and convection. For
radiation:

\[
\frac{Q}{A} = \sigma F (T_w^4 - T^4)
\]

and

\[
h_{\text{rad}} = \frac{Q}{A} \frac{T_w - T}{T_w}
\]

where

- \( \sigma \) Boltzmann constant
- \( F \) emissivity times view factor
- \( T_w \) wall temperature
- \( T \) gas temperature
- \( Q \) rate of heat flow
- \( A \) heat transfer area
- \( h_{\text{rad}} \) radiation heat-transfer coefficient

The overall \( F \) is assumed to be 0.7

The convection heat-transfer coefficient is:

\[
h_{\text{conv}} = 0.023(Re)^{0.8}(Pr)^{0.4} \frac{k}{D_h}
\]

or

\[
h_{\text{conv}} = 0.023(Re)^{0.8}(Pr)^{0.4} \frac{k}{D_h} \left[ 1 + \left( \frac{D_h}{L} \right)^{0.07} \right]
\]

where \( L \) is the maximum distance from the cylinder head to the displacer,
and

\[
h_{\text{conv}} = 1.86(\text{GRAETZ})^{0.333} \frac{k}{D_h}
\]

or

GRAETZ > 10; Re \leq 2100 (D2b)
where Graetz number = \( \text{Re} \times \text{Pr} \times \frac{\text{W}}{\text{M}^2 - K} \). The value in equation (D2c) is an assumed cutoff point (close to the natural convection coefficient). For the combined heat-transfer coefficient the values obtained from equations (D1) and (D2) are added.

**Compression Space**

Since the radiation effect is small in the compression space, only convection heat transfer is considered. Equation (D2) is used for the calculation. It is assumed that the wall temperature is known. Without detailed analysis or test data to identify this wall temperature, it seems reasonable to assume that it is about equal to the average compression space gas temperature over the cycle. The net result is that very little heat transfer takes place in the compression space and the compression-space process is essentially adiabatic.
A general form of the conservation of momentum equation for one-dimensional flow is:

\[
\frac{\partial}{\partial t} (\rho v) + \frac{\partial}{\partial x} (\rho v^2) + \frac{f}{2D_h} \rho v^2 + \frac{\partial P}{\partial x} = 0
\]  

(E1)

Rate of Rate of Rate of Rate of
accumulation momentum momentum momentum
of momentum gain by gain by gain by
per unit convection viscous pressure
volume per unit transport force per
volume volume unit volume

Expanding the first and second terms of equation (E1) yields:

\[
\rho \frac{\partial v}{\partial t} + \frac{\partial}{\partial x} (\rho v) + \frac{\partial}{\partial x} \left( \frac{\partial (\rho v)}{\partial x} \right) + \rho v \frac{\partial v}{\partial x} + \frac{f}{2D_h} \rho v^2 + \frac{\partial P}{\partial x} = 0
\]  

(E2)

By the continuity equation:

\[
\frac{\partial P}{\partial t} + \frac{\partial}{\partial x} (\rho v) = 0
\]

Therefore the second the third terms of equation (E2) can be eliminated to yield:

\[
\rho \frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial x} + \frac{f}{2D_h} \rho v^2 + \frac{\partial P}{\partial x} = 0
\]  

(E3)

The first term in equation (E3) is neglected in the model. Neglecting this term and multiplying the resulting equation by \( \frac{\partial x}{\rho} \) yields:

\[
v \frac{\partial v}{\partial x} + \frac{f}{2D_h} v^2 \frac{\partial x}{\rho} + \frac{\partial P}{\rho} = 0
\]  

(E4)

Note that at zero flow the second and third terms of equation (E3) are zero, so that it reduces to
\[ \rho \frac{\partial v}{\partial t} + \frac{\partial P}{\partial x} = 0 \]

in which case the time derivative term is responsible for any pressure drop. The significance of this time derivative term could be investigated by the use of a model which uses the complete momentum equation such as that of Urieli (ref. 18) or that of Schock (ref. 19).

Decoupled Pressure Drop Calculations:

The pressure drop calculations are decoupled from the basic thermodynamic calculations for the working space; this decoupling of pressure drop allows use of a larger time step (and less computing time) than would otherwise be possible with the explicit, one iteration per time step, numerical integration used in the model.

The effect of pressure drop on the thermodynamic calculations is accounted for as follows:

(1) Engine work, heat in and heat out per cycle are calculated assuming no pressure drop. Pressure variation with time over the cycle is the same at all control volumes in the working space. Gas flow rates are, therefore, dependent only on the variable volumes and the fluctuations in the working space gas temperatures.

(2) Using the "no pressure drop" gas flow rates calculated in step (1) above, pressure drops are calculated across each control volume; the pressure variation with time at the center of the regenerator is the same as in step (1).

(3) The pressure drops calculated in step (2) are summed up from the expansion space to the center of the regenerator and from the center of the regenerator to the compression space at each time step. Pressure variations for expansion and compression space are corrected for pressure drop.

(4) The \( \Delta p \) corrected pressure variations in the expansion and compression spaces are used to recalculate expansion space work, compression space work and total engine work per cycle. The difference between the works calculated in (1), assuming no \( \Delta p \), and the \( \Delta p \) corrected works yield:

(a) total work loss per cycle due to \( \Delta p \)

(b) work loss from expansion space to the center of the regenerator (hot side of working space) due to \( \Delta p \).

(c) work loss from center of regenerator to compression (cold side of working space) due to \( \Delta p \).
(5) The heat into the engine is now corrected for $\Delta p$ by assuming:

\[
\text{Heat into engine with $\Delta p$} = \text{Heat into engine without $\Delta p$} - \text{Work loss due to $\Delta p$ on hot side of working space}
\]

The heat out of the engine is corrected by assuming:

\[
\text{Heat out of engine with $\Delta p$} = \text{Heat out of engine without $\Delta p$} + \text{Work loss due to $\Delta p$ on cold side of working space}
\]

All calculations up to this point are completed during the first NOCYC = 25 cycle pass through the model calculations. The $\Delta p$ corrections discussed above were the only ones made in the model of reference 1. An improved correction for the effect of $\Delta p$ has been incorporated into the model by adding the following steps to the above:

(6) During the last cycle of the first pass, store the pressure variations over the cycle, corrected for $\Delta p$, for each control volume. A convenient way to do this is to store the ratio of pressure at the control volume to pressure at the center of the regenerator, for each control volume at each time step over the cycle. Thus an array of pressure ratios is created which documents the effect of $\Delta p$ on the pressure variations at each control volume over the cycle.

(7) A second pass (of NOCYC = 25 more cycles) is made through the model calculations. This time, instead of assuming a uniform pressure variation with time throughout the working space in making the thermodynamic calculations, the array of pressure ratios is used to infer pressure variation, corrected for $\Delta p$, at each control volume. A calculation of engine work with no $\Delta p$ (that is doing the expansion and compression space work integrations using the pressure at the center of the regenerator) is still made to allow a calculation of work loss due to $\Delta p$. Now, however, the correction to the heat transfer in and out over the cycle (as in (5)) is no longer necessary; this is because the effect of pressure drop (via the pressure variations at each control volume over the cycle) is now an integral part of the heat and mass transfer calculations at each time step.

The second pass through the calculations does not significantly change the calculated work loss due to $\Delta p$. However, the heat into the heater (and the expansion space work) increases more than the heat out of the cooler (and the compression space work). Thus there is a net increase in the basic work and power (that is, work and power before $\Delta p$ loss) calculated for the engine. For hydrogen at design P-40 conditions (15 MPa, 4000 RPM) the effect of the second pass was to increase brake power by 1.2 kW (3.5%).
helium at design P-40 conditions the increase is about 1.9 kW (9.7 percent). Since the model usually overpredicts power, the additional correction increases the error in predicted power at the design point; it did, however, cause the shape of the predicted curve to approximate more closely that of the experimental curve.

In developing the second pass correction, it was found that recalculating the pressure ratio array, F, at the end of the second and then making a third pass had negligible effect on the predicted performance. No attempt was made to optimize the correction procedure to get minimum computing time. For example, it may be possible to use fewer cycles during the first pass and get the same accuracy.
APPENDIX F: SYMBOLS USED IN FORTRAN SOURCE PROGRAMS, INPUT DATA SETS, AND OUTPUT DATA SETS

A Ratio of inlet and outlet areas for flow coefficient calculation
AC Compression space work per increment of crank angle, ft-lbf/rad (J/rad)
ACAN Heat conduction area for external insulation container, in$^2$ (cm$^2$)
ACDUC Compression space work, with only cooler pressure drop, per increment of crank angle, ft-lbf/rad (J/rad)
ACDUE Compression space work, with only end-effects pressure drop, per increment of crank angle, ft-lbf/rad (J/rad)
ACDUR Compression space work, with only regenerator pressure drop, per increment of crank angle, ft-lbf/rad (J/rad)
ACONDD Heat conduction area through piston, in$^2$ (cm$^2$)
ACO2 Coefficient in quadratic equation for specific heat of carbon dioxide, Btu/lbm-°R (J/kg-K)
ACP Compression space work with no pressure drop per increment of crank angle, ft-lbf/rad (J/rad)
ACS Array of control volume cross-sectional flow areas, in$^2$/regenerator flow path (cm$^2$/regenerator flow path)
ACSCOM Effective compression space cross-sectional flow area, used for end effects pressure drop calculation, in$^2$ (cm$^2$)
ACSEXP Effective expansion space cross-sectional flow area, used for end effects pressure drop calculation, in$^2$ (cm$^2$)
ACSO Alternate storage array for array ACS
AE Expansion space work per increment of crank angle, ft-lbf/rad (J/rad)
AEALT Expansion space work per increment of crank angle if all pressure drop is calculated relative to the pressure in the compression space, ft-lbf/rad (J/rad)
AEDUE Expansion space work, with only end effects pressure drop considered, per increment of crank angle, ft-lbf/rad (J/rad)
AEDUH Expansion space work, with only heater pressure drop considered, per increment of crank angle, ft-lbf/rad (J/rad)
AEDUR Expansion space work, with only regenerator pressure drop considered, per increment of crank angle, ft-lbf/rad (J/rad)
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AUXHP4  Auxiliary power requirement for engine, hp (kW)
AUXKW4  Auxiliary power requirement for engine, kW
AUXLOS  Auxiliary power requirement per cylinder, hp (kW)
AUXPWR  Engine brake power (with auxiliary power requirement subtracted), hp (kW)
AVGPC   Time averaged compression space pressure, lbf/in² (N/cm²)
AVGPE   Time averaged expansion space pressure, lbf/in² (N/cm²)
AVGPMP  Time averaged pressure at center of regenerator, MPa
AVGWSP  Time averaged pressure at center of regenerator, lbf/in² (N/cm²)
AVPCMP  Average compression space pressure, MPa
AVPEMP  Average expansion space pressure, MPa
A1      Temperature independent term in equation for specific heat at constant volume, in-lbf/lbm-oR (J/kg-K)
B       Coefficient, real gas equation of state, lbf/in² (N/cm²)
BASICP  Indicated power plus pressure drop loss, per cylinder, hp (kW)
BCO2    Coefficient in quadratic equation for specific heat of carbon dioxide, BTU/lbm-oR² (J/kg-K²)
BETA    Crank angle +π/2, rad
BHE     Sensitivity of specific heat at constant volume to temperature for helium, in-lbf/lbm-oR² (J/kg-K²)
BH2     Sensitivity of specific heat at constant volume to temperature for hydrogen, in-lbf/lbm-oR² (J/kg-K²)
BPFP1   Engine brake power per cylinder, ft-lbf/cycle (J/cycle)
BPFP4   Engine brake power, ft-lbf/cycle (J/cycle)
BPHP1   Engine brake power per cylinder (=AUXPWR), hp (kW)
BPHP4   Engine brake power, hp (kW)
BPKW1   Engine brake power per cylinder, kW
BPKW4   Engine brake power, kW
BRKEFF  Engine brake efficiency (not including effect of auxiliaries)
BRKP    Engine brake power per cylinder (not accounting for auxiliaries losses), hp (kW)
B1      Sensitivity of specific heat at constant volume to temperature, in-lbf/lbm-oR (J/kg-K)
CANIR   Insulation container inside radius, in (cm)
CANOR   Insulation container outside radius, in (cm)
CCMPDV  Cooler-compression space connecting duct volume, in³ (cm³)
CCO2  Coefficient in quadratic equation for specific heat of carbon
dioxide, Btu/lbm-°R^3 (J/kg-K^3)

CDEDV  Cooler dead volume per cylinder, in^3 (cm^3)

CFACTR  Function of average working space pressure used in calculating
auxiliary loss, dimensionless

CHCF  Cooler heat transfer coefficient multiplying factor

CHCFAC  Cooler heat transfer coefficient multiplying factor

CHE  Coefficient in equation for specific heat of helium, Btu/lbm-°R^3
(J/kg-K^3)

CH2  Coefficient in equation for specific heat of hydrogen, Btu/lbm-°R^3
(J/kg-K^3)

CH2P  Monatomic thermal conductivity of hydrogen, Btu/in-sec°R (W/cm-K)

CH2PP  Internal thermal conductivity of hydrogen, Btu/in-sec°R (W/cm-K)

CLRLOD  Cooler tube length to diameter ratio

CMIXP  Monatomic thermal conductivity of mixture of hydrogen and carbon
dioxide, Btu/in-sec°R (W/cm-K)

CMIXPP  Internal thermal conductivity of mixture of hydrogen and carbon
dioxide, Btu/in-sec°R (W/cm-K)

CMPSCL  Compression space clearance volume, in^3 (cm^3)

CNDH2O  Thermal conductivity of water, Btu/ft-sec°R (W/cm-K)

CNDSS  Cooler tube (stainless steel) thermal conductivity, Btu/ft-sec°R
(W/cm-K)

COEF  Pressure drop coefficient, dimensionless

COEFX  Pressure drop coefficient, dimensionless

COND  Array of control volume gas thermal conductivities, Btu/in-sec°R
(W/cm-K)

CONDT  Heater tube thermal conductivity, Btu/in-sec°R (W/cm-K)

CONDTB  Conduction length, top to bottom, of external insulation container
(if used), in (cm)

CO2P  Monatomic thermal conductivity of carbon dioxide, Btu/in-sec°R
(W/cm-K)

CO2PP  Internal thermal conductivity of carbon dioxide, Btu/in-sec°R
(W/cm-K)

CP  Array of control volume interface specific heats at constant
pressure, Btu/lbm-°R (J/kg-K)
**CPA**  Array of control volume specific heats at constant pressure, 
Btu/lbm-°R (J/kg-K)

**CPAO**  Alternate storage array for array CPA

**CPCGP**  Specific heat in cold appendix gap, Btu/lbm-°R (J/kg-K)

**CPCGPI**  Specific heat of gas crossing interface between cold appendix gap and 
compression space, Btu/lbm-°R (J/kg-K)

**CPCYC**  Time increments (iterations) per engine cycle

**CPHGP**  Specific heat in hot appendix gap, Btu/lbm-°R (J/kg-K)

**CPHGPI**  Specific heat of gas crossing interface between hot appendix gap and 
exansion space, Btu/lbm-°R (J/kg-K)

**CPH2O**  Cooling water specific heat, Btu/lbm-°R (J/kg-K)

**CPM**  Regenerator matrix specific heat, Btu/lbm-°R (J/kg-K)

**CR1**  Initialization constant

**CR2**  Initialization constant

**CR3**  Initialization constant

**CTBID**  Cooler tube inside diameter, in (cm)

**CTBL**  Cooler tube length, in (cm)

**CTBOD**  Cooler tube outside diameter, in (cm)

**CTBPCN**  Cooler tubes per cylinder

**CV**  Array of control volume specific heats at constant volume, Btu/lbm-°R 
(J/kg-K)

**CVF**  Function for calculating specific heat at constant volume, Btu/lbm-°R 
(J/kg-K)

**CYLDMB**  Cylinder distance between middle and bottom wall temperatures, in (cm)

**CYLDTM**  Cylinder distance between top and middle wall temperatures, in (cm)

**CYLIR**  Cylinder housing inside radius, in (cm)

**CYLORB**  Cylinder outside radius at bottom temperature, in (cm)

**CYLORM**  Cylinder outside radius at middle temperature, in (cm)

**CYLORT**  Cylinder outside radius at top temperature, in (cm)

**DALOSS**  Design auxiliary loss--four cylinders, hp (kW)

**DE**  Hydraulic diameter, ft (cm)

**DELP**  Array of pressure drops across control volumes, lbf/in² (N/cm²)

**DELPCL**  Pressure drop across cooler, lbf/in² (N/cm²)

**DELPHT**  Pressure drop across heater, lbf/in² (N/cm²)

**DELPREG**  Pressure drop across regenerator, lbf/in² (N/cm²)

**DELTIM**  Engine cycle period, sec
DELTM  Change in regenerator matrix temperature from one control volume to
the next, °R (K)
DFLOSS Design mechanical friction loss, hp (kW)
DFREQ Design engine frequency, Hz
DGAPDV  Piston-cylinder gap dead volume, in³ (cm³)
DH  Array of control volume hydraulic diameters, in (cm)
DHO Alternate storage array for array DH, in (cm)
DHX  Hydraulic diameter, in (cm)
DISPD  Piston diameter, in (cm)
DISPRD  Piston rod diameter, in (cm)
DNSTY  Array of control volume gas densities, lbm/in³ (kg/cm³)
DP  Pressure drop, lbf/in² (N/cm²)
DPCLR  Cooler pressure drop, lbf/in² (N/cm²)
DPECLD  End effects pressure drop, cold side of engine, lbf/in² (N/cm²)
DPEHOT  End effects pressure drop, hot side of engine, lbf/in² (N/cm²)
DPFRC  Total pressure drop excluding end effects, lbf/in² (N/cm²)
DPHTR  Heater pressure drop, lbf/in² (N/cm²)
DPRCLD  Regenerator pressure drop, cold side, lbf/in² (N/cm²)
DPRHOT  Regenerator pressure drop, hot side, lbf/in² (N/cm²)
DPSI  Crank angle increment, rad
DPSUM  Total pressure drop, lbf/in² (N/cm²)
DPX  Array of pressure drops, lbf/in² (N/cm²)
DRPM Design engine speed, rpm (Hz)
DSPGAP Gap width between piston and displacer, in (cm)
DSPHGT  Piston height (used in piston-cylinder gap dead volume calculation),
in (cm)
DSPWTH  Piston wall thickness, in (cm)
DTCP Change in cold appendix temperature that would occur due to change in
pressure (if appendix gap were not isothermal), °R (K)
DTCYL  Cylinder housing temperature difference between thermocouple
locations, when calculated by code, °R (K)
DTGA Change in control volume gas temperature due to heat transfer between
gas and metal, °R (K)
DTGASL  One-half of the assumed change in gas temperature across the
regenerator control volume, °R (K)
DTHGP  Change in hot appendix gap gas temperature that would occur due to change in pressure level, °R (K)
DTIME  Time increment, sec
DTM    Array of regenerator matrix temperature corrections, °R (K)
DTREG  Regenerator housing temperature difference between thermocouple locations, when calculated by code, °R (K)
DWCMP  Increment in compression space work for one crank angle increment, ft-lbf (J)
DWEXP  Increment in expansion space work for one crank angle increment, ft-lbf (J)
E      Crank eccentricity (was used in rhombic drive simulation)
ECTBL  Effective cooler tube length for heat transfer, in (cm)
EFFTOT Engine indicated efficiency
EHTBL  Effective heater tube length for heat transfer, in (cm)
EID    Engine identification (alphanumeric)
ENFCTR Enthalpy flow from cooler to regenerator per cycle, Btu (J)
ENFHTR Enthalpy flow from heater to regenerator per cycle, Btu (J)
ENFRTC Enthalpy flow from regenerator to cooler per cycle, Btu (J)
ENFRTH Enthalpy flow from regenerator to heater per cycle, Btu (J)
EN3PM  Rate at which working space volume is swept out, in³/min (cm³/min)
ETYPE  Engine type
EXPHDV Expansion space-heater connecting duct volume, in³ (cm³)
EXPSCL Expansion space clearance volume, in³ (cm³)
F      Array of flow rates at control volume interfaces, lbm/sec (kg/sec)
FACT1  Coefficient used in regenerator matrix temperature convergence method
FACT2  Coefficient used in regenerator matrix temperature convergence method
FAVG   Array of average flow rates for each control volume, lbm/sec (kg/sec)
FAVG2  Average control volume gas flow rate, lbm/sec (kg/sec)
FCGP   Flow rate between compression space and cold appendix gap, lbm/sec (kg/sec)
FCND1,FCND11,FCND12 Functions of mass fractions and thermal conductivity of pure gases used in calculating thermal conductivity of mixture of gases
FCND2,FCND21,FCND22 Functions of mass fractions of pure gases used in calculating thermal conductivity of mixture of gases
FCNPP1,FCNPP2  Functions of mass fractions and thermal conductivity of pure gases used in calculating thermal conductivity of mixture of gases

FCTR  Dimensionless function of heat transfer between gas and metal

FDEN  Parameter used in calculating matrix of coefficients for regenerator matrix temperature convergence method

FHGP  Flow rate between expansion space and hot appendix gap, lbm/sec (kg/sec)

FICLR  Gas flow rate at hot end of cooler per cylinder, lbm/sec (kg/sec)

FIHTR  Gas flow rate at hot end of heater per cylinder, lbm/sec (kg/sec)

FIJ,FIJ1,FIJ2  Functions of mass fractions and viscosities of pure gases for calculating viscosity of a mixture of gases

FIK  Array of--control volume pressure/pressure at center of regenerator--(values for each time increment over cycle)

FIKS  Alternate storage array for array FIK

FIPCV  On-off switch used to modify calculation of heat out and heat into engine

FIREG  Gas flow rate at hot end of regenerator per cylinder, lbm/sec (kg/sec)

FLFP1  Friction loss per cylinder, ft-lbf/cycle (J/cycle)

FLFP4  Friction loss for engine, ft-lbf/cycle (J/cycle)

FLHP4  Friction loss for engine, hp (kW)

FLKW4  Friction loss for engine, kW

FLOH20  Cooling water flow rate per cylinder, lbm/sec (kg/sec)

FLOPUA  Cooling water flow rate per unit cross-sectional area, lbm/sec-in² (kg/sec-cm²)

FLOW  Absolute value of gas flow rate per regenerator flow path, lbm/sec (kg/sec)

FLOWIN  Gas flow rate per regenerator flow path, lbm/sec (kg/sec)

FMA21  Function of inlet and outlet Mach numbers, dimensionless

FMULT  Multiplier for overall pressure drop

FMULTR  Multiplier for regenerator pressure drop

FNUM  Parameter used in calculating matrix of coefficients for regenerator matrix temperature convergence method

FOA  Estimate of effectiveness of radiation heat transfer from metal to gas in expansion space (emissivity * view factor)

FOCLR  Gas flow rate at cold end of cooler per cylinder, lbm/sec (kg/sec)

FOEXP  Gas flow rate at exit of expansion space, lbm/sec (kg/sec)
FOHTR  Gas flow rate at cold end of heater per cylinder, lbm/sec (kg/sec)
FOREG  Gas flow rate at cold end of regenerator per cylinder, lbm/sec (kg/sec)
FREQ    Engine speed, Hz
FRIN    Gas flow rate at hot end of regenerator per cylinder, lbm/sec (kg/sec)
FRLOSS  Friction loss per cylinder, hp (kW)
F0      Variable used in definition of function for Simpson rule integration
        (value of integrand at two time increments before current time)
F1      Variable used in definition of function for Simpson rule integration
        (value of integrand at one time increment before current time)
F2      Variable used in definition of function for Simpson rule integration
        (value of integrand at current time)
GAMMA   Ratio of gas specific heats (CP/CV)
GAMMA1  =GAMMA for adiabatic flow, =1.0 for isothermal flow
GPMH20  Cooling water flow rate per cylinder, gal/min (gm/sec)
GRAETZ  Dimensionless number for calculating convection heat transfer in
        expansion space
GRAV    Constant, 32.2 lbm-ft/lbf-sec² (1.0 kg-M/N-sec²)
H       Array of gas to metal heat transfer coefficients, Btu/sec-in²•R in
        subroutine HEATX (W/cm²-K) units converted to Btu/sec-ft²•R in
        subroutine ROMBC
HA      Array of—heat transfer coefficients * heat transfer area—between
        gas and wall), Btu/sec-•R (W/K)
HACYC   Array of average heat transfer coefficients over the engine cycle,
        Btu/sec-ft²•R (W/cm²-K)
HAWC    Dimensionless ratio—(heat transfer between gas and wall per deg of
        temperature difference)/(control volume heat capacity)
HCONV   Convection heat transfer coefficient in expansion space,
        Btu/sec-in²•R (W/cm²•K)
HDEDV   Heater dead volume per cylinder, in³ (cm³)
HFACT   Dimensionless factor used in calculating heat transfer coefficients
HHCF    Dimensionless factor used in calculating heater heat transfer
        coefficients
HHCFAC  Heater heat transfer coefficient multiplying factor
HLOD    Array of heat transfer coefficient function values for different tube
        length/diameter ratios, dimensionless
HMX  Array of maximum values of heat transfer coefficients over the cycle, Btu/sec-ft²-°R (W/cm²-K)
HRAD Effective heat transfer coefficient for radiation heat transfer in expansion space, Btu/sec-in²-°R (W/cm²-K)
HRDV Heater-regenerator connecting duct volume, in³ (cm³)
HTABL Table of values of heat transfer correlation, dimensionless
HTBID Heater tube inside diameter, in (cm)
HTBL Heater tube length, in (cm)
HTBOD Heater tube outside diameter, in (cm)
HTBPCN Number of heater tubes per cylinder
HTRLOD Heater tube length over diameter ratio
HWATR1 Clean tube, cooler tube to water heat transfer coefficient, Btu/sec-ft²-°R (W/cm²-K)
HWATR2 Fouled tube, cooler tube to water heat transfer coefficient, Btu/sec-ft²-°R (W/cm²-K)
I Index
ICOND Index; =1 calculate cylinder and regenerator housing temperatures from TM(1), TM(4), and TH20IN, =0 use input values for housing temperatures
IDEX Index
IDRUN Alphanumeric identifier for input operating conditions
IJK Index
IK Index
IMIX Index, =1 to calculate performance for mixture of hydrogen and carbon dioxide
=0 to calculate performance for pure hydrogen or pure helium
IOUT Index used as on-off switch for portion of output (that which goes into Tables VII and VIII) 1-on, 0-off
IP Index used to control printout
IPCV Index: =0 makes first pass through calculations using uniform pressure in calculating flow rates. Then, make second pass through calculations using pressure array, FIK, (created in first pass) in calculating flow rates. = 1 means eliminate second pass.
IPLT Counter used in storing data for plotting
IPRINT Index used to control printout
IPRNTO Index used to control printout
IPRNT2  Index used to control printout
IPUMP  Index:  =1 means pumping loss due to piston cylinder gap is included
         =0 means pumping loss not included
IP1    Index
IRE    Index
IREV   Index
ISC0D  Index;  =1 for separate connecting duct volumes
         =0 to lump connecting duct volumes with adjacent control
         volumes
ISIMP  Index
ISTART Index
ITER   Counts total number of iterations (time increments) since beginning of
run
ITMPS  Index:  =1 to print temperature arrays at each time increment (for
         check out)
         =0 don't print temperature arrays at each time increment
         (normally=0)
ITPCYC Number of iterations (time increments) per cycle
ITR    Counts iterations (time increments) since beginning of cycle
ITRM1  ITR-1
IVAR   Number of iterations in 5 sec
J      Index
JCYCLE Index, counts number of cycles
JI     Index
JIP    Index:  >0 for short form printout in stored dataset
         =0 long form printout
JIPI   Index
JJ     Index
JM     Index
JN     Index
K      Index
KK     Index
KI     Index
KIDEX Index used in updating cooler tube temperature
KJK    Index
KTRIG  Index used in updating cooler tube temperature
KTYPE  Index, specifies type of pressure drop calculation to be made
KWRITE Index
L   Index
M   Index
MAPLOT Index: =1 means store data for plotting
         =0 means don't store data for plotting
MWGAS Index: =2 for hydrogen working gas
         =4 use helium working gas
N   Index
NA  Index
NC  Number of cooler control volumes
NCL Index number of last (nearest the compression space) cooler control
     volume
NCLP1 NCL+1
NCOND Index used to prevent the conduction subroutine from being called
         more than once per cycle
NCS  Index number of compression space control volume
NCV  Total number of control volumes
NCVM1 NCV-1
NCVP1 NCV+1
NCVP2 NCV+2
NCVP3 NCV+3
NCVP4 NCV+4
NC1  Index number of first (nearest regenerator) cooler control volume
NC1M1 NC1-1
NC1P1 NC1+1
NES  Index number of expansion space control volume
NH  Number of heater control volumes
NHC  Index number of center heater control volume if there are an odd
     number of heater control volumes (=NH1 + (NH-1)/2)
NHL  Index number of last heater control volume
NHLP1 NHL+1
NH1  Index number of first (nearest expansion space) heater control volume
NH1M1 NH1-1
NH1P1 NH1+1
NITPC Number of time increments per cycle
NOCYC  Number of engine cycles
NOEND  Number of cycles at which regenerator matrix temperature convergence procedure is to be turned off
NPASS  Index automatically set by program on basis of input value of index, IPCV.
       If IPCV=0, then NPASS is set =2 to get two passes through calculations.
       If IPCV=1, then NPASS is set =1 to get one pass only through calculations.
NPLOTS Number of variables to be plotted
NR    Number of regenerator control volumes
NRC   Index number of center regenerator control volume
NRCM1 NRC-1
NRCP1 NRC+1
NRL   Index number of last regenerator control volume
NRLM2 NRL-2
NRLP1 NRL+1
NR1   Index number of first (nearest heater) regenerator control volume
NR1M1 NR1-1
NR1M2 NR1-2
NR1M3 NR1-3
NSTRT Number of cycles at which regenerator matrix temperature convergence procedure is turned on
OLDTIM Time at end of cycle, to use in calculating period, sec
OMEGA Engine frequency, Hz
P     Pressure at center of regenerator, lbf/in² (MPa)
PC    Pressure in compression space, lbf/in² (MPa)
PCDUC Pressure in compression space when only cooler pressure drop is accounted for, lbf/in² (MPa)
PCDUE Pressure in compression space when only end effects pressure drop is accounted for, lbf/in² (MPa)
PCDUR Pressure in compression space when only regenerator pressure drop is accounted for, lbf/in² (MPa)
PCMAX Maximum compression space pressure, lbf/in² (MPa)
PCMIN Minimum compression space pressure, lbf/in² (MPa)
PCMNP Minimum compression space pressure, Mpa
PCMP  Alternate storage location for compression space pressure, lbf/in² (MPa)
PCMXP  Maximum compression space pressure, Mpa
PCSUM  Summation of compression space pressures used in calculating time averaged compression space pressure, lbf/in² (MPa)
PCV  Array containing control volume pressures, lbf/in² (MPa)
PD  Desired mean pressure level, lbf/in² (MPa)
PDFP4  Engine pressure drop loss, ft-lbf/cycle (J/cycle)
PDHP4  Engine pressure drop loss, hp (kW)
PDKW4  Engine pressure drop loss, kW
PE  Expansion space pressure, lbf/in² (MPa)
PEALT  Expansion space pressure when pressure drop is calculated relative to pressure in compression space (instead of pressure at center of regenerator), lbf/in² (MPa)
PEDUE  Expansion space pressure when only end effects pressure drop is considered, lbf/in² (MPa)
PEDUH  Expansion space pressure when only heater pressure drop is considered, lbf/in² (MPa)
PEDUR  Expansion space pressure when only regenerator pressure drop is considered, lbf/in² (MPa)
PEMAX  Maximum expansion space pressure, lbf/in² (MPa)
PEMIN  Minimum expansion space pressure, lbf/in² (MPa)
PEMNMP  Minimum expansion space pressure, MPa
PEMXMP  Maximum expansion space pressure, MPa
PERREB  Percent error, engine energy balance
PESUM  Summation of expansion space pressures used in calculating time averaged expansion space pressure, lbf/in² (MPa)
PEXP  Alternate storage location for expansion space pressure, lbf/in² (MPa)
PHASE  Angle by which the compression volume lags the expansion volume, deg
PI  Constant=3.14159265
PIN  Pressure at control volume inlet, lbf/in² (MPa)
PIO2  PI/2
PIO4  PI/4
PLOT  Array in which variables to be plotted are stored
PMEAN  Alternate storage location for mean pressure, lbf/in² (MPa)
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLD</td>
<td>Value of reference pressure at time increment previous to current time, lbf/in² (MPa)</td>
</tr>
<tr>
<td>POUT</td>
<td>Pressure out of control volume, lbf/in² (MPa)</td>
</tr>
<tr>
<td>PR</td>
<td>Prandtl number, dimensionless in subroutine HEATX—or—pressure ratio (POUT/PIN) in subroutine XDEL</td>
</tr>
<tr>
<td>PRATAV</td>
<td>Pressure ratio—(PEMAX+PCMAX)/(PEMIN+PCMIN)</td>
</tr>
<tr>
<td>PRATC</td>
<td>Pressure ratio—PCMAX/PCMIN</td>
</tr>
<tr>
<td>PRATE</td>
<td>Pressure ratio—PEMAX/PEMIN</td>
</tr>
<tr>
<td>PREGER</td>
<td>Percent error in regenerator energy balance</td>
</tr>
<tr>
<td>PRH20</td>
<td>Prandtl number for cooling water flow</td>
</tr>
<tr>
<td>PRIN</td>
<td>Pressure at hot end of regenerator, lbf/in² (MPa)</td>
</tr>
<tr>
<td>PROSTY</td>
<td>Regenerator matrix porosity</td>
</tr>
<tr>
<td>PROUT</td>
<td>Pressure at cold end of regenerator, lbf/in² (MPa)</td>
</tr>
<tr>
<td>PRSUM</td>
<td>Summation of pressures at center of regenerator used to calculate time averaged working space pressures, lbf/in² (MPa)</td>
</tr>
<tr>
<td>PS</td>
<td>Array of variables equivalent to pressures in COMMON /PSET/</td>
</tr>
<tr>
<td>PSI</td>
<td>Crank angle, radians in subroutine ROMBC—or—conversion constant, 1/144=0.006945 ft²/in² in subroutine XDEL</td>
</tr>
<tr>
<td>PSIDEQ</td>
<td>Crank angle, deg</td>
</tr>
<tr>
<td>PSIOLD</td>
<td>Value of crank angle at time increment before current time, rad</td>
</tr>
<tr>
<td>PWRFP1</td>
<td>Engine indicated power per cylinder, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>PWRFP4</td>
<td>Engine indicated power, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>PWRHP</td>
<td>Engine indicated power per cylinder, hp (kW)</td>
</tr>
<tr>
<td>PWRHP4</td>
<td>Engine indicated power, hp (kW)</td>
</tr>
<tr>
<td>PWRKW1</td>
<td>Engine indicated power per cylinder, kW</td>
</tr>
<tr>
<td>PWRKW4</td>
<td>Engine indicated power, kW</td>
</tr>
<tr>
<td>PXIN</td>
<td>Pressure, lbf/in² (MPa)</td>
</tr>
<tr>
<td>Q</td>
<td>Array of control volume heat transfers from gas to metal, Btu/sec (W)</td>
</tr>
<tr>
<td>QADD</td>
<td>Control volume heat transfer between gas and metal for one time increment, ft-lbf (J)</td>
</tr>
<tr>
<td>QAPGAP</td>
<td>Appendix gap loss per cylinder, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QBTUPS</td>
<td>Rate of heat out through cooling water per cylinder, Btu/sec (W)</td>
</tr>
<tr>
<td>QCAN</td>
<td>Rate of heat conduction through external insulation container, Btu/sec (not used in P40-model)</td>
</tr>
<tr>
<td>QCGP</td>
<td>Rate of heat transfer between wall and cold appendix gap, Btu/sec (W)</td>
</tr>
<tr>
<td>QCGPS</td>
<td>Appendix gap loss, cold end of piston, ft-lbf/cycle (J/cycle)</td>
</tr>
</tbody>
</table>
QCLEXF  Heat out through cooling water per cylinder, ft-lbf/cycle (J/cycle)
QCLOUT Heat out through cooling water, excluding heat generated by mechanical friction, ft-lbf/cycle (J/cycle)
QCLRSV Alternate storage location for net heat out through cooler per cycle, ft-lbf/cycle (J/cycle)
QCNDCCL Heat conducted through cylinder housing, ft-lbf/cycle (J/cycle)
QCNDCN Heat conducted through insulation container, ft-lbf/cycle (J/cycle)
QCNDD Heat conducted through piston walls, ft-lbf/cycle (J/cycle)
QCNDR Heat conducted into hot end of regenerator housing, ft-lbf/cycle (J/cycle)
QCNDO Heat conducted out of cold end of regenerator housing, ft-lbf/cycle (J/cycle)
QCNDTI Heat into engine via conduction (includes shuttle) per cylinder, ft-lbf/cycle (J/cycle)
QCNDTO Heat out of engine via conduction (includes shuttle) per cylinder, ft-lbf/cycle (J/cycle)
QCOLN Cooler heat transfer from metal to gas for one time increment, ft-lbf (J)
QCOLP Cooler heat transfer from gas to metal for one time increment, ft-lbf (J)
QCOM Compression space heat transfer for one time increment, ft-lbf (J)
QCOMP Net heat transferred from gas to metal in compression space, ft-lbf/cycle (J/cycle)
QCOMPN Heat transferred from metal to gas in compression space, ft-lbf/cycle (J/cycle)
QCOMPP Heat transferred from gas to metal in compression space, ft-lbf/cycle (J/cycle)
QCOND Heat conduction through piston wall, Btu/sec (W)
QCOOL Net cooler heat transfer for one time increment, ft-lbf (J)
QCOOLN Heat transferred from gas to metal in cooler, ft-lbf/cycle (J/cycle)
QCOOLP Heat transferred from metal to gas in cooler, ft-lbf/cycle (J/cycle)
QCOOLR Net heat transferred from gas to metal in cooler, ft-lbf/cycle (J/cycle)
QCREG Rate of heat transfer through regenerator housing, Btu/sec (W)
QCRIN Heat conduction rate into hot end of regenerator housing, btu/sec (W)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCROUT</td>
<td>Heat conduction rate out of cold end of regenerator housing, Btu/sec (W)</td>
</tr>
<tr>
<td>QCYL</td>
<td>Rate of heat transfer through cylinder housing, Btu/sec (W)</td>
</tr>
<tr>
<td>QCYL1</td>
<td>Heat conduction rate from hot end to middle of cylinder housing, Btu/sec (W)</td>
</tr>
<tr>
<td>QCYL2</td>
<td>Heat conduction rate from middle to cold end of regenerator housing, Btu/sec (W)</td>
</tr>
<tr>
<td>QEIN</td>
<td>Net heat rate to engine per cylinder, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QEOUT</td>
<td>Net heat from engine per cylinder (includes heat out via cooling water plus auxiliary losses), ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QEX</td>
<td>Expansion space heat transfer for one time increment, ft-lbf (J)</td>
</tr>
<tr>
<td>QEXP</td>
<td>Net heat transferred from gas to metal in expansion space, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QEXPN</td>
<td>Heat transferred from metal to gas in expansion space, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QEXPP</td>
<td>Heat transferred from gas to metal in expansion space, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QHEAT</td>
<td>Heater heat transfer for one time increment, ft-lbf (J)</td>
</tr>
<tr>
<td>QHEATN</td>
<td>Heat transferred from metal to gas in heater, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QHEATP</td>
<td>Heat transferred from gas to metal in heater, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QHEATR</td>
<td>Net heat transferred from gas to metal in heater, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QHETN</td>
<td>Heater heat transfer from metal to gas for one time increment, ft-lbf (J)</td>
</tr>
<tr>
<td>QHETP</td>
<td>Heater heat transfer from gas to metal for one time increment, ft-lbf (J)</td>
</tr>
<tr>
<td>QHGP</td>
<td>Rate of heat transfer between cylinder wall and hot appendix gas, Btu/sec (W)</td>
</tr>
<tr>
<td>QHGPS</td>
<td>Appendix gap loss, hot end of piston, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QIN</td>
<td>Heat into engine per cylinder (accounts for heating effect of pressure drop loss in hot end of engine), ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QINB</td>
<td>Heat into engine via heater and expansion space per cylinder, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>QINFP4</td>
<td>Heat into engine (accounts for heating effect of pressure drop loss in hot end of engine), ft-lbf/cycle (J/cycle)</td>
</tr>
</tbody>
</table>
QINHP4  Heat into engine (accounts for heating effect of pressure drop loss in hot end of engine), hp (kW)
QINKW1  Heat into engine per cylinder (accounts for heating effect of pressure drop loss in hot end of engine), kW
QINKW4  Heat into engine (accounts for heating effect of pressure drop loss in hot end of engine), kW
QOA  Array of control volume heat transfer rates per unit area, Btu/sec-in\(^2\) or Btu/sec-ft\(^2\) (W/cm\(^2\))
QOAMX  Array of control volume maximum heat transfer rates per unit area, Btu/sec-ft\(^2\) (W/cm\(^2\))
QOA AVG  Array of control volume average heat transfer rates per unit area, Btu/sec-ft\(^2\)
QOAMX  Array of control volume maximum heat transfer rates per unit area, Btu/sec-ft\(^2\) (W/cm\(^2\))
QOTFP4  Heat out through cooling water for engine, ft-lbf/cycle (J/cycle)
QOTHPI  Heat out through cooling water per cylinder, hp (kW)
QOTHPI  Heat out through cooling water for engine, hp (kW)
QOTKW1  Heat out through cooling water per cylinder, kW
QINKW4  Heat out through cooling water for engine, kW
QOUT  Net heat flow to coolant (larger than heat flow to cooler by mechanical losses), ft-lbf/cycle (J/cycle)
QOUTB  Heat out through cooler and compression space per cylinder, ft-lbf/cycle (J/cycle)
QRAD  Rate of radiation heat transfer in expansion space, Btu/ft\(^2\)-hr (W/cm\(^2\))
QREGE  Regenerator heat transfer for one time increment, ft-lbf (J)
QREGEN  Net heat flow from gas to metal in regenerator, ft-lbf/cycle (J/cycle) (should be close to zero for convergent solution)
QREGN  Heat flow from metal to gas in regenerator, ft-lbf/cycle (J/cycle)
QREGP  Heat flow from gas to metal in regenerator, ft-lbf/cycle (J/cycle)
QRGN  Regenerator heat transfer from metal to gas for one time increment, ft-lbf (J)
QRGP  Regenerator heat transfer from gas to metal for one time increment, ft-lbf (J)
QSHTL  Piston shuttle loss, ft-lbf/cycle (J/cycle)
QSHTTL  Rate of heat loss via piston shuttle, Btu/sec (W)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Gas constant, (\text{in-lbf/lbm} \cdot {^\circ}\text{R} = \text{J/kg-K})</td>
</tr>
<tr>
<td>RC</td>
<td>Array of dimensionless coefficients used in regenerator matrix temperature convergence method</td>
</tr>
<tr>
<td>RCDV</td>
<td>Volume of regenerator-cooler connecting ducts per cylinder, (\text{in}^3 (\text{cm}^3))</td>
</tr>
<tr>
<td>RCRANK</td>
<td>Crank radius, in (cm)</td>
</tr>
<tr>
<td>RDEDV</td>
<td>Regenerator dead volume per cylinder, (\text{in}^3 (\text{cm}^3))</td>
</tr>
<tr>
<td>RE</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>REALGS</td>
<td>(=1) for real gas equation of state, (=0) for ideal gas equation of state</td>
</tr>
<tr>
<td>RECD1</td>
<td>Reynolds number in expansion space-heater connecting duct (based on average of inlet and outlet flow rates)</td>
</tr>
<tr>
<td>RECD2</td>
<td>Reynolds number in heater-regenerator connecting duct</td>
</tr>
<tr>
<td>RECD3</td>
<td>Reynolds number in regenerator-cooler connecting duct</td>
</tr>
<tr>
<td>RECD4</td>
<td>Reynolds number in cooler-compression space connecting duct</td>
</tr>
<tr>
<td>RECMP</td>
<td>Reynolds number at entrance of compression space</td>
</tr>
<tr>
<td>REEXP</td>
<td>Reynolds number at exit of expansion space</td>
</tr>
<tr>
<td>REFF1</td>
<td>Measure of regenerator effectiveness ((\text{ENFRTH}/\text{ENFHTR}))</td>
</tr>
<tr>
<td>REFF2</td>
<td>Measure of regenerator effectiveness ((\text{ENFCTR}/\text{ENFRTC}))</td>
</tr>
<tr>
<td>REGDB</td>
<td>Regenerator housing distance between middle and bottom temperature measurement locations, in (cm)</td>
</tr>
<tr>
<td>REGDM</td>
<td>Regenerator housing distance between top and middle temperature measurement locations, in (cm)</td>
</tr>
<tr>
<td>REGID</td>
<td>Regenerator inside diameter (matrix diameter), in (cm)</td>
</tr>
<tr>
<td>REGIR</td>
<td>Regenerator housing inside radius, in (cm)</td>
</tr>
<tr>
<td>REGL</td>
<td>Regenerator matrix length, in (cm)</td>
</tr>
<tr>
<td>REGORB</td>
<td>Regenerator housing outside radius, bottom, in (cm)</td>
</tr>
<tr>
<td>REGORM</td>
<td>Regenerator housing outside radius, middle, in (cm)</td>
</tr>
<tr>
<td>REGORT</td>
<td>Regenerator housing outside radius, top, in (cm)</td>
</tr>
<tr>
<td>REGPCN</td>
<td>Number of regenerators per cylinder</td>
</tr>
<tr>
<td>REH20</td>
<td>Reynolds number for cooling water flow rate</td>
</tr>
<tr>
<td>REIC</td>
<td>Reynolds number in cooler control volume nearest the regenerator</td>
</tr>
<tr>
<td>REIH</td>
<td>Reynolds number in heater control volume nearest the expansion space</td>
</tr>
<tr>
<td>REIR</td>
<td>Reynolds number in regenerator control volume nearest the heater</td>
</tr>
<tr>
<td>REOC</td>
<td>Reynolds number in cooler control volume nearest the compression space</td>
</tr>
<tr>
<td>REOH</td>
<td>Reynolds number in heater control volume nearest the regenerator</td>
</tr>
<tr>
<td>REOR</td>
<td>Reynolds number in regenerator control volume nearest the cooler</td>
</tr>
</tbody>
</table>
Array of Reynolds number values corresponding to values of the heat transfer correlation in array HTABL

Array of working gas control volume Reynolds numbers

Regenerator cross-sectional flow area with no matrix, in² (cm²)

Regenerator heat transfer coefficient multiplier

Regenerator matrix heat capacity per control volume (per cylinder)

Btu/°R (J/K)

Density of water, lbm/ft³ (gm/cm³)

Resistance to heat flow from cooler tube to cooling water, sec-°R/Btu (K/W)

Regenerator matrix metal density, lbm/in³ (gm/cm³)

Working gas density, lbm/ft³ (gm/cm³)

Connecting rod length, in (cm)

Working gas density, lbm/in³ (gm/cm³)

Gas constant, btu/lbm-°R (J/kg-K)

Engine speed, rpm (Hz)

Speed for auxiliary requirement calculation (assumes design speed of 4000 rpm), rpm (Hz)

Speed for auxiliary loss requirements correction, thousands of rpm

Cooler tube wall resistance, sec-°R/Btu (°K/W)

Regenerator matrix wire diameter, in (cm)

Save time required for first nocyc cycles before resetting time=0

Array of variables equivalent to work variables in COMMON /RESET/

Function used in performing Simpson rule integration

Array used to store cycle quantities to allow calculation of averages over five cycles, various dimensions

Piston stroke, in (cm)

Summation over gas control volumes of (pressure * volume)/(gas constant * temperature), dimensionless

Array used in calculating time weighted average of difference between regenerator matrix and gas temperatures, lbm (kg)

Array used in calculating time weighted average of difference between regenerator matrix and gas temperatures, lbm-°R (kg-K)

Summation of (control volumes * array of pressure ratio factors), in³ (cm³)
SUMWF  Summation of (control volume gas inventories * pressure ratio factors), lbm (kg)
SUMWT  Summation of (control volume gas inventories * control volume gas temperatures), lbm-deg R (Kg-°K)
T1     Expansion space gas temperature, °R (K)
T2     Compression space gas temperature, °R (K)
TCAN   Array of external insulation container temperatures for conduction calculations, °R (K)
TCAVG  Average cooler tube temperature, °R in subroutine CYCL--or--temperature used in heat conduction calculation, °R in subroutine CNDCT (K)
TCAVG1 Temperature used in heat conduction calculation, °R (K)
TCAVG2 Temperature used in heat conduction calculation, °R (K)
TCAVGC Average cooler tube temperature, °C
TCAVGF Average cooler tube temperature, °F (°C)
TCAVGK Average cooler tube temperature, °K
TCGP   Temperature used in appendix gap loss calculation at cold end of piston, °R (K)
TCGPI  Temperature of gas crossing interface between cold appendix gap and compression space, °R (K)
TCLRM  Inside wall cooler tube temperature, °R (K)
TCLRMO Alternate storage location for TCLRM, °R (K)
TCYL   Array of cylinder housing temperatures used in conduction calculations °R (K)
TG     Array of control volume interface gas temperatures, °R (K)
TGA    Array of control volume gas temperatures, °R (K)
TGACYC Array of time averaged control volume gas temperatures, °R (K)
TGAO   Alternate storage array for array TGA, °R (K)
TGAVG  Average temperature of piston walls, °R (K)
TGCMPA Time averaged compression space gas temperature, °R (K)
TGCYC  Array of time averaged control volume interface gas temperatures, °R (K)
TGEXPA Time averaged expansion space gas temperature, °R (K)
THAVG  Average heater tube temperature, °R (K)
THAVGC Average heater tube temperature, °C
THAVGF Average heater tube temperature, °F (°C)
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>THAVGK</td>
<td>Average heater tube temperature, °K</td>
</tr>
<tr>
<td>THCNDG</td>
<td>Average thermal conductivity of gas in gap between piston and cylinder wall, Btu/in·sec·°R (W/cm·K)</td>
</tr>
<tr>
<td>THCND1</td>
<td>Thermal conductivity, Btu/in·sec·°R (W/cm·K)</td>
</tr>
<tr>
<td>THCND2</td>
<td>Thermal conductivity, Btu/in·sec·°R (W/cm·K)</td>
</tr>
<tr>
<td>THCOND</td>
<td>Thermal conductivity, Btu/in·sec·°R (W/cm·K)</td>
</tr>
<tr>
<td>THGP</td>
<td>Temperature used in appendix gap loss calculation, hot end of piston, °R (K)</td>
</tr>
<tr>
<td>THGPI</td>
<td>Temperature of gas crossing interface between hot appendix gap and expansion space, °R (K)</td>
</tr>
<tr>
<td>TH2OAV</td>
<td>Average cooling water temperature, °R (K)</td>
</tr>
<tr>
<td>TH20IN</td>
<td>Cooling water inlet temperature, °R (K)</td>
</tr>
<tr>
<td>TH20NC</td>
<td>Cooling water inlet temperature, °C</td>
</tr>
<tr>
<td>TH20NF</td>
<td>Cooling water inlet temperature, °F (°C)</td>
</tr>
<tr>
<td>TH20NK</td>
<td>Cooling water inlet temperature, K</td>
</tr>
<tr>
<td>TIME</td>
<td>Time since beginning of first engine cycle, sec</td>
</tr>
<tr>
<td>TM</td>
<td>Array of control volume wall temperatures, °R (K)</td>
</tr>
<tr>
<td>TMA</td>
<td>Array of control volume wall temperatures, °R (K)</td>
</tr>
<tr>
<td>TMAO</td>
<td>Alternate array for array TMA, °R (K)</td>
</tr>
<tr>
<td>TMCYC</td>
<td>Array of time averaged wall temperatures, °R (K) (current model lets only regenerator wall temperatures vary over the cycle)</td>
</tr>
<tr>
<td>TMEXP</td>
<td>Expansion space wall temperature, °R (K)</td>
</tr>
<tr>
<td>TMHBR</td>
<td>Back row heater tube outside wall temperature, °R (K)</td>
</tr>
<tr>
<td>TMHFR</td>
<td>Front row heater tube outside wall temperature, °R (K)</td>
</tr>
<tr>
<td>TMIX</td>
<td>Array of control volume gas temperatures, after mixing and before heat transfer, °R (K)</td>
</tr>
<tr>
<td>TQOFP4</td>
<td>Total heat out of engine (heat out through cooling water plus auxiliary loss), ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>TQOHP4</td>
<td>Total heat out of engine (heat out through cooling water plus auxiliary loss), hp (kW)</td>
</tr>
<tr>
<td>TQOKW4</td>
<td>Total heat out of engine (heat out through cooling water plus auxiliary loss), kw</td>
</tr>
<tr>
<td>TR</td>
<td>Temperature ratio (out/in)</td>
</tr>
<tr>
<td>TRAVG1</td>
<td>Average temperature, top half of regenerator housing, °R (K)</td>
</tr>
<tr>
<td>TRAVG2</td>
<td>Average temperature, bottom half of regenerator housing, °R (K)</td>
</tr>
<tr>
<td>TRIN</td>
<td>Gas temperature at hot end of regenerator, °R (K)</td>
</tr>
</tbody>
</table>
TROUT  Gas temperature at cold end of regenerator, °R (K)
TRO   Regenerator housing temperature, hot end, used in conduction calculation, °R (K)
TR1   Regenerator housing temperature, middle, used in conduction calculation, °R (K)
TR2   Regenerator housing temperature, cold end, used in conduction calculation, °R (K)
TWOPI Constant, 2 * PI
UTOTAL Internal energy content of working space gas control volumes, ft-lbf (J)
V     Array of working space gas control volumes, in³/cylinder (cm³/cylinder)
VAR   Array of variables equivalent to the variable in COMMON /CYC/
VCAPGP Appendix gap volume at cold end of piston, in³ (cm³)
VCLC  Net compression space clearance volume (includes cold appendix volume), in³ (cm³)
VCLE  Net expansion space clearance volume (includes hot appendix gap volume), in³ (cm³)
VCO2  Volume fraction of carbon dioxide
VEL   Gas flow velocity, ft/sec (cm/sec) 
VELHD Velocity head, lbf/ft² (N/cm²)
VHAPGP Hot appendix gap volume, in³
VH2   Volume fraction of hydrogen
VIS   Array of control volume gas viscosities, lbm/in-sec
VISC  Viscosity, lbm/in-sec (kg/cm-sec)
VISC02 Viscosity of carbon dioxide, lbm/in-sec (kg/cm-sec)
VISH2 Viscosity of hydrogen, lbm/in-sec (kg/cm-sec)
VISH20 Average cooling water viscosity, lbm/ft-sec (kg/cm-sec)
VISX  Viscosity, lbm/ln-sec (kg/cm-sec)
VO    Alternative storage array for working space gas control volumes, in³ (cm³)
VOVRT Summation over the array of gas control volumes of---volume/(temperature*pressure ratio (i.e. FIK)), in⁴-lbf/lbm-°R (cm⁴-N/kg-K)
VR    Velocity ratio (out/in)
VTOTL Total working space volume, in³ (cm³)
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTOTLO</td>
<td>Alternate storage location for total working space volume,( \text{in}^3 ) (( \text{cm}^3 ))</td>
</tr>
<tr>
<td>W</td>
<td>Total working space gas inventory per cylinder, lbm (kg)</td>
</tr>
<tr>
<td>WALT</td>
<td>Total work per cycle if pressure drops are calculated relative to compression space pressure, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>WALTO</td>
<td>Alternate storage location for WALT, ft-lbf/cycle</td>
</tr>
<tr>
<td>WCDUC0, WCDUC1, WCDUC2</td>
<td>Compression space work per time increment if only cooler pressure drop is considered, three consecutive time increments, ft-lbf (J)</td>
</tr>
<tr>
<td>WCDUE0, WCDUE1, WCDUE2</td>
<td>Compression space work per time increment if only end effects pressure drop is considered, three consecutive time increments, ft-lbf (J)</td>
</tr>
<tr>
<td>WCDURO, WCDUR1, WCDUR2</td>
<td>Compression space work per time increment if only pressure drop considered is that in the cold half of the regenerator, three consecutive time increments, ft-lbf (J)</td>
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<tr>
<td>WCPO, WCPI, WCP2</td>
<td>Compression space work per time increment assuming no pressure drop, three consecutive time increments, ft-lbf (J)</td>
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<tr>
<td>WCF</td>
<td>Correction factor for gas inventory to get desired mean pressure, dimensionless</td>
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<tr>
<td>WCMPN</td>
<td>Negative compression space work per cycle, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>WCMPP</td>
<td>Positive compression space work per cycle, ft-lbf/cycle (J/cycle)</td>
</tr>
<tr>
<td>WCPC0, WCPC1, WCPC2</td>
<td>Compression space work per time increment, three consecutive time increments, ft-lbf (J)</td>
</tr>
<tr>
<td>WEALTO, WEALT1, WEALT2</td>
<td>Expansion space work per time increment if pressure drop is calculated relative to compression space pressure, three consecutive time increments, ft-lbf (J)</td>
</tr>
<tr>
<td>WEDUE0, WEDUE1, WEDUE2</td>
<td>Expansion space work per time increment if only end effects pressure drop is considered, three consecutive time increments, ft-lbf (J)</td>
</tr>
<tr>
<td>WEDUHO, WEDUH1, WEDUH2</td>
<td>Expansion space work per time increment if only heater pressure drop is considered, three consecutive time increments, ft-lbf (J)</td>
</tr>
<tr>
<td>WDTGA</td>
<td>(change in control volume gas temperature * control volume gas inventory), °R-lbm (K-kg)</td>
</tr>
<tr>
<td>WFCTR</td>
<td>(dimensionless function of control volume heat transfer * control volume gas inventory), lbm (kg)</td>
</tr>
</tbody>
</table>
WEDURO, WEDUR1, WEDUR2  Expansion space work per time increment is only regenerator pressure drop is considered, three consecutive time increments, ft-lbf (J)
WEPEO, WEPE1, WEPE2  Expansion space work per time increment, three consecutive time increments, ft-lbf (J)
WEPO, WEP1, WEP2  Expansion space work per time increment assuming no pressure drop, three consecutive time increments, ft-lbf (J)
WEXPN  Negative expansion space work per cycle, ft-lbf/cycle (J/cycle)
WEXPP  Positive expansion space work per cycle, ft-lbf/cycle (J/cycle)
WG  Array of control volume gas inventories, lbm (kg)
WGCGP  Cold appendix gap inventory, lbm (kg)
WGCGPO  Cold appendix gap inventory at time increment previous to current value, lbm (kg)
WGHGP  Hot appendix gap inventory, lbm (kg)
WGHGPO  Hot appendix gap inventory at time increment previous to current value, lbm (kg)
WGOLD  Array of control volume gas inventories, at one time increment before current value, lbm (kg)
WINT  Work integral function
WLALT  Work loss at expansion space (due to pressure drop) when pressure drop is calculated relative to reference pressure in compression space, ft-lbf/cycle (J/cycle)
WLALTO  Alternate storage location for WLALT
WLCMC  Work loss at compression space due to cooler pressure drop, ft-lbf/cycle (J/cycle)
WLCME  Work loss at compression space due to end effects pressure drop, ft-lbf/cycle (J/cycle)
WLCMR  Work loss at compression space due to regenerator pressure drop, ft-lbf/cycle (J/cycle)
WLEALT  Work loss at expansion space due to pressure drop when the pressure drop is calculated relative to the compression space pressure, ft-lbf/cycle (J/cycle)
WLEXE  Work loss at expansion space due to end effects pressure drop, ft-lbf/cycle (J/cycle)
WLEXH  Work loss at expansion due heater pressure drop, ft-lbf/cycle (J/cycle)
WLEXR  Work loss at expansion due to regenerator pressure drop, ft-lbf/cycle (J/cycle)

WRKBAS  Indicated work + pressure drop work loss, per cylinder, ft-lbf/cycle (J/cycle)

WRKCMP  Compression space work per cycle, ft-lbf/cycle (J/cycle)

WRKEXP  Expansion space work per cycle, ft-lbf/cycle (J/cycle)

WRKLC  Work loss at compression space due to cooler pressure drop, per cylinder, ft-lbf/cycle (J/cycle)

WRKLCM  Work loss at compression space due to pressure drop, ft-lbf/cycle (J/cycle)

WRKLCO  Alternate storage location for WRKLC, ft-lbf/cycle, (J/cycle)

WRKLE  Total work loss due to end effects pressure drop, ft-lbf/cycle (J/cycle)

WRKLEO  Alternate storage location for WRKLE, ft-lbf/cycle (J/cycle)

WRKLEX  Work loss at expansion space due to pressure drop, ft-lbf/cycle (J/cycle)

WRKLH  Work loss at expansion space per cylinder due to heater pressure drop, ft-lbf/cycle (J/cycle)

WRKLHO  Alternate storage location for WRKLH, ft-lbf/cycle (J/cycle)

WRKLR  Total work loss due to regenerator pressure drop, ft-lbf/cycle (J/cycle)

WRKLRO  Alternate storage location for WRKLR, ft-lbf/cycle (J/cycle)

WRKLT  Total work loss due to pressure drop, ft-lbf/cycle (J/cycle)

WRKLTO  Alternate storage location for WRKLT, ft-lbf/cycle (J/cycle)

WRKTOT  Indicated work per cycle, ft-lbf/cycle (J/cycle)

WTPCO, WTPC1, WTPC2  Total work per time increment when pressure drop is calculated relative to compression space pressure, ft-lbf/cycle (J/cycle)

WO  Array of variables equivalent to works in COMMON /TIMEO/

W1  Array of variables equivalent to works in COMMON /TIME1/

W2  Array of variables equivalent to works in COMMON /TIME2/

X  Array (two dim.) of piston positions, in (cm)

XCO2  Mass fraction of carbon dioxide

XCPA  Specific heat at constant pressure, Btu/lbm-°R (J/kg-K)

XCV  Specific heat at constant volume, Btu/lbm-°R (J/kg-K)

XGAM  Ratio of specific heats (CP/CV)
XH2  Mass fraction of hydrogen
XL   Array of control volume flow lengths, in (cm)
XLG  Length, ft (cm)
XLGTH Length, in (cm)
XLO  Alternate storage array for XL, in (cm)
XMAO Estimate of outlet Mach number
XMA1 Inlet Mach number
XMA2 Outlet Mach number
ZERO Constant =0.0
ZMCO2 Molecular wt. of carbon dioxide
ZMH2 Molecular wt. of hydrogen
ZMMIX Molecular weight of mixture of hydrogen and carbon dioxide
Predicted P-40 engine brake power and efficiencies are compared with the results of engine tests made at Lewis Research Center in figure 15. The tests were made with auxiliaries powered by the engine. The efficiencies shown are overall efficiencies. The efficiency predicted by the computer program does not account for the combustor efficiency. Thus it was necessary to use an assumed combustor efficiency to adjust the predictions of the computer program. The combustor efficiencies calculated from the Lewis P-40 test data were all about 90 percent for the test points shown. When the predicted efficiencies were multiplied by 0.90, the upper predicted efficiency curve was obtained. However, information obtained from United Stirling suggests the P-40 combustor efficiency may be closer to 80 percent for the range of operation shown. When the predicted efficiencies were multiplied by 0.80, the lower predicted efficiency curve was obtained.

The regenerator effectiveness (average of \( \text{REFF}_1 \) and \( \text{REFF}_2 \) – defined in the symbols list) was about 0.996 for the predictions of figure 15. When the computer program was modified to yield a regenerator effectiveness of about 0.990 (by multiplying DTGASL by 0.96, in subroutine HEATX) the predictions were as shown in figure 16.
References


TABLE I. - EFFECT OF CHANGING THE NUMBER OF CONTROL VOLUMES IN THE HEAT EXCHANGERS

<table>
<thead>
<tr>
<th>CONTROL VOLUME CHANGE</th>
<th>CHANGE IN TOTAL NO. OF CONTROL VOLUMES</th>
<th>EFFECT ON ENGINE POWER</th>
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<tbody>
<tr>
<td>REGENERATOR, 5 → 7</td>
<td>17 → 19</td>
<td>= + 0.5 kW</td>
</tr>
<tr>
<td>HEATER, 3 → 5</td>
<td>17 → 19</td>
<td>= + 0.25 kW</td>
</tr>
<tr>
<td>COOLER, 3 → 5</td>
<td>17 → 19</td>
<td>= + 0.25 kW</td>
</tr>
<tr>
<td>REGENERATOR, 5 → 7</td>
<td>17 → 23</td>
<td>= + 1.0 kW</td>
</tr>
<tr>
<td>HEATER, 3 → 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COOLER, 3 → 5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE II. - INPUT DATA—ENGINE PARAMETERS

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<tr>
<th>Parameter</th>
<th>Value</th>
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<td>REGORB</td>
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<td>Numeric engine identifier</td>
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<td>DISP D</td>
<td>Piston diameter, in (cm)</td>
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<tr>
<td>Disp RD</td>
<td>Piston rod diameter, in (cm)</td>
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<tr>
<td>DSPGAP</td>
<td>Piston-cylinder gap, in (cm)</td>
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<td>Displacer height, in (cm)</td>
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<tr>
<td>RODL</td>
<td>Connecting rod length, in (cm)</td>
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<tr>
<td>RCRANK</td>
<td>Crank radius, in (cm)</td>
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<tr>
<td>E</td>
<td>Eccentricity (not used)</td>
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<tr>
<td>PHASE</td>
<td>Angle by which compression volume lags expansion volume, deg</td>
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<tr>
<td>HTBOD</td>
<td>Heater tube outside diameter, in (cm)</td>
</tr>
<tr>
<td>HTBID</td>
<td>Heater tube inside diameter, in (cm)</td>
</tr>
<tr>
<td>HTBPCN</td>
<td>Number of heater tubes per cylinder</td>
</tr>
<tr>
<td>HTBL</td>
<td>Heater tube length, in (cm)</td>
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<tr>
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<td>Length of heater tube effective in heat transfer, in (cm)</td>
</tr>
<tr>
<td>REGPCN</td>
<td>Number of regenerators per cylinder</td>
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<td>REGID</td>
<td>Regenerator inside diameter, in (cm)</td>
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<td>Regenerator matrix length, in (cm)</td>
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<tr>
<td>RWIRED</td>
<td>Regenerator matrix wire diameter, in (cm)</td>
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<tr>
<td>PROSTY</td>
<td>Regenerator matrix porosity</td>
</tr>
<tr>
<td>RMDEN</td>
<td>Regenerator matrix metal density, $\frac{LB_M (gM)}{in^3}$</td>
</tr>
<tr>
<td>CPM</td>
<td>Regenerator matrix specific heat, $\frac{Btu}{LB_M - R (gM - K)}$</td>
</tr>
<tr>
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<td>Cooler tube outside diameter, in (cm)</td>
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<td>Cooler tube thermal conductivity,</td>
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81
Cooling water specific heat,
\[
\frac{\text{Btu}}{\text{ft} \cdot \text{sec} \cdot ^\circ\text{R}} = \frac{\text{Btu}}{\text{Joules}} = \frac{\text{Btu}}{\text{lb} \cdot ^\circ\text{R}} = \frac{\text{Btu}}{\text{g} \cdot ^\circ\text{R}}
\]

Density of water, \[
\frac{\text{Lb m}}{\text{ft}^3} = \frac{\text{gm}}{\text{cm}^3}
\]

Effective cooling water flow area per cylinder, \(\text{in}^2\) (cm²)

Expansion space clearance volume, \(\text{in}^3\) (cm³)

Expansion space - heater connecting duct volume, \(\text{in}^3\) (cm³)

Heater-regenerator connecting duct volume, \(\text{in}^3\) (cm³)

Regenerator-cooler connecting duct volume, \(\text{in}^3\) (cm³)

Cooler-compression space connecting duct volume, \(\text{in}^3\) (cm³)

Compression space clearance volume, \(\text{in}^3\) (cm³)

Cylinder housing outside radius, top, \(\text{in}\) (cm)

Cylinder housing outside radius, middle, \(\text{in}\) (cm)

Cylinder housing outside radius, bottom, \(\text{in}\) (cm)

Cylinder housing conduction length, top to middle, \(\text{in}\) (cm)

Cylinder housing conduction length, middle to bottom, \(\text{in}\) (cm)

Piston wall thickness, \(\text{in}\) (cm)

Regenerator housing outside radius, top, \(\text{in}\) (cm)

Regenerator housing outside radius, middle, \(\text{in}\) (cm)

Regenerator housing outside radius, bottom, \(\text{in}\) (cm)

Regenerator housing conduction length, top to middle, \(\text{in}\) (cm)

Regenerator housing conduction length, middle to bottom, \(\text{in}\) (cm)

Piston stroke, \(\text{in}\) (cm)

Insulation container outside radius (not used)
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<th>Code</th>
<th>Description</th>
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<tr>
<td>CONDTB</td>
<td>Insulation container conduction length (not used)</td>
</tr>
<tr>
<td>DFREQ</td>
<td>Design engine frequency, Hz (rpm)</td>
</tr>
<tr>
<td>DFLOSS</td>
<td>Design mechanical friction loss, hp (kW)</td>
</tr>
<tr>
<td>DALOSS</td>
<td>Design auxiliary power requirement, hp (kW)</td>
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</table>
### TABLE IV. MODEL OPTION SWITCHES AND MULTIPLYING FACTORS, AND ENGINE OPERATING CONDITIONS

```
&STRNG REALGS=1.,FACT1=0.4,FACT2=10.0,
NOCYC=25,NSTRT=1,NOEND=20,MWGAS=2,
RHCFAC=1.0,HHCFAC=1.0,CHCFAC=1.0,IPCV=0,FMULT=1.0,FMULTR=1.0,
IMIX=0,VH2=0.99,IPUMP=1,ICOND=0,
IOUT=1,JIP=0,IPRINT=500,ITMPS=0,MAPLOT=1 &END
&IHDATA IDRUN=12HREAD #123BR,P=2171.,OMEGA=66.78,TMEXP=1643.,
TMHFR=1672.,TMHBR=1672.,TCYL=1643.,1441.,1239.,TCAN=1191.,999.,TRO=1472.,
TR1=1214.,TR2=958.,GPMH2O=13.63,TH2OIN=580.1 &END
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## Table VII. Partial Listing of Long Form of Output

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CHCFAC = 1.0
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FMRTL = 1.0
FMULTR = 1.0
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VHI = 0.990
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ICOND = 0
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JIP = 0
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** INPUT DATA--ENGINE OPERATING CONDITIONS **

\$INDATA
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P = 2635.5934534073
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** CYCLE BY CYCLE SUMMARY DATA **

* CYCLE NO. 1 *

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**METAL TEMPERATURES FOR CONDUCTION CALCULATIONS**

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- **CYCLE NO. 6**

- **CYCLE NO. 7**

- **CYCLE NO. 8**

- **CYCLE NO. 9**
14 PAGES OF LISTING OMITTED
QIN = 383.717  QOUT = 259.456  WRKEXP = 382.868  WRKCM = -197.667  WRKTOT = 160.363  EFFTOT = 0.418  REFF1 = 0.997  REFF2 = 0.996
QREGEN = 0.501  PURHP = 19.971  FREQ = 66.780  WRKLT = 24.846  UTOTAL = 0.000
ENPM = 6310.710  AVGWS = 2171.642
QEXPP = -4.352  QEXPP = 0.134  QHEAT = 373.347  QHEATP = 2.753  QCQOLN = -4.808  QCQOLP = 201.681  QCQMPN = 0.000  QCQMP = 2.866
QIEXPP = -1774.769  QREGP = 1775.323  QCMPD = 5.178  QCMP = 5.178
QCHDDC = 1.388  QCQDC = 0.368  QCQDC = 0.000  TQEXPA = 1538.595  TCQMPA = 655.604  QSHTL = 1.939
QINB = 374.844  WRKBAS = 165.200  WALT = 165.200  QOUT = 199.739  WRKLEX = 0.000  WRKLCM = -0.000  WLEXR = 0.000
WLCM = -0.000  WLEXE = 0.000  WLCME = -0.000  WRKLT = 245.943  WRKLEM = 0.000
CYCLE NO 19
TIME ANGLE X(1) X(2) TRIN TROUT T1 T2 PE PC PRIN PROUT FRIN FROUT
0 2865 360.0 0.00 0.71 1487.31 708.84 1557.683. 2445.78 2458.84 2447.61 2453.64 -0.05327 -0.23034
0 2865 360.0 0.00 0.71 1487.31 708.84 1557.683. 2445.78 2458.84 2447.61 2453.64 -0.05327 -0.23034
TG = 1586. 1617. 1684. 1649. 785. 708. 690. 687. 693. 683. 683.
TIME ANGLE X(1) X(2) TRIN TROUT T1 T2 PE PC PRIN PROUT FRIN FROUT
0 2865 360.0 0.00 0.71 1487.31 708.84 1557.683. 2445.78 2458.84 2447.61 2453.64 -0.05327 -0.23034
0 2865 360.0 0.00 0.71 1487.31 708.84 1557.683. 2445.78 2458.84 2447.61 2453.64 -0.05327 -0.23034
TG = 1586. 1617. 1684. 1649. 785. 708. 690. 687. 693. 683. 683.
12
TIME ANGLE X(1) X(2) TRIN TROUT T1 T2 PE PC PRIN PROUT FRIN FROUT
0 2865 360.0 0.00 0.71 1487.31 708.84 1557.683. 2445.78 2458.84 2447.61 2453.64 -0.05327 -0.23034
0 2865 360.0 0.00 0.71 1487.31 708.84 1557.683. 2445.78 2458.84 2447.61 2453.64 -0.05327 -0.23034
TG = 1586. 1617. 1684. 1649. 785. 708. 690. 687. 693. 683. 683.
TIME ANGLE X(1) X(2) TRIN TROUT T1 T2 PE PC PRIN PROUT FRIN FROUT
0 2865 360.0 0.00 0.71 1487.31 708.84 1557.683. 2445.78 2458.84 2447.61 2453.64 -0.05327 -0.23034
0 2865 360.0 0.00 0.71 1487.31 708.84 1557.683. 2445.78 2458.84 2447.61 2453.64 -0.05327 -0.23034
TG = 1586. 1617. 1684. 1649. 785. 708. 690. 687. 693. 683. 683.
<** AVERAGE VALUES OVER LAST 5 CYCLES **>
QIN = 383.729  QOUT = 259.452  WRKEXP = 371.112  WRKCM = -200.818  WRKTOT = 160.359  EFFTOT = 0.418  REFF1 = 0.997  REFF2 = 0.996
QREGEN = 0.511  PURHP = 19.970  FREQ = 66.780  WRKLT = 24.846  UTOTAL = 0.000
ENPM = 6310.710  AVGWS = 2171.645
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QIEXPP = -1774.803  QREGP = 1775.314  QCMPD = 5.178  QCMP = 5.178
QCHDDC = 1.388  QCQDC = 0.368  QCQDC = 0.000  TQEXPA = 1538.591  TCQMPA = 655.597  QSHTL = 1.939
QINB = 374.856  WRKBAS = 165.199  WALT = 183.396  QOUT = 199.735  WRKLEX = 0.000  WRKLCM = -0.000  WLEXR = 0.000
WLCM = 1.564  WLEXE = 5.393  WLCME = 0.764  WRKLT = 6.413  WRKLEM = 1.377  WRKLE = 10.260  WALT = 13.102
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**Note:** The table above shows the results of various calculations with specific time angles, showing changes in the values of different parameters over time. The parameters include angles, coordinates, and various calculated values that seem to be related to physical measurements or simulations. The table is part of a larger document that likely discusses the outcomes of these calculations in detail. The exact interpretation would require context beyond the table itself.
<p>| TIME | TRN | T1    | T2    | PE   | PC   | PRIN | PRUT | FRIN | PRUT |
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| 0.3300 | 14.4  | 0.00  | 0.71  | 1487.36 | 708.92 | 1587. | 683.  | 2466.99 | 2459.05 | 2477.82 | 2453.85 | -0.05327 | -0.23033 |
| 0.3306 | 28.8  | 0.12  | 0.35  | 1487.36 | 708.92 | 1587. | 683.  | 2466.99 | 2459.05 | 2477.82 | 2453.85 | -0.05327 | -0.23033 |
| 0.3312 | 43.2  | 0.25  | 0.21  | 1481.42 | 689.35 | 1667. | 708.  | 2754.19 | 2785.91 | 2772.41 | 2782.27 | -0.19812 | -0.24990 |
| 0.3318 | 57.6  | 0.42  | 0.21  | 1487.76 | 684.30 | 1667. | 708.  | 2754.19 | 2785.91 | 2772.41 | 2782.27 | -0.19812 | -0.24990 |
| 0.3324 | 72.0  | 0.62  | 0.30  | 1487.36 | 672.20 | 1667. | 708.  | 2574.89 | 2576.20 | 2576.20 | 2576.20 | -0.21164 | -0.20730 |
| 0.3328 | 87.6  | 0.82  | 0.35  | 1487.36 | 672.20 | 1667. | 708.  | 2574.89 | 2576.20 | 2576.20 | 2576.20 | -0.21164 | -0.20730 |
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<td>1.388</td>
<td>QCHDRL</td>
<td>0.366</td>
<td>QCNDD</td>
<td>0.578</td>
<td>QCNDD</td>
<td>0.1538</td>
<td>0.626</td>
<td>TGCMPA</td>
<td>655.723</td>
<td>QCHDL</td>
<td>1.939</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QCHDD</td>
<td>0.368</td>
<td>QCHDD</td>
<td>0.000</td>
<td>TGCMPA</td>
<td>0.000</td>
<td>TGCMPA</td>
<td>1538.626</td>
<td>0.1028</td>
<td>0.2108</td>
<td>0.1904</td>
<td>0.1904</td>
<td>180.396</td>
<td>QWLEX</td>
<td>5.260</td>
<td>WLEXR</td>
</tr>
</tbody>
</table>

** AVG. TEMPS.--LAST 5 CYCLES, AVG. H. T. COEFS. & HEAT FLUXES--LAST CYCLE **

<table>
<thead>
<tr>
<th>TGCYC</th>
<th>1530.</th>
<th>1528.</th>
<th>1524.</th>
<th>1482.</th>
<th>703.</th>
<th>691.</th>
<th>669.</th>
<th>659.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMCYC</td>
<td>1643.</td>
<td>1672.</td>
<td>1672.</td>
<td>1672.</td>
<td>1640.</td>
<td>1400.</td>
<td>780.</td>
<td>646.</td>
</tr>
<tr>
<td>HMX</td>
<td>0.443</td>
<td>0.000</td>
<td>1.413</td>
<td>1.435</td>
<td>0.000</td>
<td>0.000</td>
<td>2.950</td>
<td>2.779</td>
</tr>
<tr>
<td>NOAVG</td>
<td>5.65</td>
<td>0.00</td>
<td>69.15</td>
<td>72.89</td>
<td>0.00</td>
<td>4.45</td>
<td>4.38</td>
<td>0.00</td>
</tr>
<tr>
<td>NOAMX</td>
<td>22.90</td>
<td>0.00</td>
<td>132.68</td>
<td>128.62</td>
<td>0.00</td>
<td>8.45</td>
<td>8.53</td>
<td>0.00</td>
</tr>
</tbody>
</table>

** P Pressue Calculations--Expansion and Compression Space **

<table>
<thead>
<tr>
<th>AVGPE</th>
<th>2172.765</th>
<th>AVGPC</th>
<th>2171.588</th>
<th>PEMAX</th>
<th>2758.990</th>
<th>PEMIN</th>
<th>1663.097</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCMAX</td>
<td>2600.018</td>
<td>PCMIN</td>
<td>1632.701</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APPMAX</td>
<td>53.280</td>
<td>APCCMIN</td>
<td>246.240</td>
<td>APCCMAX</td>
<td>54.000</td>
<td>APCCMIN</td>
<td>246.960</td>
</tr>
</tbody>
</table>

** Engine Power and Efficiency Calculations **

| BASICP | 22.487 |
| FRLOSS | 4.294  |
| BRKP | 15.176   |
| BRKEFF | 0.326 |

| AUXLOS | 2.692 |
| AUXPWR | 12.485 |
| AUXEFF | 0.268 |

** Cooler and Appendix Gap Pumping Calculations **

| TH20AV | 585.98948208376 |
| RH20 | 3.0311088482520 |
| RIURE | 0.27440452269027 |
| QTURP | 22.310718811145 |
| W | 0.296570560530555 |
| GHP | 15.3373267808887 |
| QCGP | 0.11240588565159 |

** END **
TABLE VIII. - SHORT FORM OF OUTPUT DATA
(Produced when IOUT = 1, JIP = 1)

** Run Identification **

READ #123DR.

** Calculated Control Volume and Engine Parameters, and Input Data **

**IPRAM
HIODEV = 2.1788355858357
PREDDEV = 7.0629962338519
CIDEDV = 1.4725243637283
DGAPDV = 0.38090003924925
DHO = 2*2.1650, 3*1.11810, 2 2440, 5*0.27190952380952D-02, 0.22440001, 3*0.393700D-01
2*0.169260001, 13*0.0
ACSO = 3.6813379069113, 1.8406689534556, 3*0.9589935129280D-01, 0.39549007266381D0
5*0.22938424214501001, 0.39549007266381D0, 3*0.23373402598861D0, 0.17530335352219D0
0.35060670704443901, 13*0.0
AHIO = 2*0.0, 3*11.033826006996, 0.0, 5*1035.9469775373, 0.0, 3*20.945228440128

15*0.0
XLO = 0.0, 0.73098424215499D0-01, 3*0.36833333333333D0, 0.12857465588333D0
5*0.307000D0, 0.39343591850981D0-01, 3*0.1050001, 0.52566622354121D0, 14*0.0
VO = 0.0, 0.256910, 3*0.72627852861190, 1.0170, 5*1.4084192677004, 0.31120
3*0.4906415657609, 1.8430, 14*0.0
VCLE = 0.52610003924925
VCLC = 0.17599000392493
CLRLOO = 80.010160020320
IITRLOO = 93.564775613887
RGAREA = 3.9549007266381
AP = 3.6813379069113
AR = 0.17527083646743
ARMAR = 3.5060670704439
VHAPGP = 0.38090003924925
VCAPGP = 0.38090003924925D-01
THGP = 1373.66666666667
ICGP = 646.40894661755
QHGP = 0.0
QCGP = 0.0
IPUMP = 1
ICOND = 0
END

** Input Data -- Engine Parameters **

%ENGINE
%EID = -0.47377992506120D28
ETYPE = 1.0
DISPD = 2.1650
DISPRD = 0.47240
DSFPAG = 0.15750D0-01
DSPHGT = 3.530
RODL = 3.9370

---
RCPANK = 0.78740
E = 0.0
FBASE = 90.0
HTOD = 0.17720
HIBID = 0.11810
HTBPCN = 18.0
HTIL = 11.050
ENIBL = 9.9130
REGCH = 2.0
REGID = 2.2460
REGL = 1.5350
RWIRED = 0 19690D-02
FRUSTY = 0.580
RMIND = 0 2620
CTH = 0.110
CTIOD = 0.5060D-01
CTIBID = 0.3930D-01
CTBPCN = 384.0
CTBL = 3.150
ECIBL = 2.6460
CNDSG = 0.27780D-02
CPH2O = 1.0
RHOH2O = 62.40
AEH2O = 5.0
EXPSC = 0.14520
EXPHBV = 0.26910
HRDV = 1.0170
RCBV = 0 31120
CTBPDV = 1.8430
CNPSCL = 0.13790
CLOYRT = 1.360
CYLORM = 1.310
CYLORB = 1.250
CYLDIM = 0.7870
DSPWHE = 0 750D-01
REGRT = 1.420
REGOM = 1.370
REGOD = 1.30
REGDM = 0.5940
PEGDM = 0.5940
STROKE = 1.5750
CAMI = 0.0
CANIR = 0.0
CUNDRB = 0.0
DFREQ = 66.670
DFLOSS = 17.1650
DALOSS = 10.060
END

** INPUT DATA--OPTION SWITCHES AND MULTIPLYING FACTORS **

@STRNLG
REALGS = 1.0
RACII = 0.40
FACT2 = 10.0
HCCYL = 25
HSTIR = 1
HUEND = 20
LWAS = 2
RHCFAC = 1.0
MICFAC = 1.0
CHCFAC = 1.0
IRCV = 0
IMULT = 1.0
FMULTR = 1.0
IMIX = 0
VH2 = 0.990
IFPUMP = 1
ICOND = 0
IOUT = 1
JIP = 1
IPRINT = 500
IMPS = 0
MAPLOT = 1
\END

\*\* INPUT DATA--ENGINE OPERATING CONDITIONS \*\*

\*INDATA
IDRUN = -641351228, 1081864690, -205334165
N = 635.5934534073
OMEGA = 66.780
TEXP = 1643.0
TMHFR = 1672.0
TMIOR = 1672.0
TCYL = 1643.0, 1441.0, 1239.0
TCAN = 1191.0, 999.0
TR0 = 1472.0
T1 = 1214.0
T2 = 956.0
G1MH20 = 13.630
TH20IN = 580.10
\END

\*\* METAL TEMPERATURES FOR CONDUCTION CALCULATIONS \*\*

\*SINTEMP
TCYL = 1643.0, 1441.0, 1239.0
TCAN = 1191.0, 999.0
TR0 = 1472.0
T1 = 1214.0
T2 = 956.0
\END

QIN = 378.131 QOUT = 260.212 WRKEXP = 358.513 WRCMP = -202.013 WRKTOT = 156.500 EFFTOT = 0.414 REFF1 = 0.997 REFF2 = 0.995
QREGEN = -0.658 PWRHP = 19.002 FREQ = 66.780 WRKLT = 24.634 UTOTAL = 0.000
ENSP = 63.0710 AVGWSP = 2157.025 QEXPN = -4.589 QEXP = 0.125 QHEATN = -386.310 QHEATP = 2.176 QCOLDN = -4.616 QCOLDP = 197.033 QCOMPN = 0.000 QCOMPP = 2.795
QREGN = -1761.219 QREGP = 1760.561 QCNDRI = 5.178 QCNDRO = 5.178 QCHEATN = -386.310 QCHEATP = 2.176 QCOLDN = -4.616 QCOLDP = 197.033 QCOMPN = 0.000 QCOMPP = 2.795

** LAST CYCLE **
QIN = 378.131 QOUT = 260.212 WRKEXP = 358.513 WRKCM = -202.013 WRKTOT = 156.500 EFFTOT = 0.414 REFF1 = 0.997 REFF2 = 0.995
QREGN = -0.658 PWRHP = 19.002 FREQ = 66.780 WRKLT = 24.634 UTOTAL = 0.000
ENSP = 63.0710 AVGWSP = 2157.025 QEXPN = -4.589 QEXP = 0.125 QHEATN = -386.310 QHEATP = 2.176 QCOLDN = -4.616 QCOLDP = 197.033 QCOMPN = 0.000 QCOMPP = 2.795

** AVERAGE VALUES OVER LAST 5 CYCLES **
QIN = 378.176 QOUT = 260.410 WRKEXP = 358.522 WRKCM = -202.027 WRKTOT = 156.495 EFFTOT = 0.414 REFF1 = 0.997 REFF2 = 0.995
QREGN = -0.648 PWRHP = 19.002 FREQ = 66.780 WRKLT = 24.635 UTOTAL = 0.000
ENSP = 63.0710 AVGWSP = 2157.025 QEXPN = -4.590 QEXP = 0.125 QHEATN = -386.352 QHEATP = 2.176 QCOLDN = -4.599 QCOLDP = 197.216 QCOMPN = 0.000 QCOMPP = 2.797

** AVG TEMPS.--LAST 5 CYCLES, AVERAGE H. T. COEFS. & HEAT FLUXES--LAST CYCLE **
TQCYC = 1523. 1522. 1519. 1477. 701. 689. 668. 658.
TFCYC = 1512. 1521. 1540. 1538. 1500. 1395. 778. 695. 678. 667. 663. 654.
HACYC = 1643. 1672. 1672. 1672. 1762. 1395. 778. 666. 664. 641. 646. 592.
NACYC = 0.056 0.000 0.805 0.807 0.000 1.915 1.878 0.000 0.622 0.671 0.000 0.075
H+X = 0.447 0.000 1.415 1.439 0.000 2.957 2.778 0.000 1.025 1.096 0.000 0.062
QDAVX = 5.931 0.000 71.82 74.96 0.00 4.41 4.36 0.00 22.19 18.66 0.00 4.90
QDAHX = 25.24 0.00 137.42 131.73 0.00 8.43 8.53 0.00 45.16 57.51 0.00 25.05

** PRESSURE CALCULATIONS--EXPANSION AND COMPRESSION SPACE **
AVGPE = 2158.025 AVGPC = 2156.872 PEMAX = 2735.649 PEMIN = 1653.789
PCCMAX = 2777.046 PCCMIN = 1623.724
APELAX = 52.560 APEMIN = 246.240 APCMAX = 53.280 APCMIN = 246.240

** ENGINE POWER AND EFFICIENCY CALCULATIONS **
**COOLER AND APPENDIX GAP PUMPING CALCULATIONS**

*AVG. TEMPS.--LAST 5 CYCLES, AVG. H. T. COEFS. & HEAT FLUXES--LAST CYCLE*

**LAST CYCLE**

\[
\begin{align*}
Q_{IN} &= 383.612 \\
Q_{OUT} &= 259.746 \\
Q_{REGEN} &= 0.480 \\
E_{HEATN} &= 0.154 \\
Q_{HEATP} &= 0.154 \\
A_{QREM} &= 0.980 \\
A_{QCOMP} &= 0.980 \\
Q_{REGN} &= 0.480 \\
P_{WRR} &= 19.470 \\
FREQ &= 66.780 \\
W_{RKLH} &= 6.792 \\
W_{RL} &= 6.416 \\
W_{RLM} &= 6.792 \\
W_{RLX} &= 19.589 \\
W_{RLC} &= 1.377 \\
W_{RLB} &= 10.264 \\
W_{ALT} &= 182.192 \\
W_{LE} &= 8.989 \\
W_{LCM} &= 1.275 \\
W_{LEX} &= 8.989 \\
W_{LC} &= 6.792 \\
W_{LX} &= 6.416 \\
W_{L} &= 6.792 \\
W_{LEX} &= 19.589 \\
W_{LC} &= 1.377 \\
W_{LX} &= 10.264 \\
W_{ALT} &= 21.838 \\
\end{align*}
\]

**AVG. VALUES OVER LAST 5 CYCLES**

\[
\begin{align*}
Q_{IN} &= 383.615 \\
Q_{OUT} &= 259.694 \\
Q_{REGEN} &= 0.480 \\
E_{HEATN} &= 0.154 \\
Q_{HEATP} &= 0.154 \\
A_{QREM} &= 0.977 \\
A_{QCOMP} &= 0.977 \\
Q_{REGN} &= 0.480 \\
P_{WRR} &= 19.470 \\
FREQ &= 66.780 \\
W_{RKLH} &= 6.792 \\
W_{RL} &= 6.416 \\
W_{RLM} &= 6.792 \\
W_{RLX} &= 19.589 \\
W_{RLC} &= 1.377 \\
W_{RLB} &= 10.264 \\
W_{ALT} &= 21.838 \\
\end{align*}
\]
\textbf{PRESSURE CALCULATIONS—EXPANSION AND COMPRESSION SPACE}**

\textbf{AVGCPC=2172.765 AVGPC=2171.588 PEMAX=2758.990 PEMIN=1663.097}
\textbf{PCHMAX=2600.018 PCHMIN=1632.701 APMAX=53.280 APENIN=246.240 APCMAX=54.000 APCMIN=246.960}

\textbf{ENGINE POWER AND EFFICIENCY CALCULATIONS}**

\textbf{BASICP=22.487 FRLOSS=4.294 BRKP=15.176 BRKEFF=0.326}
\textbf{AUXLOS=2.692 AUXPWR=12.485 AUXEFF=0.268}

\textbf{COOLER AND APPENDIX GAP PUMPING CALCULATIONS}**

\$CHROM$
\textbf{THEOAV=585 98948208376}
\textbf{RIVD=3.0311088482520}
\textbf{RTUBE=0.27440452269027}
\textbf{QBUPS=22.310718811145}
\textbf{W=0.457790560530550}
\textbf{QHGFS=15.37326780887}
\textbf{QGCPS=0.11240588565159}
\&END
TABLE IX. - FINAL SUMMARY PRINTOUT

ENGINE OPERATING CONDITIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Engine Speed</strong></td>
<td>4006.8 RPM</td>
</tr>
<tr>
<td><strong>Mean Pressure</strong></td>
<td>2171.7 PSI</td>
</tr>
<tr>
<td><strong>Coolant Inlet Temperature</strong></td>
<td>1672.0 R</td>
</tr>
<tr>
<td><strong>Engine Performance Summary</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Brake Power</strong> - 1 Cylinder</td>
<td>12.485 HP</td>
</tr>
<tr>
<td><strong>- 4 Cylinders</strong></td>
<td>49.939 HP</td>
</tr>
<tr>
<td><strong>Brake Efficiency</strong></td>
<td>0.258</td>
</tr>
<tr>
<td><strong>Indicated Power</strong> - 1 Cylinder</td>
<td>19.470 HP</td>
</tr>
<tr>
<td><strong>- 4 Cylinders</strong></td>
<td>77.880 HP</td>
</tr>
<tr>
<td><strong>Indicated Efficiency</strong></td>
<td>0.418</td>
</tr>
<tr>
<td><strong>Heat Rate to Engine</strong> - 1 Cylinder</td>
<td>46.577 HP</td>
</tr>
<tr>
<td><strong>- 4 Cylinders</strong></td>
<td>186.310 HP</td>
</tr>
<tr>
<td><strong>Heat Rate from Engine</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Heat Rate to Coolant</strong> - 1 Cylinder</td>
<td>31.538 HP</td>
</tr>
<tr>
<td><strong>- 4 Cylinders</strong></td>
<td>126.151 HP</td>
</tr>
<tr>
<td><strong>Auxiliary Loss (4 Cylinders)</strong></td>
<td>10.767 HP</td>
</tr>
<tr>
<td><strong>Total Rate (4 Cylinders)</strong></td>
<td>136.918 HP</td>
</tr>
<tr>
<td><strong>% Error in Energy Balance</strong></td>
<td>0.294 %</td>
</tr>
<tr>
<td><strong>Mechanical Loss (4 Cylinders)</strong></td>
<td>17.174 HP</td>
</tr>
<tr>
<td><strong>Flow Friction Loss (4 Cylinders)</strong></td>
<td>12.068 HP</td>
</tr>
<tr>
<td><strong>Indicated Work per Cycle Summary (1 Cylinder)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Expansion Space (WRKEXP)</strong></td>
<td>363.323 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Compression Space (WRKCMP)</strong></td>
<td>-202.969 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Net (WRKTOT)</strong></td>
<td>160.355 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Heat Flow Summary (1 Cylinder)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Heat Rate to Engine</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Expansion Space Heat Rate</strong></td>
<td>-4.352 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Metal to Gas (QEXPN)</strong></td>
<td>0.134 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Net (QEXP)</strong></td>
<td>-4.218 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Heater Heat Rate</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Metal to Gas (QHEATN)</strong></td>
<td>-373.281 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Gas to Metal (QHEATP)</strong></td>
<td>2.760 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Net (QHEATR)</strong></td>
<td>-370.521 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Conduction Losses</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Through Regenerator Housing (QCNDRH)</strong></td>
<td>5.178 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Through Cylinder Housing (QCNDCB)</strong></td>
<td>1.388 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Directly through Piston (QCNDD)</strong></td>
<td>0.368 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Shuttle Loss via Piston (QSHTL)</strong></td>
<td>1.939 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Net (QCNDT)</strong></td>
<td>-8.873 FT-LBF/CYCLE</td>
</tr>
<tr>
<td><strong>Net Heat Rate to Engine (QEIN)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>(- Sign means flow into engine)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Heat Rate from Engine</strong></td>
<td></td>
</tr>
</tbody>
</table>
COOLER HEAT RATE
GAS TO METAL (QC00LP) 201.942 FT-LBF/CYCLE
METAL TO GAS (QC00LN) -4.787 FT-LBF/CYCLE
NET (QC00LR) 197.155 FT-LBF/CYCLE
COMPRESSION SPACE HEAT RATE
GAS TO METAL (QC0MPP) 2.871 FT-LBF/CYCLE
METAL TO GAS (QC0MPN) 0.000 FT-LBF/CYCLE
NET (QC0MP) 2.871 FT-LBF/CYCLE
APPENDIX GAP PUMPING LOSSES
HOT GAP (QHGPS) 15.373 FT-LBF/CYCLE
COLD GAP (QC0GPS) 0.112 FT-LBF/CYCLE
NET (QAPGAP) 15.486 FT-LBF/CYCLE
CONDUCTION LOSSES (QCNDTO)
TOTAL HEAT FLOW TO COOLANT, EXCLUDING MECHANICAL LOSSES
MECHANICAL LOSSES (1 CYLINDER)
NET HEAT RATE TO COOLANT (QCLUD1)
AUXILIARY LOSSES (1 CYLINDER)
NET HEAT RATE FROM ENGINE (QEOUT)
REGENERATOR HEAT FLOW
METAL TO GAS (QREGN) -1774.724 FT-LBF/CYCLE
GAS TO METAL (QREGP) 1775.206 FT-LBF/CYCLE
NET (QREG) 0.482 FT-LBF/CYCLE
% ERROR REG. ENERGY BALANCE (PREGER)
(QREG/(MINIMUM OF ABS. VALUE OF QREGN & QREGP)) 0.027 %
REGENERATOR EFFECTIVENESS CALCULATION (BASED ON ENTHALPY FLOW PER CYLINDER)
NET ENTHALPY FLOW REG. TO HTR. (ENFRTH) 3284.703 FT-LBF/CYCLE
NET ENTHALPY FLOW HTR. TO REG. (ENFHTR) 3294.560 FT-LBF/CYCLE
REG. EFFECT. (REFF1=ENFRTH/ENFHTR) 0.9970
NET ENTHALPY FLOW CLR. TO REG. (ENFCTR) 2117.549 FT-LBF/CYCLE
REG. EFFECT. (REFF2=ENFCTR/ENFRTC) 0.9958
PRESSURE DROP LOSS SUMMARY (PER CYLINDER)
HEATER (WRKLH) 6.792 FT-LBF/CYCLE
REGENERATOR
HOT SIDE (WLEXR) 3.808 FT-LBF/CYCLE
COLD SIDE (WLCMR) 2.608 FT-LBF/CYCLE
NET (WRKLR) 6.416 FT-LBF/CYCLE
COOLER (WRKLC)
CONNECTING DUCTS (END EFFECTS)
HOT SIDE (WLEXE) 8.989 FT-LBF/CYCLE
COLD SIDE (WLCME) 1.275 FT-LBF/CYCLE
NET (WRKLE) 10.264 FT-LBF/CYCLE
NET HOT SIDE (WRKLEX) 19.589 FT-LBF/CYCLE
NET COLD SIDE (WRKLCM) 5.260 FT-LBF/CYCLE
NET ENGINE PRESSURE DROP LOSS (WRKLT) 24.848 FT-LBF/CYCLE
PRESSURES
EXPANSION SPACE
MAXIMUM (PEMAX) 2759.0 PSI 19.028 MPA
MINIMUM (PEMIN) 1663.1 PSI 11.470 MPA
MEAN (AVGPE) 2172.8 PSI 14.985 MPA
RATIO (PEMAX/PEMIN) 1.659
COMPRESSION SPACE
## Table VI. Symbol Definitions for Engine Operating Conditions

*(NAMELIST /INDATA/)*

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDRUN</td>
<td>Alphanumeric run identifier</td>
</tr>
<tr>
<td>P</td>
<td>Mean pressure, lbf/in², (MPa)</td>
</tr>
<tr>
<td>OMEGA</td>
<td>Engine frequency, hz</td>
</tr>
<tr>
<td>TMEXP</td>
<td>Expansion space wall temperature, °R (K)</td>
</tr>
<tr>
<td>TMHFR</td>
<td>Outside temperature of front row (flame side) portion of heater tubes, °R (K)</td>
</tr>
<tr>
<td>TMHBR</td>
<td>Outside temperature of back row portion of heater tubes, °R (K)</td>
</tr>
<tr>
<td>TCYL(1)</td>
<td>Cylinder housing temperature, top, °R (K)</td>
</tr>
<tr>
<td>TCYL(2)</td>
<td>Cylinder housing temperature, middle, °R (K)</td>
</tr>
<tr>
<td>TCYL(3)</td>
<td>Cylinder housing temperature, bottom, °R (K)</td>
</tr>
<tr>
<td>TCAN(1)</td>
<td>Insulation container temperature, top, °R (K)</td>
</tr>
<tr>
<td>TCAN(2)</td>
<td>Insulation container temperature, bottom, °R (K)</td>
</tr>
<tr>
<td>TR0</td>
<td>Regenerator housing temperature, top, °R (K)</td>
</tr>
<tr>
<td>TR1</td>
<td>Regenerator housing temperature, middle, °R (K)</td>
</tr>
<tr>
<td>TR2</td>
<td>Regenerator housing temperature, bottom, °R (K)</td>
</tr>
<tr>
<td>GPMH20</td>
<td>Cooling water flow rate per cylinder, gal./min (liter/sec)</td>
</tr>
<tr>
<td>TH20IN</td>
<td>Cooling water inlet temperature, °R (K)</td>
</tr>
</tbody>
</table>
### TABLE V. - SYMBOL DEFINITIONS (AND TEST CASE SETTINGS) FOR MODEL OPTION SWITCHES AND MULTIPLYING FACTORS (NAMELIST /STRLNG/)

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>SETTING</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>REALGS</td>
<td>1.</td>
<td>Use real gas equation of state</td>
</tr>
<tr>
<td></td>
<td>0.</td>
<td>Use ideal gas equation of state</td>
</tr>
<tr>
<td>FACT1</td>
<td>0.4}</td>
<td>Empirical factors used in regenerator matrix temperature convergence procedure</td>
</tr>
<tr>
<td>FACT2</td>
<td>10.0}</td>
<td>Number of engine cycles to be calculated (per pass)</td>
</tr>
<tr>
<td>NOCYC</td>
<td>1</td>
<td>Cycle number at which regenerator matrix temperature convergence procedure begins</td>
</tr>
<tr>
<td>NSTRT</td>
<td>20</td>
<td>Cycle number at which regenerator matrix temperature convergence procedure ends</td>
</tr>
<tr>
<td>NOEND</td>
<td>25</td>
<td>Use hydrogen working gas</td>
</tr>
<tr>
<td>MWGAS</td>
<td>4</td>
<td>Use helium working gas</td>
</tr>
<tr>
<td>RHCFAC</td>
<td>1.</td>
<td>Regenerator heat transfer coefficient multiplying factor</td>
</tr>
<tr>
<td>HHCFAC</td>
<td>1.</td>
<td>Heater heat transfer coefficient multiplying factor</td>
</tr>
<tr>
<td>CHCFAC</td>
<td>1.</td>
<td>Cooler heat transfer coefficient multiplying factor</td>
</tr>
<tr>
<td>IPCV</td>
<td>0</td>
<td>Make second pass through calculations to improve prediction of effect of pressure drop</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Eliminate second pass</td>
</tr>
<tr>
<td>FMULT</td>
<td>1.0</td>
<td>Overall pressure drop multiplying factor</td>
</tr>
<tr>
<td>FMULTR</td>
<td>1.0</td>
<td>Regenerator pressure drop multiplying factor</td>
</tr>
<tr>
<td>IMIX</td>
<td>1</td>
<td>Use mixture of hydrogen and carbon dioxide working gas</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>Pure hydrogen or helium working gas</td>
</tr>
<tr>
<td>VH2</td>
<td>0.99</td>
<td>Volume fraction of hydrogen in hydrogen-carbon dioxide mixture (used only if IMIX=1)</td>
</tr>
<tr>
<td>IPUMP</td>
<td>1</td>
<td>Calculate pumping loss due to piston-cylinder gap</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>Omit pumping loss calculation</td>
</tr>
<tr>
<td>ICOND</td>
<td>1</td>
<td>Calculate cylinder and regenerator housing temperatures from TM(1), TM(4) and TH20IN (Input hot and cold end temperatures)</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>Use the specified input values of the cylinder and regenerator housing temperatures for conduction calculations</td>
</tr>
<tr>
<td>IOUT</td>
<td>1</td>
<td>Write out Table VII or VIII data</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>Don't write out Table VII or VIII data</td>
</tr>
<tr>
<td>JIP</td>
<td>0</td>
<td>Write out Table VII data if IOUT=1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Write out Table VIII data if IOUT=1</td>
</tr>
<tr>
<td>IPRINT</td>
<td>500</td>
<td>Number of time steps between variable printouts in Table VII data</td>
</tr>
<tr>
<td>ITMPS</td>
<td>1</td>
<td>Write out instantaneous gas temperatures at each time step in Table VII (for debugging)</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>Don't write out instantaneous gas temperatures at each time step</td>
</tr>
<tr>
<td>MAPLOT</td>
<td>1</td>
<td>Store variables for plotting</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>Don't store variables for plotting</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td><strong>MAXIMUM (P_{C_{MAX}})</strong></td>
<td>2800.0 PSI</td>
<td>19.310 MPA</td>
</tr>
<tr>
<td><strong>MINIMUM (P_{C_{MIN}})</strong></td>
<td>1632.7 PSI</td>
<td>11.260 MPA</td>
</tr>
<tr>
<td><strong>MEAN (AVGPC)</strong></td>
<td>2171.6 PSI</td>
<td>14.976 MPA</td>
</tr>
<tr>
<td><strong>RATIO (P_{C_{MAX}}/P_{C_{MIN}})</strong></td>
<td>1.715</td>
<td></td>
</tr>
<tr>
<td><strong>MEAN PRESSURE, CTR. OF REG. (AVGWSP)</strong></td>
<td>2171.7 PSI</td>
<td>14.978 MPA</td>
</tr>
<tr>
<td><strong>AVERAGE PRESSURE RATIO ((P_{EMAX}+P_{C_{MAX}})/(P_{EMIN}+P_{C_{MIN}}))</strong></td>
<td></td>
<td>1.687</td>
</tr>
</tbody>
</table>
TABLE X. - READ/WRITE UNIT NUMBERS
USED FOR INPUT/OUTPUT

<table>
<thead>
<tr>
<th>INPUT/OUTPUT STATEMENT</th>
<th>SUBROUTINE</th>
<th>UNIT</th>
<th>INPUT/OUTPUT DATA #</th>
<th>INPUT/OUTPUT DATA (TEST CASE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. READ</td>
<td>ROMBC</td>
<td>4</td>
<td></td>
<td>TABLE II</td>
</tr>
<tr>
<td>2. READ</td>
<td>ROMBC</td>
<td>5</td>
<td></td>
<td>TABLE IV</td>
</tr>
<tr>
<td>3. WRITE</td>
<td>ROMBC,CYCL</td>
<td>6</td>
<td></td>
<td>TABLE VII (if IOUT=1 and JIP=0)</td>
</tr>
<tr>
<td>4. WRITE</td>
<td>CYCL</td>
<td>16</td>
<td></td>
<td>TABLE IX</td>
</tr>
<tr>
<td>5. WRITE</td>
<td>ROMBC</td>
<td>13</td>
<td></td>
<td>BINARY OUTPUT (if MAPLOT=1)</td>
</tr>
</tbody>
</table>
TABLE XI. - ARRAYS SET VIA EQUIVALENCE STATEMENT IN SUBROUTINE ROMBC

| COMMON/RESET/ | WRKLT, WRKLR, WRKLE, WRKLT0, WRKLR0, WRKLE0, SET(1), SET(2), SET(3), SET(4), SET(5), SET(6), SET(7) |
| COMMON/TIME0/ | WEPO, WCP0, WEPE0, WCP0, WEDU0, WCDU0, WEDU0, W0(1), W0(2), W0(3), W0(4), W0(5), W0(6), W0(7), WCDUC0, WEDUE0, WCDUC0, WEALT0, WTPC0, W0(8), W0(9) |
| COMMON/TIME1/ | WEP1, WCP1, WEPE1, WCP1, WEDU1, WCDU1, WEDU1, W1(1), W1(2), W1(3), W1(4), W1(5), W1(6), W1(7), WCDUC1, WEDUE1, WCDUC1, WEALT1, WTPC1, W1(8), W1(9), W1(10), W1(11), W1(12) |
| COMMON/TIME2/ | WEP2, WCP2, WEPE2, WCP2, WEDU2, WCDU2, WEDU2, W2(1), W2(2), W2(3), W2(4), W2(5), W2(6), W2(7), WCDUC2, WEDUE2, WCDUC2, WEALT2, WTPC2, W2(8), W2(9), W2(10), W2(11), W2(12) |
| COMMON/PSET/ | PRIN, PROUT, PEXP, PCMP, PEDUR, PCDUR, PEDUH, PCDUC, PS(1), PS(2), PS(3), PS(4), PS(5), PS(6), PS(7), PS(8), PEDUE, PCDUE, PEALT, P(9), P(10), P(11) |
Figure 1. - P40 Stirling engine cross section.
Figure 2 - Control volumes as set-up for test case

Figure 3 - Overall simulation structure

Figure 4 - Pressure vs crank angle
Figure 5 - vol vs crank angle

Figure 6 - Gas temperature vs crank angle
Figure 6. - Completed.

Figure 7. - Gas flow rate vs crank angle.

Figure 8. - Engine pressure drop vs crank angle

Figure 9 - P-V diagrams
Figure 10 - Generalized control volume

Inputs, preliminary calculations, initializations

1. Update time and crank angle, ROMBC
2. Update expansion and compression space volumes, ROMBC
3. Update thermal conductivity and viscosity for gas control volumes, HEATX
4. Update pressure level, HEATX
5. Update gas specific heats, HEATX
6. Update gas temperatures for effect of change in specific heats, HEATX
7. Update gas temperatures for effect of change in pressure, HEATX
8. Update mass distribution, HEATX
9. Update flow rates, HEATX
10. Update gas temperatures for effect of flow between control volumes, HEATX
11. Update heat transfer coefficients, HEATX
12. Update gas temperatures for effect of metal-gas heat transfer, HEATX
13. Update regenerator matrix temperatures, HEATX
14. Update friction factors and pressure drops for each control volume, XDLS
15. Update conduction and shuttle losses once each cycle, CNDCT
16. Sum up heat transfers for each component, HEATX
17. Calculate work and sum up for cycle, ROMBC
18. Is cycle complete?
   Yes
   No
   19. Revise regenerator matrix temperatures?, ROMBC
       Yes
       Make revision
       No
   20. Calculate indicated power and efficiency, CYCL
   21. Calculate mechanical friction losses, CYCL
   22. Calculate auxiliary losses and brake power and efficiency, CYCL (if specified number of cycles has been completed)
   23. Revise cooler tube temperatures?, ROMBC
       Yes
       Make revision
       No
   24. Have specified number of cycles been completed?, ROMBC
       Yes
       No
   25. Is this the second pass through no cycles?, ROMBC
       Yes
       No
   26. Reset time to 0 and make 2nd pass using 4th
       information from 1st pass
   27. Write summary of predictions and terminate run

Figure 11 - Outline of calculation procedures
Figure 12 - Sample regenerator control volume and temperature profile

Figure 13 - Mechanical power loss as a function of engine speed and mean pressure
Figure 14 - Auxiliary power requirement as a function of engine speed and mean pressure

Nominal operating conditions
15 MPa mean pressure
720°C heater set temperature
50°C coolant inlet temperature
Regenerator effectiveness = 0.996

Figure 15 - P-40 brake power and efficiency as functions of engine speed.
Nominal operating conditions:
- 15 MPa mean pressure
- 720°C heater set temperature
- 50°C coolant inlet temperature
Regenerator effectiveness = 0.990

- Measured
- Predicted

Figure 16 - P-40 brake power and efficiency as functions of engine speed
**Abstract**

To support the development of the Stirling engine as a possible alternative to the automobile spark-ignition engine, the thermodynamic characteristics of the Stirling engine were analyzed and modeled on a computer. The computer model is documented. The documentation includes a user’s manual, symbols list, a test case, comparison of model predictions with test results, and a description of the analytical equations used in the model.

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**Key Words (Suggested by Author(s))**

- Stirling engine
- Computer model
- Stirling cycle

**Distribution Statement**

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