Documentation of the Benson Diesel Engine Simulation Program

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2.0</td>
<td>OVERVIEW OF PROGRAM</td>
<td>2</td>
</tr>
<tr>
<td>2.1</td>
<td>Energy Balance - Benson Model</td>
<td>2</td>
</tr>
<tr>
<td>2.2</td>
<td>Change in Internal Energy</td>
<td>6</td>
</tr>
<tr>
<td>2.3</td>
<td>Combustion</td>
<td>6</td>
</tr>
<tr>
<td>2.3.1</td>
<td>Wiebe Model</td>
<td>6</td>
</tr>
<tr>
<td>2.3.2</td>
<td>The AVL Model</td>
<td>7</td>
</tr>
<tr>
<td>2.3.3</td>
<td>The Whitehouse-Way Model</td>
<td>7</td>
</tr>
<tr>
<td>2.3.4</td>
<td>The Watson Model</td>
<td>9</td>
</tr>
<tr>
<td>2.3.5</td>
<td>User Supplied Model</td>
<td>10</td>
</tr>
<tr>
<td>2.4</td>
<td>Heat Transfer</td>
<td>10</td>
</tr>
<tr>
<td>2.5</td>
<td>Work</td>
<td>13</td>
</tr>
<tr>
<td>2.6</td>
<td>Mass Flow Terms</td>
<td>13</td>
</tr>
<tr>
<td>3.0</td>
<td>STEADY STATE HEAT TRANSFER ANALYSIS</td>
<td>14</td>
</tr>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>14</td>
</tr>
<tr>
<td>3.2</td>
<td>Definition of Temperature</td>
<td>15</td>
</tr>
<tr>
<td>3.3</td>
<td>Network Diagram</td>
<td>15</td>
</tr>
<tr>
<td>3.4</td>
<td>Definition of Heat Generation Terms</td>
<td>22</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Friction Submodel</td>
<td>22</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Crevice Volume Heat Transfer Submodel</td>
<td>23</td>
</tr>
<tr>
<td>3.5</td>
<td>Node Equations</td>
<td>27</td>
</tr>
<tr>
<td>3.6</td>
<td>Solution Technique</td>
<td>28</td>
</tr>
<tr>
<td>4.0</td>
<td>INPUT DATA</td>
<td>29</td>
</tr>
<tr>
<td>4.1</td>
<td>Subroutine INPUT</td>
<td>29</td>
</tr>
<tr>
<td>4.2</td>
<td>Subroutine INPUT2</td>
<td>31</td>
</tr>
<tr>
<td>5.0</td>
<td>OUTPUT</td>
<td>33</td>
</tr>
<tr>
<td>6.0</td>
<td>SAMPLE CASES</td>
<td>34</td>
</tr>
<tr>
<td>6.1</td>
<td>Napier Nomad</td>
<td>34</td>
</tr>
<tr>
<td>6.2</td>
<td>Garrett CCE</td>
<td>36</td>
</tr>
<tr>
<td>7.0</td>
<td>DOCUMENTATION OF SUBROUTINES</td>
<td>38</td>
</tr>
<tr>
<td>7.1</td>
<td>Subroutine BENSON</td>
<td>38</td>
</tr>
<tr>
<td>7.2</td>
<td>Subroutine BAL</td>
<td>38</td>
</tr>
<tr>
<td>7.3</td>
<td>Subroutine CYLNDR</td>
<td>40</td>
</tr>
<tr>
<td>7.4</td>
<td>Subroutine CYLVD</td>
<td>41</td>
</tr>
<tr>
<td>7.5</td>
<td>Subroutine ELIM</td>
<td>43</td>
</tr>
<tr>
<td>7.6</td>
<td>Subroutine FCLOSE</td>
<td>43</td>
</tr>
<tr>
<td>7.7</td>
<td>Subroutine FOPEN</td>
<td>44</td>
</tr>
<tr>
<td>7.8</td>
<td>Subroutine HEADER</td>
<td>44</td>
</tr>
</tbody>
</table>
DOCUMENTATION OF THE BENSON DIESEL ENGINE SIMULATION PROGRAM

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1.0 INTRODUCTION

This report documents the Benson Diesel Engine Simulation Program and explains how it can be used to predict the performance of diesel engines. This program was obtained from the Garrett Turbine Engine Company but has been extensively modified since that time. The program is a thermodynamic simulation of the diesel engine cycle which uses a single zone combustion model. It can be used to predict the effect of changes in engine design and operating parameters such as valve timing, speed and boost pressure. The most significant change made to this program is the addition of a more detailed heat transfer model to predict metal part temperatures.

This report contains a description of the sub-models used in the Benson program, a description of the input parameters and sample program runs.

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2.0 OVERVIEW OF PROGRAM

As shown in Figure 2.1, the Benson program uses a large number of subroutines to accomplish specialized tasks during the calculation procedure. However, most of the cycle calculations are performed in two subroutines: CYLNDR, which calculates the gas exchange processes and POWER which takes care of compression, combustion and expansion. The development of the energy balance and a discussion of how it is evaluated is given below.

2.1 Energy Balance - Benson Model

The chemical equation for the combustion process in the diesel engine can be simplified to the following expression.

\[ C_{n}H_{m} + \left[ \frac{n + m/2}{\phi} \right] [O_{2} + 3.77 N_{2}] \rightarrow n CO_{2} + \frac{m}{2} H_{2}O + \left( \frac{[n + m/2]}{\phi} - n - \frac{m}{4} \right) O_{2} + 3.77 \left( \frac{n + m/2}{\phi} \right) N_{2} \]

where \( n \) and \( m \) are stoichiometric coefficients and \( \phi \) is the equivalence ratio.

The first law of thermodynamics must be satisfied at all times as this reaction occurs in the engine. For the period when the intake and exhaust ports are closed, the first law can be written for an interval of time from \( t \) to \( t + dt \),

\[ E_{2} - E_{1} = \delta Q - \delta W \]

where \( E_{2} \) and \( E_{1} \) are given by

\[ E_{2} = a_{N_{2}} e_{N_{2}}(T_{2}) + a_{O_{2}} e_{O_{2}}(T_{2}) + a_{CO_{2}} e_{CO_{2}}(T_{2}) + a_{H_{2}O} e_{H_{2}O}(T_{2}) + a_{C_{n}H_{m}} e_{C_{n}H_{m}}(T_{2}) \]
\[ E_{1} = b_{N_{2}} e_{N_{2}}(T_{1}) + b_{O_{2}} e_{O_{2}}(T_{1}) + b_{CO_{2}} e_{CO_{2}}(T_{1}) + b_{H_{2}O} e_{H_{2}O}(T_{1}) + b_{C_{n}H_{m}} e_{C_{n}H_{m}}(T_{1}) \]

The coefficients, \( a_{i} \) and \( b_{i} \), are the number of moles of species \( i \) present in the cylinder and

\[ e_{i}(T) = e_{i}(0) + [e_{i}(T) - e_{i}(0)] \]
SUBROUTINE BENSON

Open input/output files
CALL FOPEN

SUBROUTINE FOPEN

Read input variables
CALL INPUT
CALL INPUT2

SUBROUTINE INPUT
SUBROUTINE INPUT2

Initialize variables
CALL INITLZ

SUBROUTINE INITLZ
UNITF UNITP UNITW

Write file headings to output files
CALL HEADER

SUBROUTINE HEADER

Perform cycle calculations
CALL CYLNDR

SUBROUTINE CYLNDR
SPLFIT STROK SREA BAL CYLVol

RETURN

SUBROUTINE POWER

SUBROUTINE HTRANS

SUBROUTINE ELIM

Figure 2.1 Flow Chart for Benson Program
where $e_i(0)$ is the partial molar internal energy of species $i$ at absolute zero and $[e_i(T) - e_i(0)]$ is the sensible internal energy difference between absolute zero and $T$.

For convenience, the sum of the sensible terms can be defined as $E^\text{w}$

$$E^\text{w}(T) = a_{N_2}[e_{N_2}(T) - e_{N_2}(0)] + a_{O_2}[e_{O_2}(T) - e_{O_2}(0)]$$
$$+ a_{CO_2}[e_{CO_2}(T) - e_{CO_2}(0)] + a_{H_2O}[e_{H_2O}(T) - e_{H_2O}(0)]$$

Thus $E_2 - E_1$ can be written as

$$E_2 - E_1 = (E^\text{w} - E^\text{w}_1) + (a_{N_2} - b_{N_2})e_{N_2}(0) + (a_{O_2} - b_{O_2})e_{O_2}(0)$$
$$+ (a_{CO_2} - b_{CO_2})e_{CO_2}(0) + (a_{H_2O} - b_{H_2O})e_{H_2O}(0)$$
$$+ (a_{CH_n^m} - b_{CH_n^m})e_{CH_n^m}(0)$$

If $dM_f$ moles of fuel are burned as the reaction progresses from $t$ to $t+dt$, atom balances can be used to fix relations between the $a_i$ and $b_i$ coefficients.

$$a_{N_2} = b_{N_2}$$
$$a_{O_2} = b_{O_2} - [n + \frac{m}{4}] dM_f$$
$$a_{CO_2} = b_{CO_2} + n dM_f$$
$$a_{H_2O} = b_{H_2O} + \frac{m}{2} dM_f$$
$$a_{CH_n^m} = b_{CH_n^m} - dM_f$$

The constant volume heat of combustion with the water in the products present as vapor can be defined as

$$Q_v = E_{\text{prod}}(T_s) - E_{\text{reac}}(T_s)$$

where

$$E_{\text{prod}} = n e_{CO_2}(T_s) + \frac{m}{2} e_{H_2O}(T_s)$$
$$E_{\text{reac}} = [n + m/2] e_{O_2}(T_s) + e_{CH_n^m}(T_s)$$

$T_s$ = reference temperature where $Q_v$ is defined.
By combining the definition of the constant volume heat of combustion and the definition of the constant volume heat of combustion at absolute zero

$$\Delta E_o \equiv E_{\text{prod}}(0) - E_{\text{reac}}(0)$$

we can obtain

$$Q_v = \Delta E_o + n[e_{\text{CO}_2}(T_s) - e_{\text{O}_2}(0)] + \frac{m}{2}[e_{\text{H}_2\text{O}}(T_s) - e_{\text{H}_2\text{O}}(0)]$$

$$- (n + \frac{m}{4})[e_{\text{O}_2}(T_s) - e_{\text{O}_2}(0)] - [e_{\text{C}_n\text{H}_m}(T_s) - e_{\text{C}_n\text{H}_m}(0)]$$

Substituting this into the equation for $E_2 - E_1$ gives

$$E_2 - E_1 = E_2^* - E_1^* - Q_v \, dM_f - (a_{\text{CO}_2} - b_{\text{CO}_2})[e_{\text{CO}_2}(T_s) - e_{\text{O}_2}(0)]$$

$$- (a_{\text{H}_2\text{O}} - b_{\text{H}_2\text{O}})[e_{\text{H}_2\text{O}}(T_s) - e_{\text{H}_2\text{O}}(0)]$$

$$+ (a_{\text{O}_2} - b_{\text{O}_2})[e_{\text{O}_2}(T_s) - e_{\text{H}_2\text{O}}(0)]$$

$$+ a_{\text{C}_n\text{H}_m} [e_{\text{C}_n\text{H}_m}(T_2) - e_{\text{C}_n\text{H}_m}(T_s)]$$

$$- b_{\text{C}_n\text{H}_m} [e_{\text{C}_n\text{H}_m}(T_1) - e_{\text{C}_n\text{H}_m}(T_s)]$$

Since the fuel is such a small fraction of the total mass in the cylinder, the fuel internal energy terms can be neglected and the terms evaluated at $T_s$ can be written as

$$E_2 - E_1 = [E_2^* - E_2(T_s)] - [E_1^* - E_1(T_s)] - Q_v \, dM_f$$

where $E_i(T_s)$ designates the sum of the sensible internal energy terms using the composition at state 1 and evaluating the partial molar internal energies at $T_s$.

Finally, the first law of thermodynamics can be written as

$$[E_2^* - E_2(T_s)] - [E_1^* - E_1(T_s)] - Q_v \, dM_f = \delta Q - \delta W$$

for the period where the intake and exhaust ports are closed and when the ports are open the first law becomes

$$[E_2^* - E_2(T_s)] - [E_1^* - E_1(T_s)] - Q_v \, dM_f = \delta Q - \delta W + m_{\text{in}} h_{\text{in}} - m_{\text{out}} h_{\text{out}}$$
Each of the terms in this equation will be discussed in turn.

2.2 Change in Internal Energy

The internal energy is calculated using fourth order polynomial curve fits of the JANAF tables [1]. These curve fits provide the sensible enthalpy change between absolute zero and some temperature T. The values of internal energy are obtained from \( e = h - RT \).

2.3 Combustion

The rate at which fuel is burned, and its energy released, is determined by the choice of combustion model. Currently, four combustion models may be selected for use in the Benson Program along with one user supplied model. The choice of model is determined by the values of the input parameters, NPCWF and DEL3. The values of these parameters corresponding to each model are given below.

- NPCWF = 0 and DEL3 > 0. Wiebe combustion model
- NPCWF = 0 and DEL3 = 0. AVL combustion model
- NPCWF = -1 Whitehouse-Way combustion model
- NPCWF = 1 Watson combustion model
- NPCWF = 2 User supplied model

Each of the combustion models will be discussed in turn.

2.3.1 Wiebe Model

The Wiebe model is a simple functional model consisting of a two parameter exponential function which has the flexibility to assume the shape of known burning rate curves in supercharged diesel engines. The following
expression is used to calculate the fraction of fuel burned.

\[ \text{\% Fuel Burned} = 100 \times [1 - \exp(-\delta_1 \tau^{\delta_2})] \]

where \( \delta_1 \) and \( \delta_2 \) are parameters which determine the shape of the function
\( \tau \) is a dimensionless time parameter \( \tau = \frac{CA - ACB}{HRD} \)
CA is the current crank angle
ACB is the crank angle at which combustion begins
HRD is the combustion duration, equal to \( (ACF - ACB) \)

2.3.2 The AVL Model

The AVL model is the same as the Wiebe model except that AVL has recommended a way to specify the combustion duration. AVL suggests that the combustion duration parameter be chosen so that it is a linear function of the equivalence ratio.

\[ HRD = 15 + 115 \phi \]

where \( \phi \) is the fuel-air equivalence ratio.

2.3.3 The Whitehouse-Way Model

Of the models supplied with the Benson Program, the Whitehouse-Way [2,3] model is the only one that attempts to model the physics of the combustion event. The fuel injection rate is supplied as an input and the model relates the burning rate to this injection rate. The injection rate is specified by two parameters: the initial injection rate and the timing at which the maximum injection rate occurs. The injection rate is defined by the following function.
Injection Rate = $\text{AAN}(1) + \left[ \frac{\text{AA2} - \text{AAN}(1)}{\text{AAN}(2)} \right] \tau \quad 0 < \tau < \text{AAN}(2)$

$$= \frac{\text{AA2}}{\text{AAN}(2) - 1} (\tau - 1) \quad \text{AAN}(2) < \tau \leq 1$$

where $\text{AAN}(1)$ and $\text{AAN}(1)$ are user specified injection rate parameters

$\text{AA2} = 2 - \left[ \text{AAN}(2) \cdot \text{AAN}(1) \right]$  
$\tau = \text{defined same as above under Wiebe}$

Fuel is assumed to be prepared for combustion according to a relation of the form

$$p = K M_1^{1-x} M_u^x P_{O_2}^m$$

where $x$ and $m$ are empirical parameters which should be constant for a given problem.

$K$ is a parameter which needs to be determined for each individual problem.

$P$ is the fuel preparation rate.

$M_1$ is the mass of fuel injected.

$M_u$ is the mass of fuel unburnt.

The burning rate is calculated from an exponential expression of the form:

$$R = \frac{K}{N} P_{O_2} \sqrt{T} \int (P - R) \, dx \cdot \exp\left(-\frac{\text{act}}{T}\right)$$

where $R$ is the burning rate

"act" is an effective activation energy which must be specified

$P_{O_2}$ is the partial pressure of oxygen

$N$ is the engine speed, Rev/min

The integral is evaluated in the Benson program as a summation

$$\Sigma (P - R) \Delta CA$$

and $R$ is calculated using the value of the summation calculated up to the beginning of the time step.
Although the authors of this model have attempted to incorporate combustion theory into this model, it should be recognized that it is based on an understanding of diesel combustion that assumes droplet effects are important. Current understanding of diesel combustion assumes that the fuel vaporizes very soon after it is injected and that the combustion has more in common with a turbulent gaseous diffusion flame than droplet combustion.

2.3.4 The Watson Model

The Watson model [4] is a functional model, like the Wiebe model, which uses simple algebraic functions chosen for their ability to produce burning curves similar to those observed in diesel engines. The Watson model was developed to reproduce the "premixed spike" at the start of typical diesel heat release curve. Instead of a single exponential curve like the Wiebe model, the Watson model uses two curves which are superimposed. The first curve has a very high rate of combustion and simulates the premixed combustion. This curve dies out very quickly after the start of combustion and the second curve, which is an exponential exactly like the Wiebe model, becomes dominant. A weighting factor is used to determine how much emphasis is given to each of the curves. The Watson model is as follows.

\[
\% \text{Fuel Burned} = 100 \cdot \left[ \beta \left( 1 - [1 - \tau P_1] P_2 \right) + (1 - \beta) \left( 1 - \exp[-C_{d_1} \tau^{C_{d_2}}] \right) \right]
\]

where \( \beta = \text{weighting factor} = 1 - \delta_1 \phi^{-\delta_3} \cdot \text{actr} \)

\[
C_{P_1} = 2. + 1.25 \times 10^{-8} (\text{actr} \cdot \text{Nr} \cdot 60.)^{2.4}
\]

\[
C_{P_2} = 5000.
\]

\[
C_{d_1} = 14.2 \phi^{-0.644}
\]
\( C_{d_2} = 0.79 \cdot C_{d_1} \)

\( \text{actr} = \text{ignition delay period, which may be estimated from} \)

\[
\text{actr} = 3.45 \exp\left(\frac{2100}{T_m}\right) P_m^{-1.02}
\]

where \( T_m \) and \( P_m \) are the mean temperature and pressure during the ignition delay period.

\( \phi = \text{equivalence ratio} \)

\( N_r = \text{engine speed, rev/sec} \)

\( \delta_1, \delta_2, \delta_3 = \text{parameters chosen to vary shape of the model.} \)

(Watson suggests \( \delta_1 = 0.926, \delta_2 = 0.37 \) and \( \delta_3 = -0.26 \))

The Watson model, because it can simulate premixed combustion, is appropriate for conditions where premixed combustion is important such as light loads and cold starting with naturally aspirated engines. This model is also appropriate when running on low cetane fuels. Under highly supercharged conditions the amount of premixed combustion will be small (\( \beta \approx 0 \)) so the Watson model reduces to the Wiebe model.

2.3.5 User supplied model

The user may provide a mass burning rate function of any arbitrary shape through the subroutine BURNRT. The subroutine should be written so that at a given value of crank position, designated by ANGLA, the amount of fuel burned in a one degree time step is returned as DWFUEL.

2.4 Heat Transfer

\[ \frac{q}{A} = \frac{a}{D} k (Re)^b \left( T - T_w \right) + c \left( T^4 - T_w^4 \right) \]

where  
\( q \) = heat transfer 
\( A \) = Area of surface exposed to heat transfer 
\( k \) = Thermal conductivity 
\( Re \) = Reynolds number \( = \frac{\rho U_p D}{\mu} \) 
\( T \) = Gas Temperature 
\( T_w \) = Wall Temperature 
\( U_p \) = Mean Piston speed 
\( p \) = gas density 
\( \mu \) = gas viscosity 
\( D \) = Bore of engine 

\( a, b, c \) = User supplied constants, called ANNA, ANNB and ANNC in the Benson Program.

The constant, \( a \), depends on the intensity of gas motion in the cylinder and Annand recommends a value between 0.35 and 0.8, with higher values corresponding to more intense motion. The constant, \( b \), should be 0.7 and the constant \( c \) should be:

- during compression, \( c = 0 \).
- during combustion and expansion,
  \[ c = 3.266 \times 10^{-11} \frac{kW}{m^2 - K^4} \] for diesel engine
  \[ c = 4.286 \times 10^{-12} \frac{kW}{m^2 - K^4} \] for spark ignition engine

Woschni's correlation is of the following form.

\[ \frac{q}{A} = \frac{k}{D} \left( Re \right)^b \left( T - T_w \right) \]
where \( \text{Re} = \frac{\rho w D}{\mu} \)

\( w \) = in-cylinder gas velocity

\[ = 6.18 \frac{U}{P} \text{ during scavenging period, m/s.} \]
\[ = 2.28 \frac{U}{P} \text{ during compression, m/s} \]
\[ = 2.28 \frac{U}{P} + 3.24 \times 10^{-3} \frac{V_s T_1}{P_1 V_1} (p - p_0) \text{ during combustion} \]

and expansion, m/s

\( V_s \) = displacement volume.

\( p_1, \ V_1, \ T_1 \) = pressure, volume and temperature at some point when the cylinder is closed for use in estimating the trapped mass.

\( p \) = instantaneous cylinder pressure

\( p_0 \) = cylinder pressure for an unfired cycle at the same crank position and under the same conditions as \( p \).

\( a, b \) = User supplied constants, called ANNA and ANNB in the Benson program. Woschni recommends a value of 0.035 for constant \( a \) and 0.8 for constant \( b \).

The principal difference between these two correlations is that Annand's correlation separates the convective and radiative terms while Woschni's correlation combines the convection and radiation in a single term. The user supplied parameters ANNA, ANNB and ANNC are used to select which correlation will be used in the program and to adjust the significance of heat transfer in the energy balance. When ANNC is equal to 0.0, the Woschni correlation will be used, and when ANNC is equal to a non-zero number, the Annand correlation will be used. ANNB is normally set to the respective author's suggested value. ANNA is also normally set to the author's values unless data is available which indicate the total amount of heat loss for the cycle in which
case ANNA can be adjusted to obtain this amount.

2.5 Work

The work term is calculated from time step to time step by taking the average pressure for the time step multiplied by the volume change for the time step.

$$\delta W = \frac{P_1 + P_2}{2} \cdot (V_2 - V_1)$$

2.6 Mass Flow Terms

The mass flow terms are calculated using subroutine MASSFL which calculates the mass entering or leaving the cylinder through the intake or exhaust ports. The techniques involved in this calculation are explained later in the discussion of that subroutine. After calculating the mass flow rates, the enthalpy is calculated using the polynomial curve-fits to the JANAF tables.
3.0 **STEADY STATE HEAT TRANSFER ANALYSIS**

3.1 **Introduction**

The original version of the Benson Program received from Garrett contains a simple heat transfer analysis which calculates convective heat transfer coefficients using either the Annand or the Woschni correlations as described in section 2.4. The analysis described in this section has been added to the Benson program to allow prediction of the effect of varying engine design parameters and operating conditions on metal part temperatures. The analysis provides an estimate of the gas and coolant side wall temperatures for the piston crown, the cylinder wall, the head and the exhaust valve along with the top compression ring temperature.

The model is one-dimensional and assumes the temperatures of the various components do not change during the cycle. The model has been developed for a single cylinder engine and can not distinguish between end cylinders or internal cylinders of a multi-cylinder engine. Submodels for the heat generated by piston/ring friction and for crevice volume heat transfer are included.

The analysis requires that a number of critical engine dimensions be specified along with heat transfer path lengths. Although these heat transfer path lengths can be estimated, a high level of accuracy requires that experimental measurements be used to calculate these path lengths and thus "tune" the heat transfer analysis. Without experimental data, the absolute values of the temperatures provided by this analysis can be no more accurate than the path lengths supplied as input. However, even though the numerical values of temperature may be in doubt, the analysis should still predict
trends accurately.

3.2 Definition of Temperatures

Figure 3.1 shows a cross-section of the engine cylinder and identifies the various temperatures used in the analysis. Heat transfer occurs from the hot cylinder gases through the metal parts to the engine coolant. Three coolant temperatures are identified: the head coolant, the cylinder wall coolant and the piston coolant. The exhaust valve receives heat from the cylinder gases and loses it to the head by conduction through the valve seat, to the valve guide by conduction up the valve stem and to the exhaust port gases by convection.

The temperatures labeled in Figure 3.1 are defined below.

\[
\begin{align*}
TC1 &= \text{Piston cooling oil temperature} \\
TC2 &= \text{Cylinder wall coolant temperature} \\
TC3 &= \text{Head coolant temperature} \\
TWCC &= \text{Coolant side cylinder wall temperature} \\
TWGC &= \text{Gas side cylinder wall temperature} \\
TWCH &= \text{Coolant side head temperature} \\
TWGH &= \text{Gas side head temperature} \\
TWCP &= \text{Coolant side piston temperature} \\
TWGP &= \text{Gas side piston temperature} \\
TWPR &= \text{Piston rim temperature} \\
TWCR &= \text{Top compression ring temperature} \\
TWEV &= \text{Exhaust valve temperature} \\
TWEVG &= \text{Exhaust valve guide temperature} \\
TEXHP &= \text{Exhaust port gas temperature}
\end{align*}
\]

3.3 Network Diagram

It is common in heat transfer problems to take advantage of the analogy between heat transfer through thermal resistance and direct current flow through electrical resistance. Steady state heat transfer relations such as

\[
Q = h A (T_2 - T_1) \quad \text{and} \quad Q = k A \frac{(T_1 - T_2)}{L}
\]
Figure 3.1 Cross-section of Cylinder
can be written as

\[ Q = \frac{T_2 - T_1}{R_1} \quad \text{and} \quad Q = \frac{T_1 - T_2}{R_2} \]

where

\[ R_1 = \frac{1}{hA} \quad \text{and} \quad R_2 = \frac{L}{kA} \]

the temperatures \( T_1 \) and \( T_2 \) represent potentials similar to voltages and the thermal resistances \( R_1 \) and \( R_2 \) are analogous to electrical resistances. One advantage of this approach is that it allows the heat transfer problem to be represented pictorially as a resistance network diagram.

Figure 3.2 shows the network diagram of the heat transfer problem identified above. The node points in this diagram correspond to the temperatures identified in Figure 3.2. The resistances are defined below.

- \( R_1 \) = Conductive resistance between exhaust valve and the valve guide
- \( R_2 \) = Convective resistance between exhaust valve and exhaust port gases.
- \( R_3 \) = Conductive resistance between exhaust valve and the cylinder head through the valve seat.
- \( R_4 \) = Conductive resistance through the cylinder head.
- \( R_5 \) = Convective resistance between head and head coolant
- \( R_6 \) = Conductive resistance from the gas side of piston crown to oil-cooled under-side of piston.
- \( R_7 \) = Convective resistance on oil-cooled underside of piston.
- \( R_8 \) = Conductive resistance between piston and cylinder wall through the lower rings and the oil film.
- \( R_9 \) = Conductive resistance between piston crown and piston rim.
- \( R_{10} \) = Conductive resistance between top compression ring and the cylinder wall.
- \( R_{11} \) = Conductive resistance through cylinder wall.
- \( R_{12} \) = Conductive resistance between piston rim and top compression ring.
- \( R_{13} \) = Convective resistance between cylinder wall and coolant.
- \( R_{14} \) = Combined convective and radiative resistance between cylinder...
wall and cylinder gases.

\( R_{15} = \) Combined convective and radiative resistance between piston crown and cylinder gases.

\( R_{16} = \) Combined convective and radiative resistance between head and cylinder gases.

\( R_{17} = \) Combined convective and radiative resistance between exhaust valve and cylinder gases.

These resistances can be expressed in terms of more fundamental quantities as follows.

\[
\begin{align*}
R_1 &= \frac{XXEVG}{AEXVS \cdot CEXV} \\
R_2 &= \frac{1}{HEXHP \cdot AEXV} \\
R_3 &= \frac{XXEVH}{AEXST \cdot CEXV} \\
R_4 &= \frac{XXHED}{AHEAD \cdot CHEAD} \\
R_5 &= \frac{1}{HCHD \cdot AHEAD} \\
R_6 &= \frac{XXPIS}{APIST1 \cdot CPIST} \\
R_7 &= \frac{1}{HOILP \cdot APIST2} \\
R_8 &= \frac{XXPSL}{ASLEEV \cdot CPIST} \\
R_9 &= \frac{XXPCR}{APISTR \cdot CPIST} \\
R_{10} &= \frac{XXRSL}{ARING1 \cdot CRING} \\
R_{11} &= \frac{XXSLV}{ASLEEV \cdot CSLEEV} \\
R_{12} &= \frac{XXPRG}{ARING2 \cdot CRING} \\
R_{13} &= \frac{1}{HCSL \cdot ASLEEV}
\end{align*}
\]

where the heat transfer path lengths, areas, thermal conductivities, and convection coefficients are given below:

- \( XXEVG = \) Path length from exhaust valve to valve guide
- \( XXEVH = \) Path length from exhaust valve to valve seat
- \( XXHED = \) Path length through head
- \( XXPIS = \) Path length through piston
- \( XXPSL = \) Path length from piston to cylinder wall through lower rings and oil film
- \( XXPCR = \) Path length from piston crown to piston rim
- \( XXRSL = \) Path length from top compression ring to cylinder wall
- \( XXSLV = \) Path length through cylinder wall
- \( XXPRG = \) Path length from piston rim to top compression ring

- \( AEXVS = \) Area of exhaust valve stem
- \( AEXV = \) Area of exhaust valve exposed to combustion chamber
- \( AEXST = \) Exhaust valve seat contact area
AHEAD = Cylinder head area not covered by exhaust valves
APIST1= Cross-sectional area of cylinder
APIST2= Surface area exposed to oil on underside of piston
ASLEEV= Characteristic area for heat transfer through cylinder wall
APISTR= Characteristic area between piston crown and piston rim
ARING1= Contact area between top compression ring and cylinder wall
ARING2= Contact area between top compression ring and piston rim

CEXV = Thermal conductivity of exhaust valve
CHEAD = Thermal conductivity of head
CPIST = Thermal conductivity of piston
CRING = Thermal conductivity of ring
CSLEEV= Thermal conductivity of cylinder wall

HEXHP = Convection coefficient from back side of exhaust valve to
gases in exhaust port
HCHD = Convection coefficient for coolant on backside of head
HOILP = Convection coefficient for cooling oil on backside of piston
HCSL = Convection coefficient for coolant on backside of cylinder wall

$R_{14}$ through $R_{17}$ are combined convective and radiative resistances between
the time varying cylinder gas and the cylinder wall, and must be handled in a
special way. The heat transfer to one of the combustion chamber surfaces,
such as the head, piston, cylinder wall or exhaust valve, is given for an
entire cycle by

$$Q_{cycle} = \int h_i A_i (T_i - T_{gas}) \, dt$$

and the average continuous heat transfer rate is obtained by multiplying by
the engine speed

$$\dot{Q} = N_r \int h_i A_i (T_i - T_{gas}) \, dt$$

The convection coefficient, $h_i$, in this expression will be obtained from
either the Annand or Woschni correlations already present in the Benson
program. The Annand correlation includes a radiation term, $c \left( \frac{T_i^4}{T_{gas}^4} \right)$, and
this term must be included by defining a pseudo-convective coefficient as
follows.

$$\dot{Q} = (h_c + h_r) A_i (T_i - T_{gas})$$
where \( h_c \) = conventional convective coefficient,
\[
    h_r = \text{radiative coefficient} = c \left[ T_{1}^3 + T_{1}^2 T_{\text{gas}} + T_{1} T_{\text{gas}}^2 + T_{\text{gas}}^3 \right]
\]

When using the Annand Correlation, the coefficient \( h_i \) is equal to the sum of \( h_c \) and \( h_r \).

The integral in the expression for \( \dot{Q} \) can be separated and \( T_i \) can be removed from its integral since it is a constant.

\[
    \dot{Q} = N_r T_i \int h_i A_i \, dt - N_r \int h_i A_i T_{\text{gas}} \, dt
\]

or

\[
    \dot{Q} = N_r \int h_i A_i \, dt \left[ T_i - \int h_i A_i T_{\text{gas}} \, dt \right]
\]

By defining an effective gas temperature, \( T_{\text{eg}} \),
\[
    T_{\text{eg}} = \frac{\int h_i A_i T_{\text{gas}} \, dt}{\int h_i A_i \, dt}
\]

the heat transfer rate from the gas to surface \( i \) becomes

\[
    \dot{Q} = N_r \int h_i A_i \, dt \left[ T_i - T_{\text{eg}} \right]
\]

or

\[
    \dot{Q} = \frac{T_i - T_{\text{eg}}}{R}
\]

where \( R = \frac{1}{N_r \int h_i A_i \, dt} \)

It should be noted that the effective gas temperature will be a different value for each surface.

- \( T_{\text{eg,exh valve}} \) = Effective gas temperature for exhaust valve
- \( T_{\text{eg,head}} \) = Effective gas temperature for head
- \( T_{\text{eg,pist}} \) = Effective gas temperature for piston
- \( T_{\text{eg,cyl}} \) = Effective gas temperature for cylinder wall
3.4 Definition of Heat Generation Terms

In addition to the resistances and nodes shown on the network diagram in Figure 3.2, there are a number of heat source terms which are identified as either $Q_{\text{fric}}$ or $Q_{\text{cv}}$. The $Q_{\text{fric}}$ terms relate to the heat generated by friction between the cylinder wall and the piston and rings. The $Q_{\text{cv}}$ terms relate to the heat transferred from the cylinder gases as they cool in the crevice volume between the piston and cylinder wall above the top ring.

3.4.1 Friction Submodel

The friction mean effective pressure (FMEP) due to piston/ring cylinder wall friction can be predicted using a correlation developed by Bishop [7].

$$\frac{\text{FMEP}}{\rho_o \bar{U}_p^2} = \frac{6.2 \times 10^4 r^{0.2}}{\text{Re}}$$

where $\rho_o = \text{oil density}$
$\bar{U}_p = \text{mean piston speed}$
$r = \text{compression ratio}$

$\text{Re} = \text{Reynolds number} = \frac{\rho_o \bar{U}_p b}{\mu_o}$
$b = \text{bore}$
$\mu_o = \text{oil viscosity}$

The torque required to overcome this friction, in a two stroke engine, is

$$T_f = \frac{(\text{FMEP}) V_d}{2w} = \frac{(\text{FMEP}) b^2 S}{8}$$

where $V_d$ is the displacement volume and $S$ is the stroke.

The power required to overcome the friction, and thus the rate at which energy
must be dissipated by heat transfer is given by

\[ P_f = T_f \omega = 2\pi N_r T_f \]

where \( N_r \) is the engine speed.

The distribution of the heat transfer must be estimated either from measurements or more detailed analysis than that provided here. This information can be provided to the simulation through two defined parameters. 

CFRIC1 which is the fraction of the total piston/ring/cylinder wall friction which is due to the top compression ring and

CFRIC2 which is the fraction of the heat transfer resulting from top ring friction which goes to the ring side.

Using these definitions, the heat source terms for the network diagram in Figure 3.2 become

\[ \dot{Q}_{\text{fric}_1} = \text{CFRIC1} \cdot \text{CFRIC2} \cdot P_f \]
\[ \dot{Q}_{\text{fric}_2} = (1 - \text{CFRIC2}) P_f \]
\[ \dot{Q}_{\text{fric}_3} = (1 - \text{CFRIC1}) \cdot \text{CFRIC2} \cdot P_f \]

3.4.2 Crevice Volume Heat Transfer Submodel

Figure 3.3 shows a cross-section of the crevice volume region of the piston/cylinder wall above the top ring and the dimensions which must be specified to characterize this volume. Gas enters and leaves this volume as the pressure in the cylinder increases and decreases. Heat transfer from these gases to the piston and top ring can significantly raise the top ring temperature above that due to conduction from the piston and frictional heating. It is possible to calculate a characteristic time for conduction as
Figure 3.3 Crevice Volume Dimensions
\[ \tau = \frac{L^2}{\alpha} \] where \( L \) is a characteristic length and \( \alpha \) is the thermal diffusivity of the conducting medium. Assuming a 0.005 inch clearance between the piston and cylinder wall as a characteristic length and the thermal diffusivity of air at 2000 deg F, the characteristic time becomes

\[ \tau = \frac{(0.005/12 \text{ ft})^2}{2.83 \times 10^{-3} \text{ ft}^2/\text{sec}} = 6.13 \times 10^{-5} \text{ sec} \]

which is equal to 2.2 degrees of crankshaft rotation at 6000 RPM. This indicates that conduction will rapidly bring any air which enters the crevice volume into thermal equilibrium with the walls.

The following assumptions are used in the model for crevice volume heat transfer.

1. The pressure in the crevice volume is equal to the cylinder pressure.

2. The temperature of the gas in the crevice volume is constant at a value determined by an area-average of the wall temperatures.

\[ T_{cv} = \frac{A_T}{A_T} TWPR + \frac{A_R}{A_T} TWCR + \frac{A_C}{A_T} TWGC \]

where \( T_{cv} = \) Crevice volume gas temperature

\( TWPR = \) Piston rim temperature

\( TWCR = \) Top compression ring temperature

\( TWGC = \) Gas side cylinder wall temperature

\( A_T = A_p + A_r + A_c \)

3. Since the volume of the crevice is constant, and the temperature and
pressure in the crevice are known from assumptions 1 and 2, the mass of gas in the crevice can be calculated from the ideal gas equation

$$m_{cv} = \frac{P_{cyl} V_{cv}}{R T_{cv}}$$

where $P_{cyl}$ = cylinder pressure

$V_{cv}$ = volume of crevice

$R$ = Ideal gas constant for the cylinder contents

From one time step to the next, the mass added to the crevice volume will be

$$\Delta m_{cv} = \frac{V_{cv}}{R T_{cv}} [\Delta P_{cyl}]$$

where $\Delta P_{cyl}$ is the change in cylinder pressure during the time step

$\Delta m_{cv}$ is the change in mass of the crevice volume

4. Gas which enters the crevice volume is instantly cooled and this energy is delivered to the walls in proportion to their areas.

$$Q_T = \Delta m C_p (T_{gas} - T_{cv})$$

and

$$Q_{cv1} = \frac{A_p}{A_T} Q_T, \quad Q_{cv2} = \frac{A_R}{A_T} Q_T, \quad Q_{cv3} = \frac{A_C}{A_T} Q_T$$

where

$Q_T$ = energy transferred from gas to crevice volume walls.

$\Delta m$ = Increment of mass added to crevice volume in one time step

$T_{gas}$ = Cylinder gas temperature

$Q_{cv1}$ = Fraction of heat transfer which goes to piston rim

$Q_{cv2}$ = Fraction of heat transfer which goes to top compression ring

$Q_{cv3}$ = Fraction of heat transfer which goes to cylinder wall

Combining these equations gives the following expression for the crevice
volume heat transfer for one time step.

\[ Q = \left( \frac{\gamma}{\gamma - 1} \right) V_{cv} \left[ \frac{T_{gas}}{T_{cv}} - 1 \right] \Delta P_{cyl} \]

The total heat transfer for a cycle is given by summing the heat transfer at each time step

\[ Q_T = \sum_{\text{cycle}} \left( \frac{\gamma}{\gamma - 1} \right) V_{cv} \left[ \frac{T_{gas}}{T_{cv}} - 1 \right] \Delta P_{cyl} \]

and the average heat transfer rate is obtained by multiplying by the engine speed.

\[ \dot{Q}_T = N_r \cdot \sum_{\text{cycle}} \left( \frac{\gamma}{\gamma - 1} \right) V_{cv} \left[ \frac{T_{gas}}{T_{cv}} - 1 \right] \Delta P_{cyl} \]

3.5 Node Equations

Based on the concept that at steady state the currents into any node of the network diagram given in Figure 3.2 must add to zero, equations can be written which sum the heat transfer into each node. There is one equation for each of the nine unknown temperatures. These equations are given below.

\[ \frac{TC2 - TWCC}{R_{13}} + \frac{TWGC - TWCC}{R_{11}} = 0 \]
\[ \frac{TC1 - TWCP}{R_7} + \frac{TWGP - TWCP}{R_6} = 0 \]
\[ \frac{TC3 - TWCH}{R_5} + \frac{TWGH - TWCH}{R_4} = 0 \]
\[ \frac{TWEVG - TWEV}{R_1} + \frac{TEXHP - TWEV}{R_2} + \frac{TWGH - TWEV}{R_3} + \frac{T_{eg,exh\text{\,valve}} - TWEV}{R_{17}} = 0 \]
\[ \frac{TWCH - TWGH}{R_4} + \frac{TWEV - TWGH}{R_3} + \frac{T_{eg,head} - TWGH}{R_{16}} = 0 \]
\[ \frac{TWGC - TWGP}{R_8} + \frac{TWPR - TWGP}{R_9} + \frac{TWCP - TWGP}{R_6} + \frac{T_{eg,pist} - TWGP}{R_{15}} + \dot{Q}_{\text{fric}_3} = 0 \]
\[ \frac{TWGP - TWPR}{R_9} + \frac{TWCR - TWPR}{R_{12}} + \dot{Q}_{cv_3} = 0 \]
The nine node equations listed above are a system of linear algebraic equations and can be solved using a Gaussian elimination procedure. A subroutine for this purpose was obtained from Gerald [8]. The calculation is performed at the end of each cycle iteration providing an updated estimate of the nine metal temperatures. Depending on the value of the user specified parameter, NHEAT, four of these temperatures, the cylinder wall temperature, the piston crown temperature, the head temperature and the exhaust valve temperature, can be used in the next iteration so that the metal temperatures will approach their steady state values (NHEAT = 1). The other option is to fix these four metal temperatures at values specified by the user (NHEAT = 0).
4.0 INPUT DATA

Two sets of input data must be provided to the Benson program to define the particular application being considered. The first data set provides general data describing the engine and operating conditions being simulated. The second data set relates specifically to the steady state heat transfer analysis discussed in Chapter 3.0 and contains the thermal properties of the engine components and the appropriate areas and path lengths.

4.1 Subroutine INPUT

Below is listed the input data set required by the Benson program. The variable names are also provided. The current version of the program has these variables entered through a BLOCK DATA statement in the main program and then passed through a COMMON block into the program. READ statements are provided in the INPUT subroutine to read an external file to obtain these variables but these statements have been made into comment statements.

<table>
<thead>
<tr>
<th>EQUIVD</th>
<th>RPM</th>
<th>PEXH</th>
<th>PAIR</th>
<th>TAIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>BORE</td>
<td>STROKE</td>
<td>AVO</td>
<td>CONROD</td>
</tr>
<tr>
<td>EVO</td>
<td>EVC</td>
<td></td>
<td>AVC</td>
<td></td>
</tr>
<tr>
<td>TWALL</td>
<td>WFUEL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANNA</td>
<td>FMEPM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPCWF</td>
<td>DEL1</td>
<td>DEL2</td>
<td>DEL3</td>
<td>AAN(1)</td>
</tr>
<tr>
<td>VALEXH</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDE</td>
<td>NTEXH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALPHEX(1)</td>
<td>FEXH(1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALPHEX(2)</td>
<td>FEXH(2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALPHEX(NTEXH)</td>
<td>FEXH(NTEXH)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VALAIR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDA</td>
<td>WIDTHA</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
EQUIVD = Desired trapped equivalence ratio. If a specified fuel
flow rate is desired, then EQUIVD should be set to zero
and WFUEL set to the amount of fuel injected per cycle.

RPM = Crankshaft speed, revolutions per minute.
P ExH = Exhaust pressure, psia.
PAIR = Intake manifold pressure, psia.
TAIR = Intake manifold temperature, deg R.
CR = Geometric Compression ratio
BORE = Bore, inches.
STROKE = Stroke, inches
CONROD = Connecting rod length, inches.
FPISTA = Ratio of piston surface area to crosssectional area of
cylinder.
EVO = Crankangle at which exhaust valve opens, deg ATDC.
EVC = Crankangle at which exhaust valve closes, deg ATDC
AVO = Crankangle at which intake port opens, deg ATDC
AVC = Crankangle at which intake port closes, deg ATDC
TWALL = Initial estimate of cylinder wall temperature, deg R.
WFUEL = Initial estimate of fuel injected be cycle, unless
EQUIVD is zero in which case WFUEL is the actual fuel
injected per cycle, Lbm.

ACB = Start of combustion, degrees ATDC.
ACF = End of combustion, degrees ATDC
ANNA = Parameter for heat transfer model
FNEPM = Multiplier for friction model
NPCWF = Parameter for selection of combustion model
    If NPCWF = -1 Whitehouse-Way model used
    If NPCWF = 0 and DEL3 = 0. AVL model used
    If NPCWF = 0 and DEL3 > 0. Wiebe model used
    If NPCWF = 1 Watson model used
    If NPCWF = 2 User supplied model

DEL1 = Parameter for combustion model
DEL2 = Parameter for combustion model
DEL3 = Parameter for combustion model

AAN(1) = Injection rate parameter for Whitehouse-Way combustion
model
AAN(2) = Injection rate parameter for Whitehouse-Way combustion
model
VALEXH = Parameter which determines whether an exhaust valve or
port is used
    If VALEXH = 0., exhaust ports are used
    If VALEXH = 10., exhaust valves are used

CDE = Exhaust valve/port discharge coefficient
NTEXH = If an exhaust valve is used, NTEXH is the number of
crankangle area combinations provided to specify the
valve flow area

ALPHEX(I) = Array of crank positions at which valve flow area is
specified.
FEXH(I) = Array of exhaust valve flow areas corresponding to
ALPHEX(I).
VALAIR = Parameter which determines whether an intake port or valve is used
   If VALAIR = 0., intake ports are used.
   If VALAIR = 10., intake valves are used.

CDA = Intake port/valve discharge coefficient.

WIDTHA = If an intake port is used, this parameter specifies the fraction of the circumference which is taken up by port area.

4.2 Subroutine INPUT2

Below is listed the input data set required by the Steady State Heat Transfer Analysis. The variable names are provided below. The current version of the program has these variables defined within the subroutine INPUT2 although READ statements are provided to read these variables from an external file. Currently these READ statements have been made into comment statements.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TWEV</td>
<td>Initial estimate of the exhaust valve temperature, deg F.</td>
</tr>
<tr>
<td>TWGH</td>
<td>Initial estimate of the gas side head temperature, deg F.</td>
</tr>
<tr>
<td>TWGP</td>
<td>Initial estimate of the gas side piston temperature, deg F.</td>
</tr>
<tr>
<td>TWGC</td>
<td>Initial estimate of the gas side cylinder wall temperature, deg F.</td>
</tr>
<tr>
<td>TWEVG</td>
<td>Exhaust valve guide temperature, deg F.</td>
</tr>
<tr>
<td>TC1</td>
<td>Piston cooling oil temperature, deg F.</td>
</tr>
<tr>
<td>TC2</td>
<td>Cylinder wall coolant temperature, deg F.</td>
</tr>
<tr>
<td>TC3</td>
<td>Head coolant temperature, deg F.</td>
</tr>
<tr>
<td>NEXHV</td>
<td>Number of exhaust valves</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Intake port/valve discharge coefficient.</td>
</tr>
<tr>
<td>D2</td>
<td>Intake port/valve discharge coefficient.</td>
</tr>
<tr>
<td>D3</td>
<td>Intake port/valve discharge coefficient.</td>
</tr>
<tr>
<td>D4</td>
<td>Intake port/valve discharge coefficient.</td>
</tr>
<tr>
<td>D5</td>
<td>Intake port/valve discharge coefficient.</td>
</tr>
<tr>
<td>D6</td>
<td>Intake port/valve discharge coefficient.</td>
</tr>
<tr>
<td>XXEVG</td>
<td>Exhaust valve guide temperature, deg F.</td>
</tr>
<tr>
<td>XXEVH</td>
<td>Exhaust valve guide temperature, deg F.</td>
</tr>
<tr>
<td>XXPSL</td>
<td>Exhaust valve guide temperature, deg F.</td>
</tr>
<tr>
<td>XXPIS</td>
<td>Exhaust valve guide temperature, deg F.</td>
</tr>
<tr>
<td>XXPRG</td>
<td>Exhaust valve guide temperature, deg F.</td>
</tr>
<tr>
<td>XXPCR</td>
<td>Exhaust valve guide temperature, deg F.</td>
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<tr>
<td>XXSLV</td>
<td>Exhaust valve guide temperature, deg F.</td>
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<tr>
<td>AEXVS</td>
<td>Exhaust valve guide temperature, deg F.</td>
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<tr>
<td>AEXST</td>
<td>Exhaust valve guide temperature, deg F.</td>
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<tr>
<td>ASLEEV</td>
<td>Exhaust valve guide temperature, deg F.</td>
</tr>
<tr>
<td>APIST2</td>
<td>Exhaust valve guide temperature, deg F.</td>
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<tr>
<td>APISTR</td>
<td>Exhaust valve guide temperature, deg F.</td>
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<tr>
<td>ARING1</td>
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<td>ARING2</td>
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<td>CEXV</td>
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<td>CHEAD</td>
<td>Exhaust valve guide temperature, deg F.</td>
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<tr>
<td>CSLEEVE</td>
<td>Exhaust valve guide temperature, deg F.</td>
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<tr>
<td>CPIST</td>
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<td>CRING</td>
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<tr>
<td>HOILP</td>
<td>Exhaust valve guide temperature, deg F.</td>
</tr>
<tr>
<td>HCSL</td>
<td>Exhaust valve guide temperature, deg F.</td>
</tr>
<tr>
<td>HCHD</td>
<td>Exhaust valve guide temperature, deg F.</td>
</tr>
</tbody>
</table>

31
DEXHV = Diameter of exhaust valves, inches
D1 = Distance below piston surface of top ring groove, inches.
D2 = Depth of ring groove, inches.
D3 = Width of ring groove, inches.
D4 = Piston/cylinder wall clearance (piston is assumed centered in bore), inches.
D5 = Ring width, inches.
D6 = Ring depth, inches.
XXEVG = Heat transfer path length from exhaust valve to valve guide
XXEVH = Heat transfer path length from exhaust valve to valve seat
XXPSL = Heat transfer path length from piston to cylinder wall through lower rings and oil film
XXPIS = Heat transfer path length through piston
XXPRG = Heat transfer path length from piston rim to top compression ring
XXHED = Heat transfer path length through head
XXRSL = Heat transfer path length from piston crown to piston rim
XXSLV = Heat transfer path length through cylinder wall
AEXVS = Area of exhaust valve stem
AEXST = Exhaust valve seat contact area
ASLEEV = Characteristic area for heat transfer through cylinder wall
APIST2 = Surface area exposed to oil on underside of piston
APISTR = Characteristic area between piston crown and piston rim
ARING1 = Contact area between top compression ring and cylinder wall
ARING2 = Contact area between top compression ring and piston rim
CEXV = Thermal conductivity of exhaust valve
CHEAD = Thermal conductivity of head
CPIST = Thermal conductivity of piston
CRING = Thermal conductivity of ring
CSLEEV = Thermal conductivity of cylinder wall
HEXHP = Convection coefficient from back side of exhaust valve to gases in exhaust port
HOILP = Convection coefficient for cooling oil on backside of piston
HCSL = Convection coefficient for coolant on backside of cylinder wall
HCHD = Convection coefficient for coolant on backside of head
5.0 OUTPUT

The Benson program creates three output files containing the results of the engine simulation. The first file, written from UNIT 2, contains a summary of the input data and then the following results written for each iteration.

1. Fuel Flow
2. Scavenge Ratio
3. Trapping Efficiency
4. Scavenge Efficiency
5. Temperature Out (Exhaust)
6. Power
7. True Purity
8. Air Flow
9. Equivalence Ratio
10. Maximum Pressure
11. Maximum Temperature
12. Heat Loss (percent)

After the program has converged a summary of the heat transfer results is printed showing the metal part temperatures and the fraction of the heat transfer going to each part of the engine.

The second output file, UNIT 3, contains a listing of the cylinder pressure, temperature, specific heat ratio and volume as a function of crank angle for each iteration performed by the program. The last complete cycle of data corresponds to the cycle where the program converged.

The final output file, UNIT 4, contains a summary of the cycle data which is written at the end of each iteration. It includes the trapped pressure and temperature, the maximum pressure and temperature, the release pressure and temperature, the various gas exchange efficiencies described in section 7.1 and the indicated power. This data is printed for each iteration so the final listing corresponds to the listing for the converged cycle calculation.
6.0 SAMPLE CASES

6.1 Napier Nomad

The Napier Nomad was a combined cycle diesel engine developed during the early 1950's as a highly efficient aircraft engine. It is the most efficient aircraft engine ever flown, although the fuel economy of the Nomad did not provide sufficient advantage over the smaller, lighter gas turbine engine. In this example, the Benson program was combined with a simple compressor and turbine model to simulate the take-off performance of the Napier Nomad engine. Sufficient published data of the Nomad is available to confirm the analysis. The Nomad was liquid cooled, and the analysis was conducted assuming both oil and water cooling.

The input BLOCK DATA for this simulation is provided below. A summary of the results is presented in Table 6.1. A listing of the program which calls the Benson program including the turbomachinery is provided in Appendix 10.2.

```
DATA EQUIVD, RPM, PEXH, PAIR, TAIR /0.60, 2050, 134.79, 149.76, 896. /
DATA CR, BORE, STROKE, CONROD, FPISTE, FPISTA /11.17, 6.00, 7.375, 114.75, 1.13, 1.13 /
DATA EVO, EVC, AVO, AVC /105.0, 255.0, 130.0, 230.0 /
DATA TWALL, WFUEL /1460.0, 0.0001 /
DATA ACB, ACF /335.0, 10.0 /
DATA ANNA, FMEPM /0.30, 1.25 /
DATA NPCWF, DEL1, DEL2, DEL3, AAN(1), AAN(2) /-1.0, 0.01457, 0.667, 0.4, 0.4, 0.5, 0.4, 0.5 /
DATA VALEXH, CDE, WIDTHE /0.0, 0.85, 0.20 /
DATA VALAIR, CDA, WIDTHA /0.0, 0.85, 0.36 /
```
Table 6.1

Napier Nomad

Specifications:

Two Stroke, Loop Scavenged

12 Cylinders  
Bore: 6.00 inches  
Stroke: 7.375 inches

Effective Compression Ratio: 8.00

At Takeoff Power:  
Speed: 2050 rpm  
Mean Piston Speed: 2520 ft/min

Inlet Manifold Pressure: 89 psia

Inlet Manifold Temperature: 475 F

Compressor Efficiency: 0.85

Turbine Efficiency: 0.84

Under Takeoff Conditions

<table>
<thead>
<tr>
<th>Published Data</th>
<th>Benson Program (Water Cooled)</th>
<th>Benson Program (Oil Cooled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMEP</td>
<td>205 psi</td>
<td>205.1 psi</td>
</tr>
<tr>
<td>Peak Pressure</td>
<td>2200 psi</td>
<td>2186 psi</td>
</tr>
<tr>
<td>Air Flow</td>
<td>13 lb/sec</td>
<td>13.03 lb/sec</td>
</tr>
<tr>
<td>Turbine Inlet Temp</td>
<td>1222 F</td>
<td>1162 F</td>
</tr>
<tr>
<td>Diesel Power (12 cyl)</td>
<td>2660 hp</td>
<td>2654 hp</td>
</tr>
<tr>
<td>Turbine Power</td>
<td>2250 hp</td>
<td>2374 hp</td>
</tr>
<tr>
<td>Compressor Power</td>
<td>1840 hp</td>
<td>1858 hp</td>
</tr>
<tr>
<td>Total Shaft Power</td>
<td>3070 hp</td>
<td>3169 hp</td>
</tr>
<tr>
<td>Overall BSFC</td>
<td>0.345 lb/hp-hr</td>
<td>0.339 lb/hp-hr</td>
</tr>
<tr>
<td>Percent Heat Loss</td>
<td>NA</td>
<td>13.8 %</td>
</tr>
<tr>
<td>Head Temp</td>
<td>NA</td>
<td>782 F</td>
</tr>
<tr>
<td>Piston Temp</td>
<td>NA</td>
<td>834 F</td>
</tr>
<tr>
<td>Sleeve Temp</td>
<td>NA</td>
<td>791 F</td>
</tr>
</tbody>
</table>
6.2 Garrett CCE

The Garrett Turbine Engine Company, under Army contract, used the Benson program to simulate a compound cycle engine suitable for use in a light helicopter. The engine proposed by Garrett is a 6 cylinder, two stroke diesel with two expansion turbines on the diesel exhaust. The first turbine drives the compressor for the diesel intake air and the second is a power turbine which is connected directly to the engine's output shaft. As in the above example, the Benson program was combined with a simple compressor and turbine model to simulate the Garrett design for a Compound Cycle Engine. Data for the predicted performance was supplied by Garrett in the final contract report. This data is compared below in Table 6.2 with the results of the simulation for both water and oil cooling. The input data set is also provided below. A listing of the main program used to simulate the Garrett engine is provided in Appendix 10.3.

```
DATA EQUFD,RPM,PEXH,PAIR,TAIR /0.68,6122.,134.79,149.76,896./
DATA CR,BORE,STROKE,CONROD,FPISTE,FPISTA /9.1712,3.101,2.940,
  10.68,1.,1.13/
DATA EVO,EVC,AVO,AVC /90.,239.,126.,234./
DATA TWALL,WFUEL /1460.,.000145332/
DATA ACB,ACF /345.,10.5/
DATA ANNA,FMEPM /0.36,1.0/
DATA NPCWF,DEL1,DEL2,DEL3,AAN(1),AAN(2) /1.0,01457,0.667,0.4,
  0.4,0.5/
DATA VALEXH,CDE,NTEXH /10.,0.8864,13/
DATA VALAIR,CDA,WIDTHA /0.,0.8,0.5542/
DATA AIPHEX/0.0,10.97,25.00,31.61,41.00,52.25,72.89,90.95,104.00,
  111.59,119.00,132.23,149.00,37*0./
DATA FEXH/0.0,0.00093264,0.00364,0.00591222,0.00899,0.0106201,
  0.01175263,0.01111131,0.00923,0.00717595,0.00461,0.00181743,0.,
  2 37*0./
```
Table 6.2
Garrett CCF

Specifications:

Two Stroke, Uniflow Scavenged

6 Cylinders
Bore: 3.101 inches
Stroke: 2.940 inches

Effective Compression Ratio: 7.50

At Rated Power: Inlet Manifold Pressure: 149.79 psia
Inlet Manifold Temperature: 436 F
Compressor Efficiency: 0.79
Turbine Efficiency: 0.845, 0.848

Rated Power Conditions

<table>
<thead>
<tr>
<th></th>
<th>Published Data</th>
<th>Benson Program (Water Cooled)</th>
<th>Benson Program (Oil Cooled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM EP</td>
<td>400 psi</td>
<td>386.8 psi</td>
<td>386.5 psi</td>
</tr>
<tr>
<td>Peak Pressure</td>
<td>3364 psi</td>
<td>3401.1 psi</td>
<td>3429.2 psi</td>
</tr>
<tr>
<td>Air Flow</td>
<td>2.349 lb/sec</td>
<td>2.316 lb/sec</td>
<td>2.301 lb/sec</td>
</tr>
<tr>
<td>Turbine Inlet Temp</td>
<td>1752 F</td>
<td>1738 F</td>
<td>1785 F</td>
</tr>
<tr>
<td>Diesel Power (6 cyl)</td>
<td>824 hp</td>
<td>796.0 hp</td>
<td>795.5 hp</td>
</tr>
<tr>
<td>Turbine Power</td>
<td>226 hp</td>
<td>233.1 hp</td>
<td>248.6 hp</td>
</tr>
<tr>
<td>Fan Power</td>
<td>51 hp</td>
<td>51 hp</td>
<td>51 hp</td>
</tr>
<tr>
<td>Total Shaft Power</td>
<td>999 hp</td>
<td>978.1 hp</td>
<td>993.1 hp</td>
</tr>
<tr>
<td>Overall BSFC</td>
<td>0.328 lb/hp-hr</td>
<td>0.332 lb/hp-hr</td>
<td>0.323 lb/hp-hr</td>
</tr>
<tr>
<td>Percent Heat Loss</td>
<td>8.46 %</td>
<td>8.59 %</td>
<td>5.74 %</td>
</tr>
<tr>
<td>Head Temp</td>
<td>1244.3 F</td>
<td>1299.6 F</td>
<td>2078.3 F</td>
</tr>
<tr>
<td>Piston Temp</td>
<td>1279.3 F</td>
<td>1375.8 F</td>
<td>1571.3 F</td>
</tr>
<tr>
<td>Sleeve Temp</td>
<td>418.3 F</td>
<td>1344.8 F</td>
<td>1792.2 F</td>
</tr>
</tbody>
</table>
7.0 DOCUMENTATION OF SUBROUTINES

7.1 Subroutine BENSON

A simulation using the Benson program is initiated by a call to subroutine BENSON. There is no argument list for this subroutine. All data is passed into the subroutine through input files or COMMON blocks and all output data is written to the three output files discussed in Chapter 5.0.

Subroutine BENSON calls the input subroutines, the initialization subroutine, and then organizes the calls to CYLNDR and POWER to integrate the energy balance throughout the cycle. Examples of how BENSON is called from a main program are given in the Appendix for the sample cases of Chapter 6.0.

7.2 Subroutine BAL

This subroutine can be used for two purposes:

1. To find the enthalpy of combustion products given the fuel-air ratio and the temperature.
2. To find a final temperature of combustion products given an initial temperature and a rise in the enthalpy of the products.

For the combustion equation

\[ A \cdot CH_n + [0.21 \text{ O}_2 + 0.79 \text{ N}_2] \rightarrow X_1 \text{ N}_2 + X_2 \text{ O}_2 + X_3 \text{ O}_2 + X_4 \text{ H}_2\text{O} \]

the number of moles of products, per mole of air, are given by the following equations.

\[ X_1 = 0.79 \]
\[ X_2 = 0.21 - X_3 - \frac{1}{2} X_4 \]
\[ X_3 = \frac{\text{lb fuel}}{\text{lb air}} \cdot \frac{\text{lb C}}{\text{lb fuel}} \cdot \frac{\text{lb air}}{\text{mole air}} \cdot \frac{\text{mole C}}{\text{lb C}} = \frac{\text{mole C}}{\text{mole air}} \]
\[
= \text{FZA} \cdot \text{CARBON} \cdot \frac{28.85}{12.01}
\]

\[ X_4 = \frac{\text{lb fuel}}{\text{lb air}} \cdot \frac{\text{lb H}_2}{\text{lb fuel}} \cdot \frac{\text{lb air}}{\text{mole air}} \cdot \frac{\text{mole H}_2}{\text{lb H}_2} = \frac{\text{mole H}_2}{\text{mole air}} \]
\[
= \text{FZA} \cdot (1 - \text{CARBON}) \cdot \frac{28.85}{2.016}
\]

These quantities can be used to calculate mole fractions by summing the total number of moles and dividing each term by the total.

To accomplish the first purpose of this subroutine the user specifies the temperature and fuel/air ratio of the mixture as well as the mass fraction of carbon in the fuel and the subroutine calculates the mole fractions of the product gas composition and then evaluates fourth order polynomial curve fits to JANAF table data to obtain the enthalpy of the gas mixture at the specified temperature \[1\].

For the case where the subroutine is intended to locate a temperature given an initial temperature and an increment of enthalpy, the subroutine first evaluates the enthalpy at the specified initial temperature and adds the enthalpy increment to obtain the enthalpy of the unknown state. Then the subroutine guesses a temperature and tests whether the enthalpy at this temperature is the same as the unknown. If not, the program adjusts the temperature and checks again. Newton's method is used to speed convergence. When the enthalpy matches within 0.01%, the subroutine returns to the calling program.

The argument list for subroutine BAL is

\[
\text{SUBROUTINE BAL(CARBON,FZA,T1,DELH,T2,GAM,H3)}
\]

where CARBON is the mass fraction of carbon in the fuel

FZA is the fuel/air mass ratio
T1 is the initial temperature when the subroutine is being used to locate a second unknown temperature.

DELH is the enthalpy increment.

T2 is the temperature at which the enthalpy is desired or is the unknown temperature.

GAM is the ratio of specific heats evaluated at T2.

H3 is the enthalpy at T2.

7.3 Subroutine CYLNDR

This subroutine integrates the energy equation described earlier for the gas exchange portion of the cycle. The subroutine checks to see if the valves or ports are open and, if so, integrates the energy equation. If the valves are closed, then CYLNDR calls POWER to integrate the energy equation for the compression-expansion portion of the cycle. When the subroutine is called the first time step after the gas exchange has been completed, the subroutine totals the mass added and removed from the cylinder and calculates the various gas exchange efficiencies. These efficiencies are defined below.

Scavenging Efficiency: \[ \frac{\text{mass of delivered air retained in cylinder}}{\text{mass of trapped cylinder charge}} \]

Purity: \[ \frac{\text{mass of air in trapped cylinder charge}}{\text{total mass of trapped cylinder charge}} \]

Charging Efficiency based on Trapped Condition:

\[ \frac{\text{mass of delivered air retained in cylinder}}{\text{Trapped volume x trapped density}} \]
Charging Efficiency based on Inlet conditions and trapped volume:
\[
\frac{\text{mass of delivered air retained in cylinder}}{\text{Trapped volume} \times \text{inlet density}}
\]

Charging Efficiency based on inlet conditions and swept volume:
\[
\frac{\text{mass of delivered air retained in cylinder}}{\text{Swept volume} \times \text{inlet density}}
\]

Trapping Efficiency:
\[
\frac{\text{mass of delivered air retained in cylinder}}{\text{total mass of air delivered to cylinder}}
\]

Scavenge Ratio based on swept volume:
\[
\frac{\text{total mass of air delivered to cylinder}}{\text{Swept volume} \times \text{inlet density}}
\]

Scavenge Ratio based on trapped volume:
\[
\frac{\text{total mass of air delivered to cylinder}}{\text{Trapped volume} \times \text{inlet density}}
\]

Relative Charging Efficiency based on trapped volume:
\[
\frac{\text{total mass of trapped cylinder charge}}{\text{Trapped volume} \times \text{inlet density}}
\]

Relative Charging Efficiency based on swept volume:
\[
\frac{\text{total mass of trapped cylinder charge}}{\text{Swept volume} \times \text{inlet density}}
\]

7.4 Subroutine CYLVOL

This subroutine takes the piston position and the piston velocity provided by STROK and calculates the cylinder volume and the rate of change of volume.
The volume at some crank position is equal to the sum of the volume displaced by the piston plus the displacement volume. The volume displaced by the piston is equal to the piston area times the distance between the top of the piston and its position at top dead center which is XSTROK as calculated by the subroutine STROK. The clearance volume can be expressed in terms of the compression ratio as

\[ r = \frac{V_d + V_{cl}}{V_{cl}} \]

or

\[ V_{cl} = \frac{V_d}{r - 1} = \frac{S \cdot \text{AREA}}{r - 1} \]

where \( V_{cl} \) is the clearance volume,

\( V_d \) is the displacement volume

\( S \) is the stroke

\( \text{AREA} \) is the piston area

\( r \) is the compression ratio

Thus, the volume in the cylinder can be expressed as

\[ V = \text{AREA} \cdot XSTROK + \frac{S \cdot \text{AREA}}{r - 1} \]

or

\[ V = \text{AREA} \cdot [XSTROK + \frac{S}{r - 1}] \]

The rate of change of the volume is equal to the derivative of this expression or in terms of DSTROK provided by the subroutine STROK,

\[ \frac{dV}{d\theta} = \text{AREA} \cdot \text{DSTROK} \]

The argument list follows.

\text{SUBROUTINE CYLVOL(FCYLG,XSTROK,STROKE,CRR,DSTROK,VCYLG,DVCYLG)}

where FCYLG is the cross-sectional area of the cylinder

XSTROK is the piston position
STROKE is the engine stroke
CRR is the compression ratio
DSTROK is the piston velocity
VCYLG is the volume
DVCLYG is the rate of change of the volume

7.5 Subroutine ELIM

This subroutine is used to solve the system of nine linear algebraic equations developed by subroutine HTRANS for the metal part temperatures in the engine. The subroutine was copied from Gerald [8] and uses Gaussian elimination with partial pivoting. The argument list is as follows.

SUBROUTINE ELIM(AB,N,NP,NDIM)

where AB = Coefficient matrix augmented with vectors consisting of the right hand sides of the system equations (may be more than one set).

N = Number of equations.
NP = Total number of columns in the augmented matrix AB.
NDIM = First dimension of matrix AB in the calling program.

The solution vector(s) are returned in the augmentation columns of AB.

7.6 Subroutine FCLOSE

This subroutine closes the input/output files and states that the files created should be kept after completion of the program.
7.7 Subroutine FOPEN

This subroutine opens the input and output files which the Benson program reads from and writes to. Unit 1 is the input file and it is named DIESEL1.INP and units 2 through 5 are output files with names that can be specified by the user in the calling program. The user-defined names are passed to FOPEN as 16 character names in the COMMON block named OPEN.

7.8 Subroutine HEADER

This subroutine writes titles and column headings to the output files and also writes out selected values of the input parameters so the particular run can be identified. The subroutine has no argument list and all data is passed into the subroutine through COMMON blocks /GEN/ and /CYL/.

7.9 Subroutine HTRANS

This subroutine executes the procedure described in Section 2.2 for calculating the engine part temperatures. The subroutine calculates the resistances described in that section and assembles the coefficient matrix for the system of algebraic equations for solution by subroutine ELIM. HTRANS also calculates the friction mean effective pressure due to the piston/ring friction so that the heat transfer terms associated with the dissipation of this friction can be added to the coefficient matrix. The terms for the crevice volume heat transfer are evaluated in subroutine POWER but are added to the coefficient matrix in HTRANS.

After solving the system equations by calling subroutine ELIM, the various heat transfer flow paths in the network diagram are summed to provide
a summary of the distribution of the heat transfer throughout the cylinder area. This data is provided to the main program through COMMON/HEAT1/ and COMMON/HEAT2/ and may be printed if desired.

7.10 Subroutine INITLZ

This subroutine is called early in the execution of the Benson program to perform a variety of tasks necessary to starting the calculations. If necessary, input variables are converted to the proper dimensions and then many of the variables are nondimensionalized. Variables used in summing calculations are assigned initial values of zero. The values of the polynomial coefficients used to calculate gas properties are assigned in this subroutine based on curve fits to the JANAF table data. The subroutine has no argument list and all data is passed into the subroutine through COMMON blocks /XXX/, /GEN/ and /CYL/.

7.11 Subroutine INPUT

This subroutine is used to supply the Benson program with input data about the specific engine application being simulated. The subroutine contains read statements for the essential data, however, these statements have been converted to comment statements and the data is either present as assignment statements in the subroutine or is assigned in the main calling program and then passed into the subroutine through COMMON/BNSN/. This was done so that the Benson program could be repeatedly called as a subroutine itself without having to reread the input data file for every run. INPUT has no argument list and all variables are passed through to the other subroutines.
using COMMON blocks.

7.12 Subroutine INPUT2

This subroutine is used to supply the Benson program with input data for the detailed heat transfer calculations. The subroutine contains READ statements for the data, however, these statements have been converted to comment statements and the data is assigned directly to the variables by executable statements within the subroutine. To change the values of these parameters the subroutine must be edited and then recompiled. The format of the input data file and the variable name list are given in Section 3.2.

7.13 Subroutine MASSFL

Flow through the intake and exhaust ports and valves can be modeled as an adiabatic quasi-steady flow process. Potential energy effects are generally assumed negligible. With these assumptions, the energy balance for a control volume takes the following form.

\[ h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} \]

where state 1 designates the upstream condition and state 2 is the condition at the minimum area section of the flow passage. Since state 1 is normally taken to be a stagnation condition, \( V_1 \) can be assumed to be zero. Thus,

\[ V_2 = \left[2(h_1 - h_2)\right]^{1/2} \]

or for constant specific heat

\[ V_2 = \left[2 C_p (T_1 - T_2)\right]^{1/2} \]

Since the process is assumed isentropic, again for constant specific heats.
\[ \frac{T_1}{T_2} = \left[ \frac{P_1}{P_2} \right]^{\frac{\gamma - 1}{\gamma}} \]

where \( \gamma \) is the ratio of specific heats, \( \frac{C_p}{C_v} \).

Substituting this expression into the equation for \( V_2 \) gives

\[ V_2 = \left[ \frac{2}{C_p} T_2 \left( \left[ \frac{P_1}{P_2} \right]^{\frac{\gamma - 1}{\gamma}} - 1 \right) \right]^{1/2} \]

if this velocity is divided by the speed of sound at state 2, \( a_2 = \sqrt{\gamma R T} \),
then a Mach number is obtained

\[ U_m = \frac{V_2}{a_2} = \left[ \left( \frac{2}{\gamma - 1} \right) \left( \left[ \frac{P_1}{P_2} \right]^{\frac{\gamma - 1}{\gamma}} - 1 \right) \right]^{1/2} \]

if this Mach number is greater than or equal to 1., then the flow through the valve or port is choked and the velocity at section 2 will be sonic. If the Mach number is less than 1. then the flow is not choked and the velocity at section 2 will be given by the above expression.

The mass flow rate through the valve or port can be obtained from the continuity equation

\[ \dot{m} = \rho A V \]

When this equation is applied at section 2 the following expression for mass flow through the valve or port is obtained.

\[ \dot{m} = \rho_2 A_2 a_2 \left[ \frac{2}{\gamma - 1} \left( \left[ \frac{P_1}{P_2} \right]^{\frac{\gamma - 1}{\gamma}} - 1 \right) \right]^{1/2} \]

In the Benson program, the expression for mass flow rate is non-dimensionalized using several defined reference quantities. A list of these quantities follows.

\( T_{\text{ref}} = \) Reference Temperature

\( P_{\text{ref}} = \) Reference Pressure
\[ V_{\text{ref}} = \text{Reference Volume} \]

\[ F_{\text{ref}} = \text{Reference Area} \]

\[ X_{\text{ref}} = \text{Reference length} \]

\[ D_{\text{ref}} = \text{Reference diameter} \]

\[ a_{\text{ref}} = \text{Reference speed of sound}, \quad a_{\text{ref}} = \sqrt{\gamma RT} \]

\[ m_{\text{ref}} = \text{Reference mass}, \quad m_{\text{ref}} = \frac{P_{\text{ref}} V_{\text{ref}}}{RT_{\text{ref}}} = \frac{\gamma P_{\text{ref}} V_{\text{ref}}}{a_{\text{ref}}^2} \]

Using these reference quantities, which are assigned internally in the program, the mass flow equation can be rearranged to obtain the form used in the Benson program.

\[ \dot{m} = \rho_2 A_2 a_2 U_m \]

but \( \rho_2 = \rho_1 \left( \frac{P_2}{P_1} \right) \)

and \( a_2 = \sqrt{\gamma RT_2} \)

\[ \dot{m} = \rho_1 \left( \frac{P_2}{P_1} \right) A_2 \sqrt{\gamma RT_2} U_m \]

Now, from the equation defining the Mach number,

\[ \frac{P_2}{P_1} = \left[ 1 + \frac{\gamma - 1}{\gamma} U_m^2 \right]^{\frac{\gamma}{\gamma - 1}} \]

So the mass flow can be arranged as

\[ \dot{m} = \frac{\gamma P_1 A_2 U_m}{a_1 \left[ 1 + \frac{\gamma - 1}{\gamma} U_m^2 \right]^{\frac{\gamma + 1}{2(\gamma - 1)}}} \]

The non-dimensional mass flow rate, WFLOW, is equal to

\[ \text{WFLOW} = \frac{\dot{m}}{m_{\text{ref}} V_{\text{ref}}} = \frac{P_{\text{ref}}}{P_{\text{ref}}} \left( \frac{A_2}{A_{\text{ref}}} \right) \frac{\text{FM}}{\text{AO} \gamma_{\text{ref}}} \]

where \( \text{AO} = \frac{a_1}{a_{\text{ref}}} \)
\[
\text{and } \quad \text{FM} = \frac{\gamma \, U_m}{\left[ 1 + \frac{\gamma - 1}{2} \frac{U_m^2}{U_m} \right]^{\frac{\gamma + 1}{2(\gamma - 1)}}}
\]

if the flow is choked, the equation is the same but FM becomes

\[
\text{FM} = \gamma \left[ \left( \frac{2}{\gamma + 1} \right)^{\gamma - 1} \right]^{1/2}
\]

The argument for subroutine MASSFL follows.

**SUBROUTINE MASSFL(FHOLE, RUP, RDP, AO, GR, G, WFLOW)**

where FHOLE is the non-dimensional flow area, \( \left[ \frac{A_2}{A_{\text{ref}}} \right] \)

RUP is the upstream pressure divided by the reference pressure

RDP is the downstream pressure divided by the reference pressure

AO is the ratio of the speed of sound at the upstream temperature to the reference speed of sound.

GR is the reference value of \( \gamma \), the ratio of specific heats

G is \( \gamma \), the ratio of specific heats

WFLOW is the non-dimensional mass flow rate

7.14 **Subroutine POWER**

This subroutine integrates the energy balance equation for the compression-expansion portion of the cycle. The techniques used are the same as those described in detail in section 2.1 of this report.

Power is called by CYLNDR after the valves close indicating the start of the compression process. POWER calculates the gas properties at the start and end of each time step to obtain the internal energy and calculates the work and heat transfer. POWER also contains the combustion calculations resulting from the four combustion models. The amount of fuel burned is calculated and
multiplied by the constant volume heating value to obtain an effective heat release. This heat release is included in the energy balance. At the end of the expansion process, the indicated power and efficiency is calculated and printed to a file.

7.15 **Subroutine SPLFIT**

This subroutine is used to interpolate between discrete data provided to define a valve flow area curve. The calling program provides the X and Y arrays of discrete data and a value of X at which an interpolated Y is required and the subroutine fits a spline curve to the data and evaluates the spline at X. The relevant argument list follows.

SUBROUTINE SPLFIT (O,O,NP,O,O.,XKX,O,FY,O,X,Y,ITRP)

where NP is the number of points describing the curve

XKK(I) is the NP X-values defining the curve (25 points max). These points must be in ascending order

FY(I) is the array of NP Y-values defining the curve (corresponding to the X-values)

X is the X-value where the function value is required

Y is the calculate function value at the desired X-value

ITRP is an error indicator.

7.16 **Subroutine SREA**

This subroutine is used to calculate the surface area of the portion of the combustion chamber exposed to the combustion gases at a given crank position. This area will be the sum of the areas of the head surface, the
piston surface and the instantaneous exposed cylinder wall surface. Each of these areas is calculated as follows.

\[
\begin{align*}
\text{Head Area} &= \text{FPISTE} \frac{\pi}{4} (\text{BORE})^2 \\
\text{Piston Area} &= \text{FPISTA} \frac{\pi}{4} (\text{BORE})^2 \\
\text{Cylinder Wall Area} &= \pi (\text{BORE}) L
\end{align*}
\]

where FPISTE = the ratio of the head surface area to the cylinder cross-section

FPISTA = the ratio of the piston surface area to the cylinder cross-section

BORE = the cylinder diameter

L = the distance between the current position of the piston and its position at top dead center

Since the volume at any time is approximately equal to \( \frac{\pi}{4} (\text{BORE})^2 L \) it is possible to express the cylinder wall surface area in terms of the volume as

\[
\text{Cylinder wall area} = \pi (\text{BORE}) \frac{4V}{\pi (\text{BORE})^2} = \frac{4V}{\text{BORE}}
\]

Using this relation, the total surface area can be expressed as

\[
\text{AREA} = \frac{4V}{\text{BORE}} + \text{FPISTE} + \text{FPISTA} \frac{\pi}{4} (\text{BORE})^2
\]

The subroutine SREA evaluates this equation for a given set of input arguments. The argument list follows.

\[
\text{SUBROUTINE SREA (SAREA,FCYLL,DCYLL,XR,DR,FPISTA,FPISTE)}
\]

where SAREA is the total surface area

FCYLL is equal to \( \frac{\pi}{4} (\text{BORE})^2 \)

DCYLL is the Bore

XR and DR are reference dimensions (assumed = 1. in the BENSON program)
Subroutine STROK

This subroutine calculates the piston position and the rate of change of piston position (piston velocity) for a specified engine geometry and at a specified crank angle. Ferguson [9] gives the following expression for the instantaneous cylinder volume for a reciprocating engine.

\[ V = V_{cl} \left[ 1 + \frac{r-1}{2} \left( 1 - \cos \theta + \frac{1}{\varepsilon} \left( 1 - (1 - \varepsilon^2 \sin^2 \theta)^{1/2} \right) \right) \right] \]

where \( V_{cl} \) is the clearance volume
\( r \) is the compression ratio
\( \varepsilon \) is a geometric ratio \( \frac{2L}{S} \)
\( L \) is the connecting rod length
\( S \) is the stroke
\( \theta \) is the crank angle

By defining the quantity FNN

\[ FNN = \left( \frac{1}{\varepsilon^2} - \sin^2 \theta \right)^{1/2} \]

and recognizing that the compression ratio is equal to \( \frac{V_d + V_{cl}}{V_{cl}} \) so that \( (r-1) = \frac{V_d}{V_{cl}} \) it can be shown that the volume can be expressed as

\[ V = V_{cl} + \frac{V_d}{2} \left[ 1 - \cos \theta + \frac{1}{\varepsilon} - \text{FNN} \right] \]

or

\[ V = V_{cl} + \frac{\pi/4}{2} \frac{b^2}{S} \left[ 1 - \cos \theta + \frac{1}{\varepsilon} - \text{FNN} \right] \]

where \( b \) = bore
\( V_d \) = displacement volume

The subroutine STROK calculates the quantity
\[ X = \frac{S}{2} \left( 1 - \cos \theta + \frac{1}{\epsilon} - \text{FNN} \right) \]

which is the distance between the top of the piston at the specified crank angle and its position at top dead center. Thus, at TDC, when \( \theta = 0 \), the value of \( X = 0 \). This value is provided in non-dimensional form by dividing by a reference length, \( X_{\text{REF}} \)

\[ X_{\text{STROK}} = \frac{X}{X_{\text{REF}}} = \frac{S}{2X_{\text{REF}}} \left( 1 - \cos \theta + \frac{1}{\epsilon} - \text{FNN} \right) \]

The relation for the piston position can be differentiated with time to provide an expression for the piston velocity.

\[
\frac{d[X]}{dt} = \frac{S}{2} \left[ \frac{d(\cos \theta)}{dt} - \frac{d(\text{FNN})}{dt} \right]
\]

\[
= \frac{S}{2} \left[ \sin \theta + \frac{\sin 2\theta}{2\text{FNN}} \right] \frac{d\theta}{dt}
\]

\[
= \frac{S}{2} \left[ \sin \theta + \frac{\sin 2\theta}{2\text{FNN}} \right] \cdot 2\pi \cdot \text{REVENG}
\]

where \( \text{REVENG} \) is the engine speed in rev/sec.

The piston speed can be non-dimensionalized by introducing a non-dimensional time parameter, \( Z_{\text{REF}} = \frac{360 \cdot X_{\text{REF}} \cdot \text{REVREF}}{\text{AREF}} \) where \( \text{REVREF} \) is a reference engine speed and \( \text{AREF} \) is a reference speed of sound.

\[
\text{DSTROK} = \frac{1}{\text{AREF}} \left( \frac{d[X]}{dt} \right) = \frac{\pi}{360} Z_{\text{REF}} \frac{\text{REVENG}}{\text{REVREF}} \frac{S}{X_{\text{REF}}} \left[ \sin \theta + \frac{\sin 2\theta}{2\text{FNN}} \right]
\]

The non-dimensional piston position and velocity supplied by subroutine STROK
are used by other routines in the Benson program to calculate such quantities as the cylinder volume and cylinder surface area.

The argument list follows.

```plaintext
SUBROUTINE STROK(XSTROK, DSTROK, THETA, STROKE, CONROD, RPS, ZR)
```

where
- XSTROK is the nondimensional piston position returned by STROK
- DSTROK is the nondimensional piston velocity returned by STROK
- THETA is the crank position
- STROKE is the stroke normalized by XREF
- CONROD is the connecting rod length normalized by XREF
- RPS is the rotational speed of the engine, normalized by dividing by the reference engine speed
- ZR is the nondimensional time parameter (ZREF)

7.18 Subroutine UNITP

This subroutine is used to change the units of a pressure supplied as an input. The argument list follows.

```plaintext
SUBROUTINE UNITP (IA, IB, PP, PPB)
```

where IA and IB are used to designate the type of unit conversion desired, PP is the pressure which will be returned after having been multiplied by the appropriate conversion factor and PPB is the barometric pressure. PPB is required for conversions from gage pressure to absolute pressure. The values of IA and IB should be selected from the following choices.

<table>
<thead>
<tr>
<th>IA</th>
<th>IB</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>do nothing</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>do nothing</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>psia → bars (absolute)</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>bars (absolute) → psia</td>
</tr>
<tr>
<td>≠ 1,2</td>
<td>1</td>
<td>psig → bars (absolute)</td>
</tr>
<tr>
<td>≠ 1,2</td>
<td>2</td>
<td>bars (gage) → psia</td>
</tr>
</tbody>
</table>

54
7.19 Subroutine UNITT

This subroutine is used to change the units of a temperature supplied as an input. The argument list follows.

SUBROUTINE UNITT (IA, IB, TT)

where IA and IB are used to designate the type of unit conversion desired and TT is the temperature which will be returned after having been multiplied by the appropriate conversion factor. The values of IA and IB should be selected from the following choices.

<table>
<thead>
<tr>
<th>IA</th>
<th>IB</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>°K → °C</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>°K → °R</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>°K → °F</td>
</tr>
<tr>
<td>≠ 1,2,3</td>
<td>2</td>
<td>°F → °K</td>
</tr>
</tbody>
</table>

7.20 Subroutine UNITW

This subroutine is used to change the units of a mass supplied as an argument. The argument list follows.

SUBROUTINE UNITW (IA, IB, WW)

where IA and IB are used to designate the type of unit conversion desired and WW is the mass which will be returned after having been multiplied by the appropriate conversion factor. The values of IA and IB should be selected from the following choices.
<table>
<thead>
<tr>
<th>IA</th>
<th>IB</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>None</td>
</tr>
<tr>
<td>1</td>
<td>× 2</td>
<td>None</td>
</tr>
<tr>
<td>× 1</td>
<td>2</td>
<td>kg → lbm</td>
</tr>
<tr>
<td>× 1</td>
<td>× 2</td>
<td>lbm → kg</td>
</tr>
</tbody>
</table>
8.0 CONCLUSION

8.1 Suggestions for Future Work

The major weakness of thermodynamic modeling diesel engines is the lack of a reliable and simple way to predict the heat transfer and heat release rates. Correlations are available for both these quantities and they are available in the Benson program, however, these correlations were developed under conditions very different from those present in the proposed Compound Cycle Engine. Experimental measurements at speeds above 6000 RPM and boost pressures above 100 psia are not currently available in the technical literature. These measurements must be made and used to verify the correlations before they can be used reliably at these conditions.

The current combustion models in the Benson program are of two types. The Watson model, the AVL model and the Wiebe model are simple functional models and cannot be used to understand the details of the diesel combustion. The Whitehouse-Way model is an attempt to include some of the physics of the fuel injection and combustion processes in a model and so it has the potential to provide the predictive information required for design. However, the Whitehouse-Way model is based on an out-of-date understanding of diesel combustion. This model treats the spray from a droplet perspective whereas more modern approaches recognize that the droplets vaporize very quickly after entering the combustion chamber (especially in a highly rated engine) and the subsequent combustion has the characteristics of a gaseous turbulent diffusion flame. The more successful modern diesel combustion models are based on this
approach. A more modern combustion model should be added to the Benson program allowing the effects of parameters such as fuel injection pressure, injection duration, nozzle diameter, air swirl to be investigated.

Another useful feature that should be included in a model of the complete Compound Cycle Engine is second law thermodynamic analysis. Second law analysis is based on tracking the utilization and destruction of availability through the engine. Availability is defined as "the maximum amount of work that could be obtained by bringing a system into equilibrium with its surroundings." Availability enters the engine with the fuel and either leaves as work or is progressively destroyed by irreversible processes inside the engine. In contrast to conventional thermodynamic analysis which tracks energy through the system and cannot tell whether the energy could be profitably converted to work, second law analysis allows the sources of irreversibility in the engine to be identified and quantified so that their effect on the fuel efficiency of the engine can be determined.

8.2 Summary

This report documents the Benson Diesel Engine Simulation Program. This program is currently configured to simulate a loop or uniflow scavenged two stroke engine. The program can provide information about the effects of combustion timing, valve timing, heat release rate and other engine design and operating parameters. The program has been extended to include a more detailed heat transfer model that allows the prediction of metal part temperatures.


10.1 Variable Name List

ACB  = Start of Combustion
ACF  = End of Combustion
AIR  = An indicator of whether the intake valve/port is open or closed during the cycle (=0 when closed, =10 when open)
AIRVMX = Maximum flow area of intake valves/ports
ALPAIR = Array of crank positions corresponding to the intake valve flow areas given in FAIR, degrees.
ALPHAT = Cumulative total crankangle during integration.
ALPHEX = Array of crank positions corresponding to the exhaust valve flow areas given in FEXH, degrees.
ANGEND = Maximum number of crank degrees allowed before integration is terminated.
AAN(1) = Fuel injection parameters for Whitehouse-Way model.
AAN(2) = Fuel injection parameters for Whitehouse-Way model.
AVC  = Intake valve/port closing angle, degrees.
AVO  = Intake valve/port opening angle, degrees.
AREF = Reference value for speed of sound (based on TREF).
ANNA, ANNB, ANNC = Parameter for Annand or Woschni Heat Transfer model.
BETA = Parameter in Watson combustion model.
CARBON = Mass fraction of carbon in fuel.
CALVAL = Constant volume heat of combustion with water present as vapor in the products.
CD1, CD2 = Parameters in Watson combustion model.
CDA  = Discharge Coefficient for intake valve/port.
CDE  = Discharge Coefficient for exhaust valve/port.
CEFFYI = Charging efficiency based on inlet conditions and trapped volume.
CHEFFY = Charging efficiency based on trapped conditions.
CONDY = Thermal Conductivity of cylinder contents.
CYCLE = 2 for a two stroke engine, = 4 for a four stroke engine.
COEFFA, COEFFB, COEFFC, COEFFD = Coefficient for polynomial fit to JANAF tables.
CP1, CP2 = Parameter in Watson Combustion model.
CPT  = Specific heat at constant pressure.
CVT  = Specific heat at constant volume.
DEL1, DEL2, DEL3 = Parameter in either Wiebe or Whitehouse-Way combustion models.
DHEAT = Heat transfer rate from cylinder during gas exchange.
DREF = Reference diameter.
DZ = Nondimensional time increment.
DQF = Heat addition to cylinder due to combustion.
DQCR = Heat transfer from cylinder due to radiation.
DQCY = Heat transfer from cylinder due to convection.
ETI = Internal energy of gases in cylinder at start of time step.
ETF = Internal energy of gases in cylinder at end of time step.
EVC = Exhaust valve/port opening angle, degrees.
EVO = Exhaust valve/port closing angle, degrees.
EXH = An indicator of whether the exhaust valve/port is open or closed during the cycle. (=0 when closed, =10 when open).

EXHVMX = Maximum flow area of exhaust valves/ports.
FCY = Crosssectional area of cylinder.
FMEP1, FMEP2, FMEP3 = Parameters in FMEP correlation.
FMEPM = Multiplier for FMEP correlation.
FPISTA = Ratio of surface area of piston top to crosssectional area of cylinder.
FPISTE = Ratio of surface area of head exposed to combustion chamber to crosssectional area of cylinder.
FAIR = Array specifying the geometric intake valve flow area.
FEXH = Array specifying the geometric exhaust valve flow area.
PREF = A reference area used to normalize areas in the program.
FZA = Fuel/air mass ratio.
GA = Ratio of specific heats for air.
GE = Ratio of specific heats for exhaust products.
GREF = Reference ratio of specific heats.
HEATG = Total heat transfer during gas exchange.
HEATRF = Heat released due to combustion
HCl ... HCS = Integral of the convective coefficient times the area for steady state heat transfer analysis.
HCT1 ... HCT8 = Integral of the convective coefficient times the gas temperature times the area for steady state heat transfer analysis.
HTA = Enthalpy of air entering cylinder
HTF = Enthalpy of cylinder contents at end of time step.
NPCWF = Parameter which determines which combustion model is used in the program

    when NPCWF.LT.0 Whitehouse-Way Model
    when NPCWF.EQ.0 and DEL3.EQ.0 AVL Model
    when NPCWF.EQ.0 and DEL3.GT.0 Wiebe Model
    when NPCWF.GT.0 Watson Model

NTAIR = Number of points provided in ALPAIR and FAIR to specify the intake valve flow area. FAIR(NTAIR), ALPAIR(NTAIR)
NTEXH = Number of points provided in ALPHEX and FEXH to specify the exhaust valve flow area. FEXH(NTEXH), ALPHEX(NTEXH)
PBARAB = Barometric pressure.
PI = 3.141592654
PO2 = Partial pressure of oxygen.
PREF = Reference pressure.
PORTED = 1 for loop scavenged, = 2 for uniflow scavenged.
PVEL = Mean piston speed.
PURITY = Purity. Ratio of mass of air in trapped cylinder charge to total mass of trapped cylinder charge.
RELCHG = Relative charging efficiency based on trapped volume.
RELCHS = Relative charging efficiency based on swept volume.
REVENG = Engine speed, rev/sec.
REVREF = Reference engine speed, rev/sec.
REY = Reynolds number of cylinder contents.
SCAEFF = Scavenging Efficiency
SCASW = Scavenge ratio based on swept volume.
SCAVR = Scavenge ratio based on trapped volume.
STOIC = Stoichiometric fuel/air ratio.
SURFC = Surface area of cylinder wall exposed to combustion.
SURFH = Surface area of head exposed to combustion chamber.
SURFP = Surface area of piston.
TAIR = Temperature of air entering cylinder through intake.
TEXH = Exhaust temperature (initial estimate specified as input)
TREF = Reference temperature.
TREFF = Trapping Efficiency.
TWALL = Cylinder wall temperature.
VALAIR = 0 if engine has intake ports, = 10 if engine has intake valves.
VALEXH = 0 if engine has exhaust ports, = 10 if engine has exhaust valves.
VCYL = Cylinder volume.
VEFFYI = Charging efficiency based on inlet conditions and swept volume.
VISCTY = Viscosity of cylinder contents.
WABU = Mass of air required to burn fuel under stoichiometric conditions.
WAR = Water to air ratio.
WCA = Air retained in the cylinder.
WCAIR = Total mass of air trapped in cylinder.
WCHG = Mass of air plus residual in cylinder per cycle.
WCO = Total mass flow rate through exhaust valve.
WCYL = Total mass in cylinder.
WCYLT = Trapped mass in cylinder.
WIDTHA = Fraction of cylinder circumference allocated for intake ports.
WIDTHE = Fraction of cylinder circumference allocated for exhaust ports.
WFUEL = Mass of fuel injected per cycle.
WMW = Molecular weight.
WN(I) = Number of moles of species I.
WNA = Number of moles of air trapped in cylinder.
WNI(I) = Number of moles of each species present at start of time step.
WNF(I) = Number of moles of each species present at end of time step.
WNP = Increase in number of moles in cylinder due to combustion (moles air - moles products).
WNR = Number of moles of residual trapped in cylinder.
WNTF = Total number of moles of gases in cylinder.
WRES = Mass of residual gases in cylinder.
WTOT = Total mass in cylinder, air+residual+fuel
MAIN PROGRAM

CHARACTER*16 FNAME1,FNAME2,FNAME3,FNAME4
CHARACTER*2 INC1,INC2,INC3,INC4
COMMON/BNS/ EQUV, RPM, PEXH, PAIR, TAIR,
1 CR, BORE, STROKE, CONROD, FPISTB, FPISTA,
2 EVO, EVC, AVO, AVC,
3 TWALL, WFUEL,
4 AGB, ACF,
5 ANNA, FMEPM,
6 NPCF, DEL1, DEL2, AAN(2),
7 VALEXH, CDE, NTEXH, WIDTHH, ALPHH(50), FEXH(50),
8 VALAIR, CDA, NTIAR, WIDTHA, ALPAIR(50), FAIR(50)
COMMON/GEN/ALPHAT, ANGEND, ANGRES, AIRPO, EXHPO, IMOLS,
1 APAIR, APEXH, AREF, AP(2),
1 APN(2), CYCLE, DALPHA,
1 DREF, DZ, FREF,
1 IPOWER, IREV, GA, GE, GREF, IUNITL,
1 IUNITP, IUNTIT, IUNITK, IUNITW, IUNITQ,
1 WAR, PBAR, PBARAB,
1 PI, PREF, REVENG, REVREF, RPAIR, RPEXH, RP(2),
1 RNP(2), STEP2, TEXH, TREF, VREF, WREF, XREF,
1 Z, ZREF, HAIAT, HREF, SCMULT, NC
COMMON/COMB/ AIRFL, EQUV, TEXTH, SHPS, FZA, HRD, SASW, TREFF, SCAEFF,
1 AIRVMX, EXHVMX, PORTED, ST0IC, WC0, LLBACK, FUEL, BHP
COMMON/OPEN/ FNAME1,FNAME2,FNAME3,FNAME4
COMMON/TEMP/TW, TWG, TWG, TWG, TW, TW, TW, TW, TW, TW, TEXHP,
1 TWVEG, TC1, TC2, TC3
COMMON/HEAT1/ QF, QFC, QC, QCPC, A1, A1PC, A2, A2PC, A3, A3PC, A4, A4PC,
1 QCYL, QCYLP
COMMON/HEAT2/ QEVG, QEVPC, QEXH, QEXHPC,
1 QTC1, QTC1PC, QTC2, QTC2PC, QTC3, QTC3PC, QOUT, QOUTPC
FNAME1='FILE01.AAA'
FNAME2='FILE01.BBB'
FNAME3='FILE01.CCC'
FNAME4='FILE01.DDD'
INC1='02'
INC2='03'
INC3='04'
INC4='05'

ASSUME COMPRESSOR PRESSURE RATIO AND PRESSURE RATIO ACROSS DIESEL

P2P1=6.0544
P6P5=1.1.171

INLET CONDITIONS
T1 = 518.7
P1 = 14.7

C COMPRESSOR OUTLET CONDITIONS
C
ETACTT = 0.85
P2 = P2P1 * P1
DUMMY = P2P1 ** 0.2857 - 1.
T2 = T1 * (DUMMY / ETACTT + 1.)
WC = 0.24 * T1 / ETACTT * DUMMY

C LOSSES TO AFTERCOOLER/AFTERCOOLER INLET CONDITIONS
C
P3 = 0.98 * P2
P3 = P2
T3 = T2

C AFTERCOOLER EXIT CONDITIONS
C
E = 0.4
T4 = T3 - E * (T3 - T1)
P4 = 0.98 * P3
T4 = T3
P4 = P3

C LOSSES TO DIESEL/DIESEL INLET CONDITIONS
C
P5 = P4
T5 = T4
PAIR = P5
TAIR = T5
PEXH = P6P5 * PAIR

C RUN DIESEL PROGRAM
C CALL BENSON

C EXHAUST CONDITIONS
C
P6 = PEXH
T6 = TEXHS

C LOSSES TO HIGH PRESSURE TURBINE/TURBINE INLET CONDITIONS
C
P7 = 0.98 * P6
T7 = T6

C TURBINE OUTLET CONDITIONS - WORK MATCHED TO COMPRESSOR REQUIREMENTS
C ASSUMES 2% LOSS TO BEARING FRICTION
C
ICHK = 0
TS=T7
PS=14.7
30 TM=(TS+T7)/2.
CALL PROP(EQUIVD, TM, CPX, GX)
ETAT1=0.84
DUMMY=1.-(PS/PT)*(GX-1.)/GX
T8=T7*(1.-DUMMY*ETAT1)
WT=ETAT1*CPX*TM*DUMMY*(FUEL+AIRFL)-3600./2544.
IF(ICHK.EQ.1) GO TO 40
ICHK=1
GO TO 30
40 CONTINUE
C

C

TWCCF=TWCC*1.8-460.
TWCPF=TWCP*1.8-460.
TWCHF=TWCH*1.8-460.
TWEVF=TWEV*1.8-460.
TWGHF=TWGH*1.8-460.
TWPFRF=TWPR*1.8-460.
TWCCF=TWCC*1.8-460.
TWCRF=TWCR*1.8-460.

C

WRITE(2,1010)
1010 FORMAT(/5X,'ENGINE PART TEMPERATURES',40X,'HEAT TRANSFER SUMMARY')
WRITE(2,1011) TWGH,TWGHF,QF,QFPC
1011 FORMAT(/2X,'GAS SIDE HEAD TEMPERATURE',7X,F8.1,9' K',F11.1,9' F',
1 12X,'FRICTION GENERATED HEAT TRANSFER',3X,F10.3,F11.2,' %')
WRITE(2,1012) TWGP,TWGF,QQC,QQPC
1012 FORMAT(2X,'GAS SIDE PISTON CROWN TEMPERATURE',F7.1,' K',F11.1,
1 ' F',12X,'CREVICE VOLUME HEAT TRANSFER',F17.3,F11.2,' %')
WRITE(2,1013) TWGC,TWCF,AA1,AA1PC
1013 FORMAT(2X,'GAS SIDE SLEEVE TEMPERATURE',5X,F8.1,' K',F11.1,' F',
1 12X,'HEAT TRANSFER TO CYLINDER WALL',F15.3,F11.2,' %')
WRITE(2,1014) TWEV,TWEVF,AA2,AA2PC
1014 FORMAT(2X,'EXHAUST VALVE TEMPERATURE',7X,F8.1,' K',F11.1,' F',
1 12X,'HEAT TRANSFER TO PISTON',4X,F18.3,F11.2,' %')
WRITE(2,1015) TWOF,TWOF,A3,A3PC
1015 FORMAT(2X,'PISTON RIM TEMPERATURE',10X,F8.1,' K',F11.1,' F',
1 12X,'HEAT TRANSFER TO HEAD',6X,F18.3,F11.2,' %')
WRITE(2,1016) TWC,TCWF,AA4,AA4PC
1016 FORMAT(2X,'COMPRESSION RING TEMPERATURE',4X,F8.1,' K',F11.1,' F',
1 12X,'HEAT TRANSFER TO EXHAUST VALVE',F15.3,F11.2,' %')
WRITE(2,1017) TWCH,TWCHF,QQCYL,QQCYLPC
1017 FORMAT(2X,'COOLANT SIDE HEAD TEMPERATURE',3X,F8.1,' K',F11.1,' F',
1 12X,'TOTAL HEAT INPUT TO NETWORK',3X,F15.3,F11.2,' %')
WRITE(2,1018) TWCP,TWCPF
1018 FORMAT(2X,'OIL SIDE PISTON TEMPERATURE',5X,F8.1,' K',F11.1,' F')
WRITE(2,1019) TWCC,TWCF
1019 FORMAT(2X,'COOLANT SIDE SLEEVE TEMPERATURE',F9.1,' K',F11.1,' F')
WRITE(2,1002) QEVG, QEVGPC, QEXHP, QEXHPC,
1  QTC1, QTC1PC, QTC2, QTC2PC, QTC3, QTC3PC, QOUT, QOUTPC
1002 FORMAT(69X, 'HEAT TRANSFER TO EXH VALVE GUIDE', F10.3, F11.2, ' %')
2  69X, 'HEAT TRANSFER TO EXHAUST PORT GASES', F10.3, F11.2, ' %')
3  69X, 'HEAT TRANSFER TO PISTON COOLING OIL', F10.3, F11.2, ' %')
4  69X, 'HEAT TRANSFER TO SLEEVE COOLING OIL', F10.3, F11.2, ' %')
5  69X, 'TOTAL HEAT TRANSFER FROM NETWORK', F10.3, F11.2, ' %')

WC=-WC*(FUELF+AIRFL)*3600./2544.
THP=BHP+WC+WT
BSFC=FUELF*THP*3600.
WRITE(2,1030) BHP, WC, WT, THP, BSFC
1030 FORMAT(3X, 'DIESEL BRAKE POWER', F10.2, ' HP'/
1  3X, 'COMPRESSOR POWER', F12.2, ' HP'/3X, 'TURBINE POWER', F15.2,
2  ' HP'/3X, 'TOTAL SHAFT POWER', F11.2, ' HP'/3X, 'BSFC', F11.4)

CALL FCLOSE
STOP
END

SUBROUTINE PROP(EQUIV, T, CFX, GX)
IF(EQUIV.GT.0.) GO TO 10
X1=0.
X2=0.
X3=0.21
X4=0.79
GO TO 20
10 CARBON=0.85561
   HC=12.011/1.008*(1.-CARBON)/CARBON
   ASTO=(2.+HC/2.)/2./0.21
   Y1=1.
   Y2=HC/2.
   Y3=ASTO/EQUIV*0.21 - 1. - HC/4.
   Y4=ASTO/EQUIV * 0.79
   YTOT=Y1+Y2+Y3+Y4
   X1=Y1/YTOT
   X2=Y2/YTOT
   X3=Y3/YTOT
   X4=Y4/YTOT
20 CP1=16.2-6.53E3/T+1.41E6/T**2
   CP2=19.86-597./SQRT(T)+7500./T
   CP3=11.515-172./SQRT(T)+1530./T
   CP4=9.47-3.47E3/T+1.16E6/T**2
   CPX=X1*CP1+X2*CP2+X3*CP3+X4*CP4
   AVM=X1*44.01+X2*18.016+X3*32.00+X4*28.01
   CPX=CPX/AVM
   RX=1545./778./AVM
   CVX=CPX-RX
   GX=CPX/AVM
RETURN
END
10.3 Garrett CCE program listing

```
MAIN PROGRAM

CHARACTER*16 FNAME1,FNAME2,FNAME3,FNAME4
CHARACTER*2 INC1,INC2,INC3,INC4

COMMON/BNSN/ EQUIV, RPM, PEXH, PAIR, TAIR,
1 CR, BORE, STROKE, CONROD, FPISTE, FPISTA,
2 EVO, EVC, AVO, AVC,
3 T WALL, WFUEL,
4 ACB, ACF,
5 ANNA, FNEM,
6 NPCWF, DEL1, DEL2, DEL3, AAN(2),
7 VALEXH, CDE, NTEXH, WIDTHH, ALPHEX(50), FEXH(50),
8 VALAIR, CDA, NTAIR, WIDTHA, ALPAIR(50), FAIR(50)

COMMON/GEN/ ALPHAT, ANGEND, ANGRES, AIRPO, EXHPO, IMOLS,
1 APAIR, APEXH, AREF, AP(2),
1 APN(2), CYCLE, DALPHA,
1 DREF, DZ, FREF,
1 IPower, IREV, GA, GE, GREF, IUNITL,
1 IUNITP, IUNITT, IUNITK, IUNITW, IUNITQ,
1 WAR, PBAR, PBARAB,
1 PI, PREF, REVENC, REVREF, RP AIR, RPEXH, RP(2),
1 RPN(2), STEP2, TEXH, TREF, VREF, WREF, XREF,
1 Z, ZREF, HAIR, HREF, SCMULT, NC

COMMON/COMB/ AIRFL, EQUIV, TEXHS, SHPS, FZA, HRD, SCASW, TREFF, SCAEFF,
1 AIRVMX, EXHVMX, PORTED, ST01C, WCO, BLBACK, FUELF, BHP

COMMON/OPEN/ FNAME1, FNAME2, FNAME3, FNAME4

COMMON/TEMP/ TWEV, TWGH, TWGP, TWCR, TWPR, TWCP, TWOC, TWCH, TEXHP,
1 T WEVG, TC1, TC2, TC3

COMMON/HEAT1/ QF, QFPC, QC, QCPC, A1, A1PC, A2, A2PC, A3, A3PC, A4, A4PC,
1 QCYL, QCYLP C

COMMON/HEAT2/ QEVG, QEVGPC, QEXHP, QEXHPC,
1 QTC1, QTC1PC, QTC2, QTC2PC, QTC3, QTC3PC, QOUT, QOUTPC

FNAME1='FILE01.AAA'
FNAME2='FILE01.BBB'
FNAME3='FILE01.CCC'
FNAME4='FILE01.DDD'
INC1='02'
INC2='03'
INC3='04'
INC4='05'

C ASSUME COMPRESSOR PRESSURE RATIO AND PRESSURE RATIO ACROSS DIESEL
C
P2P1=10.61
PGP5=1.111

C INLET CONDITIONS
C
T1=518.7
```
P1=14.7

COMPRESSOR OUTLET CONDITIONS

ETACTT=0.79
P2=P2P1*P1
DUMMY=P2P1*0.2857 - 1.
T2=T1*(DUMMY/ETACTT + 1.)
WC=0.24*T1/ETACTT*DUMMY

LOSSES TO AFTERCOOLER/AFTERCOOLER INLET CONDITIONS

P3=0.98*P2
P3=P2
T3=T2

AFTERCOOLER EXIT CONDITIONS

E=0.4
T4=T3-E*(T3-T1)
P4=0.98*P3

LOSSES TO DIESEL/DIESEL INLET CONDITIONS

P5=P4*0.98
T5=T4
PAIR=P5
TAIR=T5
PEXH=P6*PAIR

RUN DIESEL PROGRAM

CALL BENSON

EXHAUST CONDITIONS

P6=PEXH
T6=TEXHS

LOSSES TO HIGH PRESSURE TURBINE/TURBINE INLET CONDITIONS

P7=0.98*P6
T7=T6

AFTERBURNER OUTLET CONDITIONS

F=0.0
TIN=T6
CALL TBURN(EQUIVD,F,TIN,TOUT)
T7=TOUT
XFUEL=F*(AIRFL+FUEL)
C TURBINE OUTLET CONDITIONS - WORK MATCHED TO COMPRESSOR REQUIREMENTS
C ASSUMES 2% LOSS TO BEARING FRICTION
C
ICHK=0
T8=I7
30 TM=(T8+T7)/2.
   CALL PROP(EQUIVD,TM,CPX,GX)
   ETAT1=0.845
   WT1=1.02*WC
   PS=P7*(1.0-T1/(ETAT1*CPX*T7))**(GX/(GX-1.))
   DUMMY=1.0-(PS/P7)**((GX-1.)/GX)
   T8=T7*(1.0-DUMMY*ETAT1)
   IF(ICHK.EQ.1) GO TO 40
   ICHK=1
   GO TO 30
40 CONTINUE
C LOSSES BETWEEN TURBINES/POWER TURBINE INLET CONDITIONS
C
   P9=0.98*P8
   T9=T8
C POWER TURBINE OUTLET CONDITIONS
C
ICHK=0
TIO=T9
50 TM=(T9+TIO)/2.
   CALL PROP(EQUIVD,TM,CPX,GX)
   WRITE(6,1) 'CPX, GX', CPX, GX
   P10=14.7
   ETAT2=0.848
   DUMMY=1.0-(P10/P9)**((GX-1.)/GX)
   TIO=T9*(1.0-DUMMY*ETAT2)
   IF(ICHK.EQ.1) GO TO 60
   ICHK=1
   GO TO 50
60 CONTINUE
   WT2=ETAT2*CPX*T9*DUMMY*(FUEL+AIRFL)*3600./2544.
   WRITE(6,1) 'T9, P9, TIO, P10', T9, P9, TIO, P10
C
TWCCF=TWCC*1.8-460.
TWCPF=TWCP*1.8-460.
TWCHF=TWCH*1.8-460.
TWEVF=TWEV*1.8-460.
TWGHF=TWGH*1.8-460.
TWGPF=TWGP*1.8-460.
TWPRF=TWPR*1.8-460.
TWGCF=TWGC*1.8-460.
TWCRF=TWCR*1.8-460.
WRITE(2,1010)
1010 FORMAT(/5X,'ENGINE PART TEMPERATURES',40X,'HEAT TRANSFER SUMMARY')
WRITE(2,1011) TWG, TWGHP, QF, QFPC
1011 FORMAT(/2X,'GAS SIDE HEAD TEMPERATURE',7X,F8.1,' K',F11.1,' F',
1 12X,'FRICTION GENERATED HEAT TRANSFER',3X,F10.3,F11.2,' %')
WRITE(2,1012) TWCP, TWCPF, QC, QCPC
1012 FORMAT(2X,'GAS SIDE PISTON CROWN TEMPERATURE',F7.1,' K',F11.1,
1 ' F',12X,'CREVICE VOLUME HEAT TRANSFER',F17.3,F11.2,' %')
WRITE(2,1013) TWCC, TWCF, A1, A1PC
1013 FORMAT(2X,'GAS SIDE SLEEVE TEMPERATURE',5X,F8.1,' K',F11.1,' F',
1 12X,'HEAT TRANSFER TO CYLINDER WALL',F15.3,F11.2,' %')
WRITE(2,1014) TWEV, TWEPF, A2, A2PC
1014 FORMAT(2X,'EXHAUST VALVE TEMPERATURE',7X,F8.1,' K',F11.1,' F',
1 12X,'HEAT TRANSFER TO PISTON',4X,F18.3,F11.2,' %')
WRITE(2,1015) TWCP, TWCPF, A3, A3PC
1015 FORMAT(2X,'PISTON RIM TEMPERATURE',10X,F8.1,' K',F11.1,' F',
1 12X,'HEAT TRANSFER TO HEAD',6X,F18.3,F11.2,' %')
WRITE(2,1016) TWCR, TWCPF, A4, A4PC
1016 FORMAT(2X,'COMPRESSION RING TEMPERATURE',4X,F8.1,' K',F11.1,' F',
1 12X,'HEAT TRANSFER TO EXHAUST VALVE',F15.3,F11.2,' %')
WRITE(2,1017) TWH, TWHCF, QC, QCPL
1017 FORMAT(2X,'COOLANT SIDE HEAD TEMPERATURE',3X,F8.1,' K',F11.1,' F',
1 12X,'TOTAL HEAT INPUT TO NETWORK',3X,F15.3,F11.2,' %')
WRITE(2,1018) TWCP, TWCPF
1018 FORMAT(2X,'OIL SIDE PISTON TEMPERATURE',5X,F8.1,' K',F11.1,' F')
WRITE(2,1019) TWCC, TWCF
1019 FORMAT(2X,'COOLANT SIDE SLEEVE TEMPERATURE',F9.1,' K',F11.1,' F')
WRITE(2,1002) QEC, QECPC, QEXH, QEXHP,
1 QC1, QC1PC, QC2, QC2PC, QC3, QC3PC, QC4, QC4PC
1002 FORMAT(6X,'HEAT TRANSFER TO EXH VALVE GUIDE',3X,F10.3,F11.2,' %'/
1 6X,'HEAT TRANSFER TO EXHAUST PORT GASES',F10.3,F11.2,' %'/
2 6X,'HEAT TRANSFER TO PISTON COOLING OIL',F10.3,F11.2,' %'/
3 6X,'HEAT TRANSFER TO SLEEVE COOLING OIL',F10.3,F11.2,' %'/
4 6X,'HEAT TRANSFER TO HEAD COOLING OIL ',F10.3,F11.2,' %'/
5 6X,'TOTAL HEAT TRANSFER FROM NETWORK ',F10.3,F11.2,' %')
C
FANP=51.6.
THP=BHP+WT2-FANP
BSFC=(FUEL+XFUEL)/THP*3600.
WRITE(2,1030) BHP, WT2, FANP, THP, BSFC
1030 FORMAT(/3X,'DIESEL BRAKE POWER',F10.2,' HP'/
1 3X,'TURBINE POWER',F15.2,' HP'/
2 3X,'FAN POWER ',F15.2,
3 ' HP'/3X,'TOTAL SHAFT POWER',F11.2,' HP'/3X,'BSFC',15X,F11.4)
WRITE(6,*) 'BSFC = ',BSFC
C
CALL FCLOSE
STOP
END
BLOCK DATA
COMMON/BNSN/ EQUVID, RPM, PEXH, PAIR, TAIR,
1 CR, BORE, STROKE, CONROD, FPISTE, FPISTA,
2 EVO, EVC, AVO, AVC,
3 T WALL, W FUEL,
4 ACB, ACF,
5 ANNA, FMEPM,
6 NPCW F, DEL1, DEL2, DEL3, AAN(2),
7 V ALEXH, CDE, NTEXH, WIDTHA, ALPAIR(50), FAIR(50),
8 DATA EQUIV, RPM, PEXH, PAIR, T AIR /0.68, 6.122, 134.79, 149.76, 896./
DATA CR, BORE, STROKE, CONROD, FPISTE, FPISTA /9.1712, 3.101, 2.940,
1 7.168, 1., 1.13/1
DATA EVO, EVC, AVO, AVC /90., 239., 126., 234. /
DATA TWALL, W FUEL /1460., 0.000145332/1
DATA ACB, ACF /345., 10.5/
DATA ANNA, FMEPM /0.36, 1.0/
DATA NPCWF, DEL1, DEL2, DEL3, AAN(2), AAN(2) /-1, 0.01457, 0.667, 0.4,
1 0.4, 0.5/
DATA VALAIR, CDA, NTAIR, WIDTHA, ALPAIR(50), FAIR(50),
8 DATA ALPHAX, DEXH, NTEXH /10., 0.8664, 13/
DATA VALAIR, CDA, WIDTHA /0., 0.8, 0.5542/
DATA ALPHAX/0.00, 10.97, 25.00, 31.61, 41.00, 52.25, 72.89, 90.95, 104.00,
1 111.59, 119.00, 132.23, 149.00, 37*0.3
DATA FEXH/0.0, 0.00093264, 0.00364, 0.00591222, 0.00899, 0.0106201,
1 0.01175263, 0.01111131, 0.00923, 0.00717895, 0.00461, 0.00181743, 0.,
2 37*0.3
END
C
SUBROUTINE PROP(EQUIV, T, CPX, GX)
IF(EQUIV.GT.0.) GO TO 10
X1=0.
X2=0.
X3=0.21
X4=0.79
GO TO 20
10 CARBON=0.85561
HC=12.011/1.005*(1.-CARBON)/CARBON
ASTO=(2.+HC/2.)/2./0.21
Y1=1.
Y2=HC/2.
Y3=ASTO/EQUIV*0.21 - 1. - HC/4.
Y4=ASTO/EQUIV * 0.79
YTOT=Y1+Y2+Y3+Y4
X1=Y1/YTOT
X2=Y2/YTOT
X3=Y3/YTOT
X4=Y4/YTOT
20 CP1=16.2-6.353E3/T+1.41E6/T**2
CP2=19.86-597./SQRT(T)+7500./T
CP3=11.515-172./SQRT(T)+1530./T
CP4=9.47-3.47E3/T+1.16E6/T^2
CPX=X1*CP1+X2*CP2+X3*CP3+X4*CP4
AVM=X1*44.01+X2*18.016+X3*32.00+X4*28.01
CPX=CPX/AVM
RX=1545.778./AVM
CVX=CPX-RX
GX=CPX/CVX
RETURN
END

SUBROUTINE TBURN(EQUIV,F,T1,T2)
HV=18600.
CALL PROP(EQUIV,T1,CP1,G1)
T537=537.
CALL PROP(EQUIV,T537,CP0,G0)
CPAVE=(CP1+CP0)/2.
DELH1=CPAVE*(T1-T537)
DELH=DELH1+HV*F
CARBON=0.85561
STOIC=1./((CARBON/12.01+(1.-CARBON)/(1.008*4.))*((32.0+3.76*28.0)))
EQUIV2=(F+1.)*EQUIV+F/STOIC
WRITE(6,*)'STOIC,EQUIV2',STOIC,EQUIV2
TOLD=2300.
CALL PROP(EQUIV2,TOLD,CP2,G2)
T537=537.
CALL PROP(EQUIV2,T537,CP0,G0)
CPAVE=(CP2+CP0)/2.
DELH2=CPAVE*(TOLD-T537)*(1.+F)
ZOLD=DELH2-DELH
TNEW=TOLD*1.05
CALL PROP(EQUIV2,TNEW,CP2,G2)
CPAVE=(CP2+CP0)/2.
DELH2=CPAVE*(TNEW-T537)*(1.+F)
ZNEW=DELH2-DELH
DELT=ZNEW*(TNEW-TOLD)/(ZOLD-ZNEW)
T2=TNEW+DELT
WRITE(6,*)'ZNEW,T2',ZNEW,T2
IF(ABS(DELT).LT.0.001) GO TO 50
TOLD=TNEW
TNEW=T2
ZOLD=ZNEW
GO TO 25
WRITE(6,*)'DELH,DELH2',DELH,DELH2
RETURN
END
10.4 Benson Program Listings

C VARIABLE NAMES:
C ACBB = DUMMY VARIABLE USED TO STORE ACB, START OF COMBUSTION
C ACFF = DUMMY VARIABLE USED TO STORE ACF, END OF COMBUSTION
C AIR = AN INDICATOR OF WHETHER INTAKE VALVE/PORT IS OPEN OR
C CLOSED DURING THE CYCLE (=0 WHEN CLOSED, =10 WHEN
C OPEN.
C ALPAIR = ARRAY OF CRANK POSITIONS CORRESPONDING TO THE INTAKE
C VALVE FLOW AREAS GIVEN IN FAIR, DEGREES (INPUT)
C ALPHAT = CUMULATIVE TOTAL CRANK ANGLE DURING INTEGRATION
C ALPHEX = ARRAY OF CRANK POSITIONS CORRESPONDING TO THE EXHAUST
C VALVE FLOW AREAS GIVEN IN FEXH, DEGREES (INPUT)
C ANGEND = MAXIMUM NUMBER OF CRANK DEGREES ALLOWED BEFORE
C INTEGRATION IS TERMINATED
C AAN(1) = FUEL INJECTION PARAMETER FOR WHITEHOUSE-WAY MODEL
C AAN(2) = FUEL INJECTION PARAMETER FOR WHITEHOUSE-WAY MODEL
C ACB = BEGINNING OF INJECTION WHEN NPCWF.LT.0
C BEGINNING OF HEAT RELEASE WHEN NPCWF.GT.0
C ACF = END OF INJECTION WHEN NPCWF.LT.0
C END OF HEAT RELEASE WHEN NPCWF.GT.0
C AVC = INTAKE VALVE/PORT OPENING ANGLE, DEGREES
C AVO = INTAKE VALVE/PORT CLOSING ANGLE, DEGREES
C AREF = REFERENCE VALUE FOR SPEED OF SOUND (BASED ON TREF)
C ANNA = PARAMETER FOR ANNAND OR WOSCHNI HEAT TRANSFER MODEL
C ANNB = PARAMETER FOR ANNAND OR WOSCHNI HEAT TRANSFER MODEL
C ANNC = PARAMETER FOR ANNAND OR WOSCHNI HEAT TRANSFER MODEL
C BETA = PARAMETER IN WATSON COMBUSTION MODEL
C CARBON = MASS FRACTION OF CARBON IN FUEL
C CD1 = PARAMETER IN WATSON COMBUSTION MODEL
C CD2 = PARAMETER IN WATSON COMBUSTION MODEL
C CYCLE = 2 FOR TWO CYCLE ENGINE, = 4 FOR FOUR CYCLE ENGINE
C COEFFA = COEFFICIENT FOR POLYNOMIAL FIT TO JANAF TABLES
C COEFFB = COEFFICIENT FOR POLYNOMIAL FIT TO JANAF TABLES
C COEFFC = COEFFICIENT FOR POLYNOMIAL FIT TO JANAF TABLES
C COEFFD = COEFFICIENT FOR POLYNOMIAL FIT TO JANAF TABLES
C CP1 = PARAMETER IN WATSON COMBUSTION MODEL
C CP2 = PARAMETER IN WATSON COMBUSTION MODEL
C CYCLE = 2 FOR TWO STROKE ENGINE, = 4 FOR A FOUR STROKE ENGINE
C SURFC = SURFACE AREA OF CYLINDER WALL EXPOSED TO COMBUSTION
C DEL1 = PARAMETER FOR EITHER WIEBE OR WHITEHOUSE-WAY MODEL
C DEL2 = PARAMETER FOR EITHER WIEBE OR WHITEHOUSE-WAY MODEL
C DEL3 = PARAMETER FOR EITHER WIEBE OR WHITEHOUSE-WAY MODEL
C DHEAT = HEAT TRANSFER RATE FROM CYLINDER DURING GAS EXCHANGE
C DQF = HEAT ADDITION TO CYLINDER DUE TO COMBUSTION
C DQCR = HEAT TRANSFER FROM CYLINDER DUE TO RADIATION
C DQCY = HEAT TRANSFER FROM CYLINDER DUE TO CONVECTION
C ETI = INTERNAL ENERGY OF GASES IN CYLINDER AT START OF
C TIME STEP
C ETF = INTERNAL ENERGY OF GASES IN CYLINDER AT END OF
TIME STEP

EVC = EXHAUST VALVE/PORT OPENING ANGLE, DEGREES
EVO = EXHAUST VALVE/PORT CLOSING ANGLE, DEGREES
EXH = AN INDICATOR OF WHETHER THE EXHAUST VALVE/PORT IS OPEN OR CLOSED DURING THE CYCLE. (=0 WHEN CLOSED, =10 WHEN OPEN)

FCYL = CROSS SECTIONAL AREA OF CYLINDER
FMEP1 = PARAMETER IN FMEP CORRELATION
FMEP2 = PARAMETER IN FMEP CORRELATION
FMEP3 = PARAMETER IN FMEP CORRELATION
FPISTA = RATIO OF SURFACE AREA OF PISTON TOP TO CROSS SECTIONAL AREA OF CYLINDER
FPISTE = RATIO OF SURFACE AREA OF HEAD EXPOSED TO COMBUSTION CHAMBER TO CROSS SECTIONAL AREA OF CYLINDER
FAIR = ARRAY SPECIFYING THE GEOMETRIC INTAKE VALVE FLOW AREA
FEXH = ARRAY SPECIFYING THE GEOMETRIC EXHAUST VALVE FLOW AREA
FREF = A REFERENCE AREA USED TO NORMALIZE AREAS IN THE PROGRAM
FZA = FUEL/AIR MASS RATIO
GA = RATIO OF SPECIFIC HEATS FOR AIR
GE = RATIO OF SPECIFIC HEATS FOR EXHAUST PRODUCTS
GREF = REFERENCE RATIO OF SPECIFIC HEATS
HEATG = TOTAL HEAT TRANSFER DURING GAS EXCHANGE
NPCWF = PARAMETER WHICH DETERMINES WHICH COMBUSTION MODEL IS USED IN THE PROGRAM

PO2 = PARTIAL PRESSURE OF OXYGEN
PORTED = 1 FOR LOOP SCAVENGED, = 2 FOR UNIFLOW SCAVENGED
STOIC = STOICHIOMETRIC FUEL/AIR RATIO
SURFP = SURFACE AREA OF PISTON
SURFH = SURFACE AREA OF HEAD EXPOSED TO COMBUSTION CHAMBER
TAIR = TEMPERATURE OF AIR ENTERING CYLINDER THROUGH INTAKE
TEXH = EXHAUST TEMPERATURE (INITIAL ESTIMATE SPECIFIED AS INPUT)
TREF = REFERENCE TEMPERATURE (INPUT)

TWALL = CYLINDER WALL TEMPERATURE
VALAIR = 0 IF ENGINE HAS INTAKE PORTS, = 10 IF ENGINE HAS INTAKE VALVES
VALEXH = 0 IF ENGINE HAS EXHAUST PORTS, = 10 IF ENGINE HAS EXHAUST VALVES
WABU = MASS OF AIR REQUIRED TO BURN FUEL UNDER STOICHIOMETRIC CONDITIONS, MASS UNITS
WCA = AIR RETAINED IN CYLINDER PER CYCLE, MASS UNITS
WCHG = MASS OF AIR PLUS RESIDUAL IN CYLINDER PER CYCLE, MASS UNITS
WCO = TOTAL MASS FLOW RATE THROUGH EXHAUST VALVE, MASS/TIME
WIDTHA = FRACTION OF CYLINDER BORE OCCUPIED BY INTAKE PORTS
WIDTHB = FRACTION OF CYLINDER BORE OCCUPIED BY EXHAUST PORTS
WFUEL = MASS OF FUEL INJECTED PER CYCLE, MASS UNITS
WMW = MOLECULAR WEIGHT
WN (I) = NUMBER OF MOLES OF SPECIES I
WNA = NUMBER OF MOLES OF AIR TRAPPED IN CYLINDER
WNI (I) = NUMBER OF MOLES OF EACH SPECIES PRESENT AT START OF
TIME STEP
WNF (I) = NUMBER OF MOLES OF EACH SPECIES PRESENT AT END OF
TIME STEP
WN = INCREASE IN NUMBER OF MOLES IN CYLINDER DUE TO
COMBUSTION (MOLS AIR — MOLES PRODUCTS)
WNR = NUMBER OF MOLES OF RESIDUAL TRAPPED IN CYLINDER
WNF = TOTAL NUMBER OF MOLES OF GASES IN CYLINDER, GMOLES
WORKGA = WORK DONE WHEN VALVES ARE CLOSED
WORKGE = WORK DONE DURING GAS EXCHANGE
WRES = MASS OF RESIDUAL GASES IN CYLINDER, MASS UNITS
WITOT = TOTAL MASS IN CYLINDER, AIR+RESIDUAL+FUEL, MASS UNITS

SUBROUTINE BENSON
CYLINDER PRESSURE, TEMPERATURE, VOLUME ON DIESEL3.OUT
IMPLICIT REAL(A—H, O—Z), INTEGER(I—N)
COMMON/BNSN/EQUIVZ, RPZ, PEXZ, PAIZ, TAIZ,
1 CZ, BORZ, STROKZ, CONROZ, FPISTY, FPISTZ,
2 EVOZ, EVCZ, AVOZ, AVCZ,
3 TWALLZ, WFUEZ,
4 ACBZ, ACFZ,
5 ANNAZ, PMEPMZ,
6 NPCWFZ, DEL1Z, DEL2Z, DEL3Z, AANZ (2),
7 VALEXZ, CDEZ, NTEXHZ, WIDTZ, ALPHEZ (50), FEXHZ (50),
8 VALAIZ, CDAZ, NTAIRZ, WIDTAZ, ALPAIRZ (50), FAIRZ (50)
COMMON/XXX/ EQUIVXD, RPM, PEXH, PAIR, TAIR,
1 CR, BORE, STROKE, CONROD, FPISTE, FPISTA,
2 EVO, EVC, AVO, AVC,
3 TWALL, WFUEL,
4 ACB, ACF,
5 ANNA, PMEPM,
6 NPCWF, DEL1, DEL2, DEL3, AAN (2),
7 VALEXH, CDE, NTEXH, WIDTHH, ALPHEX (50), FEXH (50),
8 VALAIR, CDA, NTAIR, WIDTHA, ALPAIR (50), FAIR (50)
COMMON/GEN/ALPHAT, ANGEND, ANGRES, AIRPO, EXHP0, IMOLS,
1 APAIR, APEXH, AREF, AP (2),
1 APN (2), CYCLE, DALPHA,
1 DREF, DZ, PREF,
1 IPower, IREV, GA, GE, GREF, IUNITL,
1 IUNITP, IUNITT, IUNITK, IUNITW, IUNITQ,
1 WAR, PPARAB,
1 P1, PREF, REVENG, REVFRED, RPAIR, RPEXH, RP (2),
1 RPN (2), STEP2, TEXH, TREF, VREF, WREF, XREF,
1 Z, ZREF, HAIR, HREF, SCMULT, NC
COMMON/CYL/ACS B, AIPHAE, ANNB, ANNC, AC,
1 ACN, ACR, ALPHAC,
1 CALVAL, CARBON,
1 COEFFA (4), COEFFB (4), COEFFC (4), COEFFD (4),
1 COEFFE (4), COEFF2 (4), CRANK, DCYL, DHEAT,
DRC, DVCYL, DWCIN, DWCP (2), DWCYL, FCYL, HEATG, PURITY, FUEL, PCR, PCYL, PORTS, RC, RCN, RCR, SURFC, TCR, TCYL, VSWEPT, VCYL, WCIN, WCAIR, WCOUT, WCYL, WMW (4), WPCNT (4), WCYL, WN (4), WORKGA, WORKGE, XCR, XSTA, NCD, WCYL, DWCINT, TPIST, THEAD, TEXV, CID

COMMON/COMB/AIRFL, EQUIV, TEXHS, SHPS, FZA, HRD, SCAST, TREFF, SCAEFF, + AIRVMX, EXHV, PORTED, STOIC, WCO, BLC, FUEL, BHP

COMMON/HEAT/NHEAT, QSLEV1, QPIST1, QHEAD1, QEXHV1, QTOT1, 1 QSLEV2, QPIST2, QHEAD2, QEXHV2, QTOT2, HC1, HC2, HC3, HC4, HC5, HC6, HC7, HC8, 3 HCT1, HCT2, HCT3, HCT4, HCT5, HCT6, HCT7, HCT8

COMMON/STOP/ ISTOP

WRITE (6, *) 'INSIDE BENSON'

EQUIV=EQEVZ

RPM=RPZ

P/E=PEXZ

PAIR=PAIZ

TAIR=TAIZ

CR=CZ

BOR=BORZ

STROKE=STROKZ

CONROD=CONROZ

FPISTE=FPISTY

FPISTA=FPISTZ

EVO=EV0Z

EVC=EVCZ

AVO=AV0Z

AVC=AVCZ

TWALL=TWALLZ

WFUEL=WFUEZ

ACB=ACBZ

ACF=ACFZ

ANNA=ANNAZ

FMEPM=FMEPMZ

NPCWF=NPCWFZ

DELL1=DELL1Z

DELL2=DELL2Z

DELL3=DELL3Z

AAN (1)=AANZ (1)

AAN (2)=AANZ (2)

VALEXH=VALEXZ

CDE=CDEZ

NTXH=NTXHZ

WIDTH=WIDTH2E

VAIAR=VAIARZ

CDA=CDAZ

NTAIR=NTAIRZ

WIDTH=WIDTH2A

DO 444 I=1,50
ALPHEX(I) = ALPHEZ(I)
FEXH(I) = FEXHZ(I)
ALPAIR(I) = ALPAIZ(I)
444 FAIR(I) = FAIRZ(I)

C
C
ISTOP = 0
ZERO = 0.0
ONE = 1.0
PI = 3.1415927

C
SELECT HEAT TRANSFER MODEL
C
NHEAT = 1

C
OPEN OUTPUT DATA FILES
C
CALL FOPEN
WRITE(6, *) 'RETURNED FROM FOPEN'

C
This section gets and prints the time and date of this run on the outputs
C
CALL GETTIM (IHOUR, INMIN, IDUM1, IDUM2)
CALL GETDAT (IYEAR, IMONTH, IDAY)
DO 2 IZZZ = 2, 4
WRITE (IZZZ, 1) IMONTH, IDAY, IYEAR, IHOUR, INMIN
1 FORMAT ('DATE: ', I2, '/', I2, '/', I4,15X, 'TIME: ', I2, ':', I2)
2 CONTINUE

TEXHS = 0.
SHPS = 0.
FZA = 0.
EQUIV = .5
AIRVMX = 0.
EHVMX = 0.

C
CALL INPUT
WRITE(6, *) 'RETURNED FROM INPUT'

C
CALL INPUT2
WRITE(6, *) 'RETURNED FROM INPUT2'

C
CALL HEADER
WRITE(6, *) 'RETURNED FROM HEADER'

C
WRITE(3, 2048)
2048 FORMAT (4X, 5HANGLE, 5X, 8HPRESSURE, 3X, 11HTEMPERATURE, 4X, + 5HGAMMA, 5X, 6HVOLUME, 5X, 9HMEAN TEMP/)
JJJJJ = 1
Z = 0.000
CALL UNITP (IUNITP, I, PREF, PBARAB)

C
SET UP TEMPERATURES TO S.I. UNITS
CALL UNITT (IUNITT, I, TREF)
AREF = SQRT (287.1*GREF*TREF)
C ENTER CALCULATION FIRST TIME
XREF=1.
DREF=1.
FREF=1.
VREF=1.
WREF=GREF*PREF*VREF*1.0E5/AREF**2
ZREF=360.0*XREF*REVREF/AREF
REVENG=REVENG/REVREF
CALL UNIT1 (UNIT1,1,TEXH)
CALL UNIT1 (UNIT1,1,TAIR)
CALL UNITP (UNITP,1,PEXH,PBARAB)
CALL UNITP (UNITP,1,PAIR,PBARAB)
CALL BAL(0.0,0.0,0.0,TAIR,GA,HAIR)
CALL BAL(0.0,0.0,0.0,TREF,DUM,HREF)
WRITE(6,*) 'ENTERING LOOP'
C
RPEXH=PEXH/PREF
PAIR=PAIR/PREF
APEXH=(SQRT (0.287E3*GE*TEXH))/AREF
AEX=APEXH/RPEXH**((GE-1.0)/(2.0*GE))
APAIR=(SQRT (0.287E3*GA*TAIR))/AREF
C
DZ = STEP2/(ZREF*REVENG)
Z = Z+DZ
ALPHAT = Z*ZREF*REVENG
C
IF (JJJJ.EQ.1) CALL INITLZ
C
CALL CYINDR (JJJJ)
C CHECK TO SEE IF CALCULATION IS COMPLETED
C
IF (ISTOP.EQ.1) GO TO 999
C CHECK TO SEE IF MAXIMUM NUMBER OF ITERATIONS IS EXCEEDED
C
IF (ALPHAT.GT.ANGEND) GO TO 7
JJJJ=2
C REENTER CALCULATION AGAIN
GO TO 6
7 CONTINUE
WRITE(6,*) 'MAXIMUM NUMBER OF ITERATIONS EXCEEDED'
C
This section gets and prints the time and date of this run on the outputs
C
CALL GETTIM (IHOUR,IMINUT,IDUM1,IDUM2)
CALL GETDAT (IYEAR,IMONTH,IDAY)
DO 4 IZZZ=2,4
WRITE (IZZZ,3) IMONTH, IDAY, IYEAR, IHOUR, IMINUT
3 FORMAT ('DATE: ',I2,'/',I2,'/',I4,15X,'TIME: ',I2,:,I2)
4 CONTINUE
C
C999 CALL FCLOSE

80
**CONTINUE**

RETURN

**C**

**SUBROUTINE INITLZ**

**COMMON/XXX/ EQUIVD, RPM, PEHX, PAIR, TAIR,**

1 CR, BORE, STROKE, CONROD, FPISTE, FPISTA,
2 EVO, EVC, AVO, AVC,
3 TWALL, WFUEL,
4 ACF, ACF,
5 ANNA, FMEP,
6 NPCW, DEL1, DEL2, DEL3, AN(2),
7 VALEXH, CDE, NTEXH, WIDTHE, ALPHEX(50), FEXH(50),
8 VALAIR, CDA, NTAIL, WIDTHA, ALPAIR(50), FAIR(50)

**COMMON/GEN/ALPHAT, ANGEND, ANGRES, AIRPO, EXHPO, IMOLS,**

1 APAIR, APEXH, AREF, AP(2),
2 APN(2), CYCLE, DPHIA,
3 DREF, DZ, FREF,
4 IPOWER, TREV, GA, GE, GREF, IUNITL,
5 IUNITP, IUNITT, IUNITK, IUNITW, IUNITQ,
6 IUNITI, IUNITP, IUNITT,
7 IUNITK, IUNITQ,
8 IUNITP, IUNITT,
9 WAR, PBARAB,
10 PI, PREF, REVENG, REVREF, RPAIR, RPEN, RPEN(2),
11 RPEN(2), STEP2, TWIN, TREF, VREF, WREF, XREF,
12 P, Z, ZREF, HAIR, HREF, SCMULT, NC

**COMMON/CYL/ACSB, ALPHACL, ALPHAC, ANNB, ANNC, AC,**

1 ACN, ACRY, ACRYAC,
2 CALVAL, CARBON,
3 COEFFA(4), COEFFB(4), COEFFC(4), COEFFD(4),
4 COEFFE(4), COEFFF(4), CRANK, DCYL, DHEAT,
5 DC, DVCYL, DWCR, DWCP(2), DWCYL,
6 FCYL, HEATG,
7 Purity, PVEL, PCR, PCYLIT,
8 PORTS, RC, RCR, SURFC,
9 TCR, TCYLIT, VSWEPT,
10 VCYL, WCYLT, WCRIN,
11 WCRIN, WCYL, WM(4), WPCNT(4), WCYLR,
12 WN(4), WORKGA, WORKGE, XCYLA, XSTA,
13 NCD, WCYLT, DWCYL,
14 TPIST, THEAD, TEXV, CID

**COMMON/COMB/AIRFL, EQUIV, EXHS, SHPS, FZA, HRD, SCASW, TREFF, SCAEFF,**

+ AIRVFX, EXHEFX, PORTED, STOIC, WOO, BLACK, FUELF, BHP

**C**

**CONVERT TO SI UNITS**

**C**

**C********************************************************************

11 DCYL=DCYL/3.281
12 XSTA=XSTA/3.281
13 XCRA=XCRA/3.281
14 IF(VALEXH.EQ.0.0) GO TO 15
15 DO 14 N=1, NTEXH
16 FEXH(N)=FEXH(N)/3.281**2
17 IF(VALEIR.EQ.0.0) GO TO 17
18 DO 16 N=1, NTAIL
19 FAIR(N)=FAIR(N)/3.281**2
20 CALL UNITP (UNITP, 1, PCYLIT, PBARAB)
CALL UNITT(IUNITT,1,TCYL)
IF (IUNITW.EQ.1) GO TO 22
WFUEL=W FUEL/2.205
22 CALL UNITT(IUNITT,1, TWALL)
CALL UNITT(IUNITT,1, TPIST)
CALL UNITT(IUNITT,1, THEAD)
CALL UNITT(IUNITT,1,TEXV)

C ********************************************************************
C ENTER ENTHALPY AND VISCOSITY COEFFICIENTS, MOLECULAR WEIGHT
C JANAF CURVE FIT 400 K TO 2400 K
C ********************************************************************

COEFFA(1)=3.00845
COEFFA(2)=2.94628
COEFFA(3)=3.29003
COEFFA(4)=3.50953
COEFFB(1)=6.15041E-4
COEFFB(2)=1.03617E-3
COEFFB(3)=2.69417E-3
COEFFB(4)=6.54488E-4
COEFFC(1)=-1.09800E-7
COEFFC(2)=-3.39775E-7
COEFFC(3)=-8.66074E-7
COEFFC(4)=9.41722E-8
COEFFD(1)=5.68186E-12
COEFFD(2)=4.75627E-11
COEFFD(3)=1.11529E-10
COEFFD(4)=3.43661E-11
DO 49 I=1,4
49 COEFFE(I)=8.3143*((COEFFA(I)-1.)*TREF+COEFFB(I)*TREF**2+
+ COEFFC(I)*TREF**3+COEFFD(I)*TREF**4)
WMM(1)=28.016
WMM(2)=32.000
WMM(3)=44.010
WMM(4)=18.016
IMOIS=0

C SET UP ANGLES FOR EACH CYLINDER
ALPHAC=EVO-CRANK
IF(ALPHAC.LT.0.) ALPHAC=ALPHAC+180.*CYCLE

C SET UP NON-DIMENSIONAL PARAMETERS
FCYL=(PI/4.0)*DCYL**2
30 IF(VALEXH.EQ.0.0) GO TO 31
DO 32 N=1,NTEXH
32 FEXH(N)=FEXH(N)/FREF
GO TO 33
31 CONTINUE
ZERO=0.0
43 CALL STROK(EXHO, ZERO, EVO, XSTA, XCRA, REVEN, ZREF)
33 IF(VAILAIR.EQ.0.0) GO TO 34
DO 35 N=1,NTAIR
35 FAIR(N)=FAIR(N)/FREF

82
GO TO 36
34 ZERO=0.0
   CALL STROK (AIRPO, ZERO, AVO, XSTA, XCRA, REVENG, ZREF)
36 PVEL=2.0*XSTA*XREF*REVREF*REVENG
   WORKGA=0.
   WORKGE=0.
   HEATG=0.
   IMOLS=100
   CALL POWER (1, 0)

37 CONTINUE
   RCR=PCR/PREF
   ACR=SQR (0.287E3*GE*TCR)/AREF
  *********************************************************************
   CAICLrfATE INITIAL CONDITIONS IN CYLINDER
   *********************************************************************
   EST=-I
   CALL STROK (XST, DST, EVO, XSTA, XCRA, REVENG, ZREF)
   CALL CYLVOL (FCYL, XST, XSTA, CR, DST, VCYL, DVCYL)
39 VCYL=XSTA*FCYL
   DVCYL=0.0
41 CONTINUE
   WCYL=GE*RCR*VCYL/((((ACR)**2)*GREF)
   WCYLR=WCYL
   DRC=0.
   RC=RCR
   AC=ACR
   WORKGA=0.0
   WORKGE=0.0
   HEATG=0.0
   WCIN=0.0
   SUMIMP=0.
   SUMCAP=0.
   WCOU=0.0
   AIRNET=0.
   WCAIR=0.0
   DWCYL=0.0
   RETURN
END

SUBROUTINE CYLNDR(JJJJ)
DIMENSION XMOL(4)
   IMPLICIT REAL(A--H,O--Z), INTEGER(I--N)
   COMMON/XXX/EQV,EQUIV,RPM,PEXH,PAIR,TAIR,
   1 CR, BORE, STROKE, CONROD, FPISTE, FPISTA,
   2 EVO, EVC, AVO, AVC,
   3 TWAH,WFUEL,
   4 ACB, ACF,
   5 ANNA, FSEP,
   6 NPCF, DEL1, DEL2, DEL3, ANA(2),
   7 VAEXH, CDE, NTExH, WIDTH, ALPHEx(50), FEXH(50),
   8 VALAIR, CD, NTAIR, WIDTHA, ALPAIR(50), FAIR(50)
   COMMON/GEN/ALPHAT, ANGEND, ANGRES, AIRPO, EXHO, IMOLS,
APAIR, APEXH, AREF, AP(2),
APN(2), CYCLE, DALPHA,
DREF, DZ, FREF,
IPOWER, IREV, GA, GE, GREF, IUNITL,
IUNITP, IUNITT, IUNITK, IUNITW, IUNITQ,
WAR, PBARAB,
PI, PREF, REVENG, REVREF, RPAIR, RPEXH, RP(2),
RPN(2), STEP2, TEXH, TREF, VREF, WREF, XREF,
Z, ZREF, HAIR, HREF, SCMULT, NC
COMMON/CYL/ACSB, ALPHA, ALPHAE, ANNB, ANNCE, AC,
ACN, ACR, ALPHAC,
CALVAl, CARBON,
COEFFA(4), COEFFB(4), COEFFC(4), COEFFD(4),
COEFFE(4), COEFFZ(4), CRANK, DCYL, DHEAT,
DRC, DVCYL, DWCIN, DWC(2), DWCYL,
FCYL, HEATG,
PURITY, PVEL, PCR, PCYL,
PORTS, RC, RCN, RCR, SURFC,
T CR, TCYL, VSWEPT,
VCYL, WCAIR, WCIN,
WCO, WCYL, WM(4), WPCNT(4), WCYL,
WN(4), WORKGA, WORKGE, WCPA, XSTA,
NCD, WCYLT, DWCINT,
TPIST, THEAD, TEXV, CID
COMMON/COMB/AIRFL, EQUIV, TEXH, SHPS, FZA, HDR, SCASW, TREFF, SCAEFF,
AIRVMX, EXHVMX, PORTED, STOIC, WCO, BLBACK, FUELF, BHP
COMMON/CPURE/VCW, WCHG, IMIX
COMMON/ENERGY/ UTILITL, UFINAL, HOUT
COMMON/TEMP/TWEV, TWCH, TWGP, TWC, TWCR, TWPR, TWCP, TWCC, TWCH, TEXHP,
TWEVG, TC1, TC2, TC3
COMMON/INPT2/
XXEVG, XXEVEVH, XXPSL, XXPS, XXPROG, XXHED, XXPCR, XXRS, XXSLV,
AEXV, AEXV, AEXST, AHEAD, ASLEEV, APIST1, APIST2, APISTR, ARING1, ARING2,
CEXV, CHEAD, CSLEEV, CPIST, CRING,
HEXHP, HOILP, HCSL, HCHD, NEXHV, DEXHV,
D1, D2, D3, D4, D5, D6, VCV, APP, ARR, ASS
COMMON/HEAT/ NHHEAT, QSLEV1, QPST1, QHEAD1, QEXHV1, QTOT1,
QSLEV2, QPST2, QHEAD2, QEXHV2, QTOT2,
HC1, HC2, HC3, HC4, HC5, HC6, HC7, HC8,
HCT1, HCT2, HCT3, HCT4, HCT5, HCT6, HCT7, HCT8
COMMON/STOP/ ISTOP
RPS=REVENG*REVREF
2 CONTINUE
ACN=AC
RCN=RC
NEX=1
APN(NEX)=AP(NEX)
RPN(NEX)=RP(NEX)
C SET UP CRANK ANGLE
101 ALPHAC=ALPHAC+DZ*ZREF*REVENG
IF(ALPHAC, LT, 180.0*CYCLE) GO TO 52
ALPHAC=ALPHAC-180.0*CYCLE
52 ALPHA=ALPHAC
ALPHAE=ALPHA
C *********************************************************************
C TEST IF CYLINDER OPEN TO EXHAUST AFTER FIRST REVOLUTION
C IF SO, START GAS EXCHANGE CALCULATIONS
C IF NOT, GO TO STATEMENT 12 WHICH INITIALIZES VARIABLES AND RETURNS TO MAIN
C *********************************************************************

CRANK = CRANK - DZ * ZREF * REVENG
IF (CRANK .LE. 0.0) GO TO 102

150 DRP(NEX) = 0.
151 PORQ_O = 0.
GO TO 12

C SET UP CYLINDER CONDITIONS
102 RC = RC + DZ * DRC
WCYL = WCYL + DZ * DWCYL

C *********************************************************************
C CALCULATE CYLINDER VOLUME, VOLUME CHANGE AND SURFACE AREA
C *********************************************************************

DVCYL = 0.0
DST = 1.0
CALL STROK (XST, DST, ALPHA, XSTA, XGRA, REVENG, ZREF)
XHTA = XST
CALL CYLVOL (FCYL, XST, XSTA, CR, DST, WCYL, DVCYL)
FPISTE = 1.0
CALL AREA (SURFC, VCYL, FCYL, DCYL, XREF, DREF, 1, FPISTA, FPISTE)

C CALCULATE SURFACE AREA OF SLEEVE
SURFC = SURFC - (FPISTA + FPISTE) * FCYL

C CALCULATE SURFACE AREA OF PISTON
SURFP = FPISTA * FCYL

C CALCULATE SURFACE AREA OF EXHAUST VALVE(S)
SURFE = FPISTE * FCYL - SURFE

C CALCULATE SURFACE AREA OF HEAD
SURFH = FPISTE * FCYL - SURFE

C CALCULATE AC
AC = SQRT(GR * RC * VCYL / (WCYL * GREF))

C *********************************************************************
C TEST WHETHER PORTS AND VALVES ARE OPEN, IF SO, SET FLAGS
C *********************************************************************

AIR = 10.
IF (ALPHA .GE. AVC .OR. ALPHA .LE. AVO) AIR = 0.0
EXH = 10.
IF (ALPHA .GE. EVC .OR. ALPHA .LE. EVO) EXH = 0.0

C *********************************************************************
C TEST WHETHER GAS EXCHANGE IS COMPLETE
C IF SO, PRINT OUT MASS FLOW TOTALS
C CALCULATE GAS EXCHANGE EFFICIENCIES
C CALL POWER TO DO COMBUSTION CALCULATIONS
C *********************************************************************

C HAS COMPRESSION STARTED YET?
IF (ALPHA LT ACSB) GO TO 152
D ALPHA = DZ * ZREF * REVENG

C IS THIS THE FIRST TIME STEP AFTER GAS EXCHANGE? IF SO, DO CALCULATIONS.
C OTHERWISE, SKIP TO BOTTOM
IF (ALPHA - ACSB .GT. DALPHA * 0.99) GO TO 152

85
C IF (ALPHA--ACSB. GE. DALPHA) GO TO 152
C *********************************************************************
C PRINT OUT MASS FLOW TOTALS
C *********************************************************************
BAL2 =-HEATG-WORKGA+HIN-HOUT-4JINI L+U INAL
BAL2=BAL2/(_n3EL*CALVAL) .100.
WRITE (6,2223) BAL2
2223 FORMAT (2X, 'GAS EXCHANGE ENERGY BALANCE',F8.4,' % OF FUEL ENERGY')
C
C BACK=1.-AIRNET/WCN
AIRFL=AIRNET*WREF*2.205*RPS*2./CYCLE
IF (CYCLE.EQ.4.) GO TO 248
IF (SCMULT.NE.1.) GO TO 247
IF (PORTED.EQ.1.) GOTO 247
SC.ASW-'-%_ZIN*WREF*.002871*TAIR/(PAIR*FCYL*XSTA)
VEFFYI=1.9811*EXP(-1.1201*SCASW)
WCAIR=VEFFYI*PAIR*FCYL*XSTA/(WREF*.002871*TAIR)
GO TO 248
247 WCAIR=WCAIR*ST
C
C CALCULATE AND PRINT OUT THE TOTAL AIR SUPPLIED TO THE CYLINDER
C
248 WCI=WCIN*WREF*2.0*RPS/CYCLE
CALL UNITW(IUNITW,2,WCI)
IF (IUNITW.EQ.2) GO TO 270
WRITE (4,251) WCI
251 FORMAT (35H TOTAL AIR SUPPLIED PER SECOND (KG) =, F11.6)
GO TO 273
270 WRITE (4,252)WCI
252 FORMAT (35H TOTAL AIR SUPPLIED PER SECOND (LB) =, F11.6)
C
C CALCULATE AND PRINT OUT THE MASS FLOW RATE THROUGH THE EXHAUST VALVE
C
273 WCO=WCOUT*WREF*2.0*RPS/CYCLE
CALL UNITW(IUNITW,2,WCO)
IF (IUNITW.EQ.2) GO TO 271
WRITE (4,253) WCO
253 FORMAT (50H TOTAL MASS FLOW THROUGH EXH VALVE PER SECOND (KG) =, 1 F11.6)
GO TO 274
271 WRITE (4,254)WCO
254 FORMAT (50H TOTAL MASS FLOW THROUGH EXH VALVE PER SECOND (LB) =, 1 F11.6)
C
C CALCULATE AND PRINT OUT THE MASS OF AIR RETAINED IN THE CYLINDER
C
274 WCA=WCAIR*WREF
CALL UNITW(IUNITW,2,WCA)
IF (IUNITW.EQ.2) GO TO 272
WRITE (4,255) WCA
255 FORMAT (34H TOTAL AIR RETAINED PER CYCLE (KG) =, F11.6)
GO TO 275
272 WRITE (4,256)WCA
256 FORMAT (34H TOTAL AIR RETAINED PER CYCLE (LB) =, F11.6)
C
C
275 SCAVR=Wcin*Wref/((Pair*1.0E5*Vcyl*Vref)/
 1 (0.2871*1.0E3*Tair))
WRITE(4,257)SCAVR
257 FORMAT(16H SCAVENGE RATIO=,F6.4)
SCASW=Wcin*Wref/(Pair*Xsta*Xref*Pi*((Dcyl*Dref)**2)/(4.
 1*Tair*.00287))
WRITE(4,261)SCASW
261 FORMAT(33H SCAVENGE RATIO ON SWEPT VOLUME =,F6.4)
CHEFFY=Wcair*100.0/Wcyl
PURITY=CHEFFY/100.
ONE=1.0000
PURITY=MIN1(PURITY,ONE)/(1.+WAR)
CHEFFY=Wcair*Wref*100.0/((Pair*1.0E5*Vcyl*Vref)/
 1 (0.2871*1.0E3*Tair))
VEFFY=CHEFFY*Vcyl/(Xsta*Fcyl)
WRITE(4,258)CHEFFY
WRITE(4,259)CHEFFYI
WRITE(4,260)VEFFY
258 FORMAT(20H CHARGING EFFICIENCY,
 1 28H BASED ON TRAPPED CONDITION =, F6.2)
259 FORMAT(20H CHARGING EFFICIENCY,
 1 43H BASED ON INLET CONDITION AND TRAPPED VOL. =, F6.2)
260 FORMAT(20H CHARGING EFFICIENCY,
 1 41H BASED ON INLET CONDITION AND SWEPT VOL. =, F6.2)
WSUPL=Wcin*Wref
WCA=Wcair*Wref
WCHG=Wcyl*Wref
WCA=MIN1(WCA,WCHG)
WDISP=PAIR*1.0E5*Vcyl*Vref/(.2871*1.0E3*Tair)
WDISPS=PAIR*1.0E5*Fcyl*Fref*Xsta*Xref/(.2871*1.0E3*Tair)
TREFF=Wca/WSUPL*100.
RELCHG=WCHG/WDISP*100.
RELCHS=WCHG/WDISPS*100.
SCAEFF=Wca/WCHG*100.
WRITE(4,401)TREFF
WRITE(4,402)RELCHG
WRITE(4,404)RELCHS
WRITE(4,403)SCAEFF
401 FORMAT(23H TRAPPING EFFICIENCY =, F6.2)
402 FORMAT(32H RELATIVE CHARGING EFFICIENCY =, F6.2)
403 FORMAT(23H SCAVENGE EFFICIENCY =, F6.2)
404 FORMAT(47H RELATIVE CHARGING EFF BASED ON SWEPT VOLUME =, F6.2)
WRITE(4,405)STOIC
405 FORMAT(33H STOICOMETRIC FUEL AIR RATIO =, F6.4)
C *********************************************************************
C SET UP PARAMETERS FOR NEXT TIME
C *********************************************************************
WCIN=0.0
WOOUT=0.0
SUMMP=0.0
SUMCAP=0.0
WCAIR=0.0
AIRNET=0.0
C *********************************************************************
C CALCULATE TRAPPED PRESSURE AND TEMPERATURE
C *********************************************************************
N=1
PCYLIT=PREF*(RC-(RC-RCN)*(ALPHA-ACSB)/DALPHA)
ACT=AC-(AC-ACN)*(ALPHA-ACSB)/DALPHA
TCYLIT=(GREF*TREF*ACT**2)/GE
IF(IPOWER.EQ.0) GO TO 188
IMOLS=100
C *********************************************************************
C CALL POWER TO DO COMBUSTION CALCULATIONS
C *********************************************************************
CALL POWER(I, i)
IF (ISTOP. EQ. I)
C
188 RCR=PCR/PREF
ACR=SQRT((GREF*TCR)/(GREF*TREF))
DST=1.0
CALL STROK(XST, DST, EVO, XSTA, XCRA, REVENG, ZREF)
CALL CYLVOL(PCYL, XST, XSTA, CR, DST, VCYL, DVCYL)
WCYL=GE*RCR*VCYI/((ACR)**2)*GREF)
WORKGE=0.0
WORKGA=0.0
HEATG=0.0
QSLEV2=0.
QPIST2=0.
QHEAD2=0.
QEXHV2=0.
HOUT=0.0
HIN=0.0
HOUT2=0.0
HIN2=0.0
HC5=0.
HC6=0.
HC7=0.
HC8=0.
HCT5=0.
HCT6=0.
HCT7=0.
HCT8=0.
C STORE RELEASE MASS
WCYLR=WCYL
C TEST IF BOTH AIR AND EXHAUST CLOSED
152 IF(EXH.NE.0.0) GO TO 124
IF(AIR.NE.0.0) GO TO 124
GO TO 150
C *********************************************************************
C CALCULATE GAS EXCHANGE WORK
C *********************************************************************
124 WORKGE=WORKGE+0.5*PREF*(RC+RCN)*(DVCYL-DVCYLE)*DZ*100.
WORKGE=WORKGE+0.5*PREF*(RC+RCN)*(DVCYL-DVCYLE)*DZ*100.
C *********************************************************************
C CALCULATE FLOW THROUGH VALVES/PORTS
C *********************************************************************

PORTS=100.0
IF(EXH.GT.0.0) GO TO 129
C EXHAUST VALVE/PORT IS CLOSED, SET MASS FLOW EQUAL TO ZERO
DWCP(NEX)=0.
GO TO 126
C C EXHAUST VALVES/PORTS OPEN
C CHECK WHETHER ENGINE HAS EXHAUST VALVES OR PORTS
C 129 IF(VALEXH.NE.0.0) GO TO 140
C ENGINE IS PORTED. CALCULATE PORT FLOW AREA AND NONDIMENSIONALIZE.
XHTE=XHTA
141 FEXHV=WIDTH*PI*DCYL* (XHTE–EXHPO)
FEXHV=FEXHV*DREF*XREF/FREF
GO TO 542
C ENGINE IS VALVED, USE SPLINE ROUTINE TO INTERPOLATE USER
C SUPPLIED EXHAUST VALVE FLOW AREA DATA AT THIS CRANK POSITION
140 CALL SPLFIT (0,0, NTEXH, 0, 0.0, _, 0, FEXH, 0, _, FEXHV, ITRP)
542 CONTINUE
533 FEXHV=CDE*FEXHV
EXHRN_ = AMAX1 (EXHRN, Exhmx)
C C MASS FLOW EXHAUST
C C CHECK WHETHER FLOW IS IN OR OUT OF CYLINDER
C IF(RPEXH.LT.RC) GO TO 590
CALL MASSFL (FEXHV, RPEXH, RC, APEXH, GREF, GE, DWCP (NEX))
DWCP (NEX)=–DWCP (NEX)
GO TO 547
590 CALL MASSFL(FEXHV, RC, RPEXH, AC, GREF, GE, DWCP (NEX))
547 CONTINUE
C TEST FOR AIR PORTS
126 IF(AIR.GT.0.0) GO TO 130
127 DWCIN=0.0
GO TO 147
C C INTAKE VALVES/PORTS OPEN
C CHECK WHETHER ENGINE HAS INTAKE VALVES OR PORTS
C 130 IF(VAILAIR.NE.0.0) GO TO 144
C ENGINE IS PORTED. CALCULATE PORT FLOW AREA AND NONDIMENSIONALIZE.
FAIRV=WIDTHA*PI*DCYL* (XHTA–AIRPO)
FAIRV=FAIRV*DREF*XREF/FREF
GO TO 189
C ENGINE IS VALVED, USE SPLINE ROUTINE TO INTERPOLATE USER
C SUPPLIED INTAKE VALVE FLOW AREA DATA AT THIS CRANK POSITION
144 CALL SPLFIT (0,0, NTAIR, 0, 0.0, ,PHAIR, 0, ,FAIR, 0, ,ALPHA, ,FAIRV, ITRP)
189 CONTINUE
133 FAIRV=CDIA*FAIRV
AIRVMX = AMAX1 (AIRVMX, FAIRV)
C MASS FLOW AIR
IF(RPAIR.LT.RC) GO TO 190
CALL MASSFL (FAIRV, RPAIR, RC, APAIR, GREF, GA, DWCIN)
GO TO 147
190 CALL MASSFL(FAIRV, RC, RPAIR, AC, GREF, GE, DWCIN)
   DWCIN=-DWCIN
   IF(NCD.EQ.1) DWCIN=0.
C ******************************************************************************
C MASS BALANCE
C ******************************************************************************
147 DWCYI=DWCIN-DWCP(NEX)
C
C KEEP TRACK OF AMOUNT OF NEW AIR ADDED TO CYLINDER
C ASSUMES CYLINDER CONTENTS ARE PERFECTLY MIXED
C
177 IF ((ALPHA-EVO)-(DZ*ZREF*REVENG) ) 170,171,171
170 DZT= (_--EVO)
   / (ZREF*REVENG)
   GO TO 172
171 DZT=DZ
C TEST FLOW DIRECTION THROUGH AIR VALVE
172 IF(DWCIN.GT.0.0) GO TO 174
C (XnTI£_ _ AIR VALVE
C TEST FLOW DIRECTION THROUGH EXHAUST VALVE
   IF(DWCP(NEX) .GT.0.0) GO TO 173
C OUTFLOW AIR VALVE, INFLOW EXH VALVE
   DWEAIR=WCAIR*DWCIN/WCYL
   WCAIR=WCAIR+DWEAIR*DZT
   GO TO 176
C OUTFLOW AIR VALVE, OUTFLOW EXH VALVE
173 DWEAIR= (DWCIN-DWCP(NEX)) *WCAIR/WCYL
   WCAIR=WCAIR+DWEAIR*DZT
   GO TO 176
C TEST FLOW DIRECTION THROUGH EXHAUST VALVE
174 IF(DWCP(NEX) .GT.0.0) GO TO 175
C INFLOW AIR VALVE, INFLOW EXH VALVE
   DWEAIR=0.0
   WCAIR=WCAIR+DWCIN*DZT
   WCIN=WCIN+DWCIN*DZT
   GO TO 176
C INFLOW AIR VALVE, OUTFLOW EXH VALVE
175 DWEAIR=WCAIR*DWCP(NEX)/WCYL
   WCAIR=WCAIR+ (DWCIN-DWEAIR) *DZT
   WCIN=WCIN+DWCIN*DZT
C TOTAL MASS FLOW THROUGH EXHAUST VALVE
176 WOUT=WOUT+DWCP(NEX) *DZT
C TOTAL MASS FLOW THROUGH INTAKE VALVE
   AIRIN=AIRIN+DWCIN*DZT
C ******************************************************************************
C CALCULATE HEAT TRANSFER
C ******************************************************************************
   TC=(GREF*TREF*AC**2)/GE
   TEXH=TC
   RHO=RC*PREF*1.0E2/(0.287*TC)
   WMOLS=RC*PREF*VCYL*VREF*1.0E2/(8.3143*TC)
   IF(IPOWER.NE.0) GO TO 160
   WN(1)=0.79*WMOLS
   WN(2)=0.21*WMOLS
WN(3)=0.0
WN(4)=0.0
GO TO 168
160 IF(IMOLS.EQ.0) GO TO 164
C CALCULATE PERCENT BY WT. OF CONSTITUENTS AT END OF POWER CYCLE
WT=0.0
DO 165 I=1,4
165 WT=WT+WWM(I)*WN(I)
DO 166 J=1,4
166 WPCNT(J)=WMM(J)*WN(J)/WT
IMOLS=0
C CALCULATE INSTANTANEOUS NO. OF MOI. IN GAS EXCHANGE
164 WN(1)=WREF*(0.767*WCAIR+WPCNT(1))
1 *(WCYL-WCAIR)/WMW(1)
WN(2)=WREF*(0.233*WCAIR+WPCNT(2))
1 *(WCYL-WCAIR)/WMW(2)
WN(3)=WREF*WPCNT(3)*(WCYL-WCAIR)/WMW(3)
WN(4)=WREF*WPCNT(4)*(WCYL-WCAIR)/WMW(4)
C ********************************************************************
C CALCULATE HEAT TRANSFER DATA
C ********************************************************************
168 DO 161 I=1,4
161 WN(I)*(COEFFA(I)+2.0*COEFFB(I)*TC+3.0*COEFFC(I)*TC**2
1 +4.0*COEFFD(I)*TC**3)
CPT=8.3143*CPT/(WCYL*WREF)
SUMMOL=WN(1)+WN(2)+WN(3)+WN(4)
RGAS=8.3143*SUMMOL/(WCYL*WREF)
GE=CPT/(CPT-RGAS)
SUMMP=SUMMP+TC*CPT*DWCP(I)*DZ
SUMCAP=SUMCAP+CPT*DWCP(I)*DZ
TAVG=1.8*SUMMP/SUMCAP
PRESS=14.5*PREF*RC
TRANK=1.8*TC
VOL=61032.7*VREF*VCYL
WRITE(3,1020) ALPHA,PRESS,TRANK,GE,VOL
1020 FORMAT(5(IX,E11.5))
XSTIN=XST*39.372
C
C CALCULATE ENTHALPY OF AIR ENTERING CYLINDER
HTA=0.0
XMOL(1)=.79
XMOL(2)=.21
DO 21 I=1,2
21 HTA=HTA+XMOL(I)*(8.3143*((COEFFA(I))*TAIR+COEFFB(I)*TAIR**2
1 +COEFFC(I)*TAIR**3+COEFFD(I)*TAIR**4)-COEFFE(I))
HTA=HTA/28.85
C CALCULATE ENTHALPY AND INTERNAL ENERGY OF CYLINDER CONTENTS AT
C THE END OF THE TIME STEP
C
HTF=0.0
DO 91 I=1,4
91 HTF=HTF+XMOL(I)*((COEFFA(I))*TC+COEFFB(I)*TC**2
1 +COEFFC(I)*TC**3+COEFFD(I)*TC**4)-COEFFE(I))
HTF = HTF * SUMMOL / (WREF * WCYL)
ETF = HTF * 6.3142 * TC * SUMMOL / (WREF * WCYL)

C

DHOUT = DWCP(1) * HTF * WREF * DZT
HOUT = HOUT + DHOUT
DHIN = DWCIN * HTA * WREF * DZT
HIN = HIN + DHIN

C CALCULATE COEFFICIENTS FOR GAS VISCOSITY EQUATION
A = 0.0
B = 0.0
DO 162 I = 1, 4
   A = WN(I) * COEFFZ(I) * SQRT(WMW(I)) + A
   162 B = WN(I) * SQRT(WMW(I)) + B

C *********************************************************************
C CALCULATE HEAT TRANSFER DURING GAS EXCHANGE
C *********************************************************************

IF (NHEAT .EQ. 0) GO TO 777
TWALL = TWGC
TPIST = TWGP
THEAD = TWGH
TEXV = TWEV

777 VISCTY = (A * TC ** 0.645) / B
CONDY = CPT * VISCTY / 0.7
REY = RHO * PVEL * DCYL * DREF / VISCTY
IF (ANNC .EQ. 0) REY = REY * 6.18
H = (ANNA * CONDY * REY ** ANNBJ) / (DCYL * DREF)
DHEAT = SURFC * H * (TWALL - TC) * VREF ** 1000. / AREF
DHEAT = DHEAT + (SURFP * (TPIST - TC) + SURFH * (THEAD - TC)) * H * VREF ** 1000. / AREF
C TOTAL HEAT TRANSFER DURING GAS EXCHANGE (KJ)
HEATG = HEATG + DHEAT * DZ / 1.0E - 3

C

DQSLEV = SURFC * H * (TWALL - TC) * VREF ** 1000. / AREF
DQPIST = SURFP * H * (TPIST - TC) * VREF ** 1000. / AREF
DQHEAD = SURFH * H * (THEAD - TC) * VREF ** 1000. / AREF
DQEXHV = SURFE * H * (TEXV - TC) * VREF ** 1000. / AREF
QSLEV2 = QSLEV2 + DQSLEV * DZ / 1000.
QPIST2 = QPIST2 + DQPIST * DZ / 1000.
QHEAD2 = QHEAD2 + DQHEAD * DZ / 1000.
QEXHV2 = QEXHV2 + DQEXHV * DZ / 1000.
QTOT2 = QTOT2 + QSLEV2 + QPIST2 + QHEAD2 + QEXHV2

HC5 = HC5 + H * SURFC * 2.
HC6 = HC6 + H * SURFP * 2.
HC7 = HC7 + H * SURFH * 2.
HC8 = HC8 + H * SURFE * 2.
HCT5 = HCT5 + H * SURFC * TC * 2.
HCT6 = HCT6 + H * SURFP * TC * 2.
HCT7 = HCT7 + H * SURFH * TC * 2.
HCT8 = HCT8 + H * SURFE * TC * 2.

C *********************************************************************
C FIRST LAW OF THERMODYNAMICS
C ENERGY BALANCE AND PRESSURE CHANGE FOR GAS EXCHANGE
C *********************************************************************
CVT=CPT-8.3143*SUMMOL/(WREF*WCYL)
DTEMP=(DHEAT/1000.+WREF*(DWCIN*HTA-DWCP(1)*HTF-DWCYL
+
*TETF)-RC*PREF*DVCYL*VREF*100.)/(WREF*WCYL*CVT)
DRC=RC*(DTEMP/TC+DWCYL/WCYL-DVCYL/VCYL)
C
12 IF(PORTS.NE.0.0) GO TO 100
  RC=RCR
  AC=ACR
  DRC=0.0
  DWCYL=0.0
  DWCIN=0.0
100 CONTINUE
1 RETURN
END
C
SUBROUTINE ELIM(AB,N,NP,NDIM)
DIMENSION AB(NDIM,NP)
C THIS SUBROUTINE SOLVES A SET OF LINEAR EQUATIONS.
C THE GAUSS ELIMINATION METHOD IS USED, WITH PARTIAL PIVOTING.
C MULTIPLE RIGHT HAND SIDES ARE PERMITTED, THEY SHOULD BE SUPPLIED
C AS COLUMNS THAT AUGMENT THE COEFFICIENT MATRIX
C PARAMETERS ARE —
C AB COEFFICIENT MATRIX AUGMENTED WITH R.H.S. VECTORS
C N NUMBER OF EQUATIONS
C NP TOTAL NUMBER OF COLUMNS IN THE AUGMENTED MATRIX
C NDIM FIRST DIMENSION OF MATRIX AB IN THE CALLING PROGRAM.
C THE SOLUTION VECTOR(S) ARE RETURNED IN THE AUGMENTATION
C COLUMNS OF AB.
C REFERENCE: APPLIED NUMERICAL ANALYSIS, 2ND EDITION
C CURTIS F. GERALD P. 132
C
C BEGIN THE REDUCTION
NM1=N-1
DO 35 I=1,NM1
C FIND THE ROW NUMBER OF THE PIVOT ROW. WE WILL THEN
C INTERCHANGE ROWS TO PUT THE PIVOT ELEMENT ON THE DIAGONAL.
  IPVT=I
  IP1=I+1
  DO 10 J=IPI,N
    IF(ABS(AB(IPVT,J)) .LT. ABS(AB(J,I))) IPVT=J
10 CONTINUE
C CHECK TO BE SURE THE PIVOT ELEMENT IS NOT TOO SMALL, IF SO
C PRINT A MESSAGE AND RETURN
  IF((ABS(AB(IPVT,I)) .LT. 1.E-5)) GO TO 99
C NOW INTERCHANGE, EXCEPT IF THE PIVOT ELEMENT IS ALREADY ON
C THE DIAGONAL, DON'T NEED TO.
  IF(IPVT.EQ.I) GO TO 25
  DO 20 JCOL=1,NP
    SAVE=AB(I,JCOL)
    AB(I,JCOL)=AB(IPVT,JCOL)
    AB(IPVT,JCOL)=SAVE
20 CONTINUE
C NOW REDUCE ALL ELEMENTS BELOW THE DIAGONAL IN THE I-TH ROW. CHECK
C FIRST TO SEE IF A ZERO ALREADY PRESENT. IF SO,
C CAN SKIP REDUCTION FOR THAT ROW.
25 DO 32 JROW=IP1,N
   IF(AB(JROW,I) .EQ.O) GO TO 32
   RATIO=AB(JROW,I)/AB(I,I)
   DO 30 KCOL=IP1,NP
      AB(JROW,KCOL) = AB(JROW,KCOL) —RATIO*AB(I,KCOL)
30 CONTINUE
32 CONTINUE
35 CONTINUE
C WE STILL NEED TO CHECK A(N,N) FOR SIZE
IF(ABS(AB(N,N)) .LT. 1.E—5) GO TO 99
C NOW WE BACK SUBSTITUTE
NP1=N+1
DO 50 KCOL=NP1,NP
   AB(N,KCOL)=AB(N,KCOL)/AB(N,N)
   DO 45 J=2,N
      NVBL=NP1—J
      L=NVBL+1
      VALUE=AB(NVBL,KCOL)
      DO 40 K=L,N
         VALUE=VALUE—AB(NVBL,K)*AB(K,KCOL)
40 CONTINUE
   AB(NVBL,KCOL)=VALUE/AB(NVBL,NVBL)
45 CONTINUE
50 CONTINUE
RETURN
C MESSAGE FOR A NEAR SINGULAR MATRIX
99 WRITE(6,100)
100 FORMAT(2X, 'SOLUTION IS NOT FEASIBLE. A NEAR ZERO PIVOT WAS ENCOUN
1TERED. ')
   RETURN
END

SUBROUTINE POWER (N, IPUR)
DIMENSION VCVIA (360), VCYLE (360), VCVILP (360), PFCP (360), TCP (360),
1 PRANG (360), CANG(2), PCFINT (2), WNI (4), WNF (4)
C IMPLICIT REAL(A—H,O—Z), INTEGER(I—N)
COMMON/XXX/ EQUIVD, RPM, PEXH, PAIR, TAIR,
1 CR, BORE, STROKE, CONROD, FPSTE, FPISTA,
2 EVO, EVC, AV0, AVC,
3 TWALL, WFUEL,
4 ACB, ACF,
5 ANNA, FMEPM,
6 NPCWF, DEL1, DEL2, DEL3, AAN(2),
7 VALAIR, CDE, NTEXH, WIDHE, ALPHEX(50), FEXH(50),
8 VALAIR, CDA, NTAIR, WIDTHA, ALPAIR(50), FAIR(50)
COMMON/GEN/ALPHAT, ANGEND, ANGRES, AIRP0, EXHPO, IMOLS,
1 APAR, APFHX, AREP, AP(2),
1 ANP(2), CYCLE, DALPHA,
C ********************************************************************
C SET UP ANG7
C ********************************************************************
RPS=REVENG*REVREF
ANGIA=ACSB
ANGLE=ACSB
ANGLP=180.0*CYCLE-ACSB+EVO
ANGLC=0.0
K=1
PRANG (1)=ACSB
C SET UP COMBUSTION ANGLES
ACBB=ACB
IF (ACBB .LT. 180.0) ACBB = 180.0 * CYCLE + ACBB
ACFF = ACF
IF (NPCWF .EQ. 0 .AND. DE3 .EQ. 0.) HRD = 15. + 115. * EQUIV
IF (NPCWF .EQ. 0) ACFF = ACBB - 180. * CYCLE + HRD
IF (ACFF .LT. 180.0) ACFF = 180.0 * CYCLE + ACFF

C CALCULATE TRAPPED VOLUME
DST = 0.0
CALL STROK (XST, DST, ANGLA, XSTA, XCRA, REVENG, ZREF)
CALL CYLVOL (FCYL, XST, XSTA, CR, DST, VCYLA(1), DVCY)
FPISTE = 1.0
VCYLE(1) = 0.0
VCYIA(1) = VCYIA(1) * VREF
VCYLE(1) = VCYLE(1) * VREF
VCYLP(1) = VCYLA(1) + VCYLE(1)
WORKA = 0.0
WORKE = 0.0
HEATRF = 0.0
DQCR = 0.0
DQCR1 = 0.0
DQCR2 = 0.0
DQCR3 = 0.0
DQCR4 = 0.0
ICOMB = 0
QHEAD1 = 0.
QSLEV1 = 0.
QPISTI = 0.
QEXH1 = 0.
QCY = 0.
HC1 = 0.
HC2 = 0.
HC3 = 0.
HC4 = 0.
HCT1 = 0.
HCT2 = 0.
HCT3 = 0.
HCT4 = 0.
C ********************************************
C CALCULATE TRAPPED GAS COMPOSITION—NO. OF MOLS OF AIR (WNA),
C NO. OF MOLS OF RESIDUALS (WNR), INCREASE IN MOLS OF PRODUCTS (WNP)
C ********************************************
VCYLT = VCYLP(1)
C CALCULATE TOTAL NUMBER OF MOLES OF GASES IN CYLINDER
WNTF = PCYLT * VCYLT * 100.0 / (8.3143 * TCYLT)
IF (IPUR .EQ. 0) GO TO 7
C CALCULATE MASS OF RESIDUAL WRES = WCHG + WCA
C CALCULATE TOTAL MASS IN CYLINDER (AIR+RESIDUAL+FUEL)
WTOT = WCHG + WFUEL
C CALCULATE STOICHIOMETRIC MASS OF AIR REQUIRED TO BURN FUEL
WABU = 32. * (CARBON/12.01 + (1. - CARBON)/4.032) * WFUEL/.233
ZERO = 0.0
WAIR = WCA + WRES * MAX1 (WCA - WABU, ZERO) / (WTOT - WRES)
IF (WABU .GT. WCA) WRITE (4, 8)
8 FORMAT (17H *** WARNING *** , 32HBURNED AIR EXCEEDS AVAILABLE AIR)
7 CONTINUE
C CALCULATE NUMBER OF MOLES OF AIR IN CYLINDER
WNA=PURITY*WNF
C CALCULATE NUMBER OF MOLES OF RESIDUAL IN CYLINDER
WNR=WNF-WNA
C CALCULATE INCREASE IN NUMBER OF MOLES OF DUE TO COMBUSTION
C LB FUEL * (MOLES OF PRODUCTS-MOLES OF AIR)/LB FUEL
WNF=WNUF*(1.0-CARBON)/4.032
C CALCULATE NUMBER OF MOLES OF (1) NITROGEN, (2) OXYGEN,
C (3) CARBON DIOXIDE, (4) WATER VAPOUR
WNF(1)=0.79*WNA*(WNA+WNF+WNR)/(WNA+WNF)
IF(WNF(1).LE.0.) WRITE(6,*) 'WNA,PURITY,WNTF,WNF(1)',WNA,PURITY,
1 WNF,WNF(1)
WNF(4)=2.0*WNF*WNR/(WNA+WNF)
WNF(3)=2.016*CARBON*WNF(4)/(12.01*(1.0-CARBON))
WNF(2)=0.21*WNF(1)/0.79-WNF(3)-0.5*WNF(4)
C TRAPPED MASS IN CYLINDER
WMF=0.0
DO 10 I=1,4
10 WMF=WMF+WNF(I)*WNF(I)
TRAF=28.85*WNA/WMF
WAIR=WNF(2)*32./233
PURE=WAIR/WMF/28.85
WRITE(4,499) IX/RE
499 FORMAT (14H TRUE IX/RITY =,F6.4)
TRMF=WMF/WMF
EAFR=32.0*WNF(2)*100./(23.3*WMF)
EQUIV=1./(STOIC*EAFR)
WRITE(4,4) EQUIV
4 FORMAT (21H EQUIVALENCE RATIO = ,F6.4)
IF (EQUIV.GT. 0. ) WFUEL=32.*WNF(2)*STOIC*/23.3
PSUM=0.
RSUM=0.
FUELS=0.
DUR=0.
C STORE TRAPPED PRESSURE, TEMPERATURE
PCF=PCYLT
PCP(1)=PCF
CALL UNITP(IUNITP, 2,PCP(1),PBARAB)
TF=TCYLT
TCP(1)=TF
CALL UNITT(IUNITT,2,TCP(1))
C *********************************************************************
C CALCULATE INTERNAL ENERGY OF TRAPPED CONTENTS IN KJ
C *********************************************************************
ETF=0.0
DO 11 I=1,4
11 ETF=ETF+WNF(I)*8.3143*((COEFFA(I)-1.0)*TF+COEFFB(I)*TF**2
1 +COEFFC(I)*TF**3+COEFFD(I)*TF**4-COEFFE(I))
UNITL=ETF
C *********************************************************************
C START NEXT STEP
C *********************************************************************
23 K=K+1
   ANGLC=ANGLC+1.0
   ANGLA=ANGLA+1.0
   ANGLE=ANGLE+1.0
   PRANG(K)=ANGLA
   IF (PRANG(K).GE.(180.0*CYCLE)) PRANG(K)=PRANG(K)-180.0*CYCLE
   ETI=ETF
   PCI=PCF
   TI=TF
C   TEST IF COMBUSTION HAS STARTED
   IF (ANGLA.LE.ACBB) GO TO 12
C   COMBUSTION HAS STARTED —CALCULATE FUEL BURNED IN STEP
   IF (ICOMB.EQ.0) KC=-K-q
   ICOMB=100
   CANS (1)=ANGLA-1.0
   CANS (2)=ANGLA
   DUR=ANGLA-ACBB
   ONE=1.000
   DA=AMINI(DUR,ONE)
C   CALCULATE PER CENT FUEL BURNED AT START AND END OF TIME STEP
   DO 25 I=1,2
      WRITE(6,*) 'CANG(I),ACBB',CANS(I),ACBB
      ANG=CANG(I)-ACBB
      IF (ANG) 26,26,27
   26 PCFINT(I)=0.0
      GO TO 25
   27 IF(NPCWF.LT.0) GO TO 290
      IF(NPCWF.EQ.2) CALL BURNRT(ANGIA,ACB,ACF,WFUEL,DWFUEL)
      WRITE(6,*) ANGLA
      IF(NPCWF.EQ.2) GOTO 250
      TAU=ANG/HRD
C   **********************************************************
C   WEIBE COMBUSTION MODEL
C   **********************************************************
   29 IF (NPCWF.EQ.0) PCFINT(I)=100.*(1.-EXP(-DELI*TAU**DEL2))
C   **********************************************************
C   WATSON COMBUSTION MODEL
C   **********************************************************
   RZTA=1.0-DELI*EQUIV**DEL2/1.5E4**DEL3
   CPI=2.+(1.25E-6*(1.5E4*REVREF*60.)**2.4
   CP2=5000.
   CD1=14.2/EQUIV**.644
   CD2=.79*CD1**.25
   IF (NPCWF.GT.0) PCFINT(I)=100.*(BETA*(1.-((1.-TAU**CP1)**CP2)+
      *(1.-BETA)*(1.-EXP(-CD1*TAU**CD2))))
      IF (NPCWF.GE.0) GO TO 25
C   **********************************************************
C   WHITEHOUSE—WAY COMBUSTION MODEL
C   **********************************************************
   290 PO2=PCF*WNF(2)/WNTF
      ZERO=0.0
      PO2=AMAX1(PO2,ZERO)
C RAMP FUEL INJECTION SCHEDULE ASSUMED
TAU=DUR/HRD
AA2=2. - AAN(1) * AAN(2)
IF (TAU.LE.AAN(2)) FINJ=WFUEL*(AAN(1)*TAU + 
+ (AA2-AAN(1))/(2. * AAN(2)) ) * TAU**2)
IF (TAU.GE.1.) GO TO 295
IF (TAU.GT.AAN(2)) FINJ=WFUEL*(((AAN(1)+AA2) * AAN(2)/2. + 
+ AA2/(1. - AAN(2)) * (TAU-TAU**2/2. + AAN(2)**2/2. - AAN(2))))
295 FINJ=AMIN1(FINJ, W FUEL)
IF (DUR.GT.HRD) FINJ=WFUEL
IF (FINJ.LE.PSUM) GO TO 250
PREP=DEL1*FINJ**2*(1.-DEL2) *(FINJ-PSUM)**DEL2*PO2**DEL3
PSUM=PSUM+PREP*DA
PSUM=AMIN1(PSUM, FINJ)
REACT=1.2E10*PO2*EXP(-1.5E4/TF) *(PSUM-RSUM)/(60.*REVREF*SQRT(TF))
ZERO=0.0
REACT=AMAX1(REACT, ZERO)
RSUM=RSUM+REACT*DA
IF (RSUM.LE.PSUM) DWFUEL=REACT*DA
IF (RSUM.GT.PSUM) DWFUEL=PREP*DA
IF (REACT.EQ.0.) DWFUEL=PSUM-FUELS
C MODIFIED BURNING RATE MODEL
GO TO 250
C ACF1=ACF+360.
C ACB1=ACB+0.8*(ACF1-ACB)
C IF (ANGLA.LT.ACB) DWFUEL=0.
C IF (ANGLA.GT.ACB .AND. ANGIA.LE.ACB1) DWFUEL
C 1 =WFUEL*(2./(ACF1-ACB))*((ANGIA-ACB)/(ACB1-ACB))
C IF (ANGLA.GT.ACBI .AND. ANGIA.LT.ACF1) DWFUEL
C 1 =WFUEL*(2./(ACF1-ACB))*((ACF1-ANGIA)/(ACF1-ACB1))
C IF (ANGLA.GE.ACF1) DWFUEL=0.
25 CONTINUE
C********************************************************************
C CALCULATE HEAT RELEASE DUE TO COMBUSTION OF FUEL
C********************************************************************
DWFUEL=0.01*(PCFINT(2)-PCFINT(1))*WFUEL
250 DQF=DWFUEL*CALVAL
FUELS=FUELS+DWFUEL
C********************************************************************
C CALCULATE NEW GAS COMPOSITION
C********************************************************************
C STORE OLD COMPOSITION
WNIT=WNTF
WMF=WMF
DO 13 I=1,4
13 WNI(I)=WNTF(I)
C X=DWFUEL*(1.0-CARBON)/4.032
Y=DWFUEL*CARBON/12.01
WNTF=WNTF+X
WMF=WMF+DWFUEL
WN=0.5*(WMF+WNTF)
WNTF(2)=WNI(2)-X-Y
WNF(3) = WNI(3) + Y
WNF(4) = WNI(4) + 2.0 * X
DO 14 I = 1, 4
14 WN(I) = 0.5 * (WNF(I) + WNI(I))
GO TO 15

C *********************************************************************
C COMBUSTION HAS NOT STARTED YET
C *********************************************************************

12 DQF = 0.0
DQCR = 0.0
WNFI = WNTF
WNI = WNTF
DO 16 I = 1, 4
16 WN(I) = WNF(I)

C *********************************************************************
C CALCULATE CYLINDER VOLUME AND SURFACE AREA
C *********************************************************************

15 DST = 0.0
CALL STROK(XST, DST, ANGLA, XSTA, XCR, REVENG, ZREF)
CALL CYLVOL(FCYL, XST, XSTA, CR, DST, VCYLA(K), DVCY)
FPISTE = 1.0
VCYLA(K) = 0.0
17 VCYLP(K) = VCYLA(K) + VCYLE(K)
CALL SREA(SURFC, VCYLP(K), FCYL, DCYL, XREF, DREF, FPISTA, FPISTE)

C CALCULATE SURFACE AREA OF CYLINDER EXPOSED TO COMBUSTION
SURFC = SURFC - (FPISTA + FPISTE) * FCYL
SURFC = SURFC * FREF

C CALCULATE SURFACE AREA OF PISTON (SQUARE METERS)
SURFP = FPISTA * FCYL * FREF

C CALCULATE SURFACE AREA OF EXHAUST VALVE(S)
SURFE = FLOAT(NEXHV) * 0.7854 * DEXHV ** 2 / (39.37) ** 2

C CALCULATE SURFACE AREA OF HEAD EXPOSED TO COMBUSTION CHAMBER
SURFH = FPISTE * FCYL * FREF - SURFE

C
VCYLA(K) = VCYLA(K) * VREF
VCYLE(K) = VCYLE(K) * VREF
VCYLP(K) = VCYLP(K) * VREF
IF (VCYLP(K) .LT. VCYLP(K-1)) VOLMIN = VCYLP(K)

C AVERAGE VOLUME AND DENSITY
VC = 0.5 * (VCYLP(K) + VCYLP(K-1))
RHO = WM / VC

C ESTIMATE GAS TEMPERATURE AT END OF STEP
TF = TI * (VCYLP(K-1) / VCYLP(K)) ** 0.4 + 4.0 * DQF / WM

C CALCULATE AVERAGE GAS TEMPERATURE
22 TM = 0.5 * (TI + TF)

C *********************************************************************
C CALCULATE CONVECTIVE HEAT TRANSFER IN KJ
C
USE ANNAND CORRELATION IF ANNC. GT. 0
USE WOSCHNI CORRELATION IF ANNC. EQ. 0

C *********************************************************************
C CALCULATE CP FOR GAS MIXTURE

100
CPT=0.0
DO 18 I=1,4
18 CPT=CPT+WN(I)*(COEFFA(I)+2.0*COEFFB(I)*TM+3.0*COEFFC(I)*TM**2
   +4.0*COEFFD(I)*TM**3)
CPT=8.3143*CPT/WM

C CALCULATE VISCOSITY OF GAS MIXTURE
A=0.0
B=0.0
DO 19 I=1,4
   C=WN(I)*SQRT(WMW(I))
   A=A+COEFFZ(I)*C
   19 B=B+C
VISCY=(A*TM**0.645)/B
IF(VISCY.LE.0.) WRITE(6,*) 'VISCY,WN(I)S',VISCY,WN

C CALCULATE THERMAL CONDUCTIVITY OF GAS MIXTURE (ASSUME PRANDTL = 0.7)
CONDY=CPT*VISCY/0.7
REY=RHO*PVEL*DCYL*DREF/VISCY
IF(REY.LE.0.) WRITE(6,*) 'REY,RHO,PVEL,DCYL,DREF,VISCY',
   1 REY, RHO, PVEL, DCYL, DREF, VISCY
PMOT=PCYL*T*(VCYL/VCPY(K))**1.32
TERM1=2.28*PVEL
TERM2=0.
IF(ANGIA.GT.ACBB) TERM2=3.24E-3*.7854*DCYL**2*XSTA*TCYL*/
   + (PCF--REYf)/ (PCYL*VCYL)
IF(ANNC.EQ.0.) REY=REY*(TERM1+TERM2)/PVEL
H=(ANNA*CONDY*REY**ANNB)/(DCYL*DREF)

C
C UNITS: SURFC=SQUARE METERS
C   TM = DEG KELVIN
C   RPS = REV PER SECOND
C   DQCY = KJ/DEG CA
HR1=0.
HR2=0.
HR3=0.
HR4=0.
IF (NHEAT.EQ.0) GO TO 777
TWA=TWGC
TPIST=TWGP
THEAD=TWGH
TEXV=TWEV
777 DQCY=(SURFC*H*(TM-TWALL))/(360.0*RPS)
   DQCY=DQCY+(SURFP*(TM-TPIST)+SURFH*(TM-THEAD)+SURFE*(TM-TEXV))*H/
   + (360.*RPS)
C
   DQCY1=SURFC*H*(TM-TWALL)/(360.*RPS)
   DQCY2=SURFP*H*(TM-TPIST)/(360.*RPS)
   DQCY3=SURFH*H*(TM-THEAD)/(360.*RPS)
   DQCY4=SURFE*H*(TM-TEXV)/(360.*RPS)
   IF (ICOMB.EQ.0) GO TO 20
C
C *******************
C RADIANT HEAT TRANSFER (AFTER START OF COMBUSTION ONLY)
C    —ANNAND CORRELATION ONLY —
C *******************
DQCR=SURFC*ANNC*(TM**4-TWALL**4)/(360.*RPS)

101
DQCR1 = SURFC * ANNC * (TM**4 - TFWALL**4)/(360. * RPS)
DQCR2 = SURFP * ANNC * (TM**4 - TFWALL**4)/(360. * RPS)
DQCR3 = SURFH * ANNC * (TM**4 - THEAD**4)/(360. * RPS)
DQCR4 = SURFE * ANNC * (TM**4 - TFWALL**4)/(360. * RPS)

20 CONTINUE
C *********************************************************************
C
PRESSURE AT END OF STEP
C *********************************************************************

PCF = PCI * VCYLP (K—I) * TF * WNTF / (VCYLP (K) * WNTI * TI)
C
C WORK DONE BY GAS DURING TIME STEP IN KJ
C
DWORKA = 0.5 * (PCF + PCI) * (VCYIA (K) — VCYIA (K—I)) * 0.0
DWORKE = 0.5 * (PCF + PCI) * (VCYLE (K) — VCYLE (K—I)) * 100.0
C
C INTERNAL ENERGY AT END OF TIME STEP
C
ETF = 0.0
DO 21 I = 1, 4
21 ETF = ETF + WNF (I) * (8.3143 * ((COEFFA (I) — 1.0) * TF + COEFFB (I) * TF**2
1 + 3.0 * COEFFC (I) * TF**2 + 4.0 * COEFFD (I) * TF**3)) — COEFFE (I))
UFINAL = ETF
C
C ***** CALCULATE HEAT TRANSFER FROM CREEVICE VOLUME ************
C
C CREEVICE VOLUME GAS TEMPERATURE — DEG K
TCV = (ASS * TGWC + APP * TWGP + ARR * TWCR) / (ASS + APP + ARR)
C HEAT TRANSFER DUE TO INCOMING HOT GAS — KJ/Crankangle
DQCV = GE / (GE — 1.0) * (TM / TCV — 1.0) * VCV * (PCF — PCI) * 1.0
IF (PCF .LT. PCI) DQCV = 0.0
C
C FIRST LAW OF THERMODYNAMICS. FOR BALANCE, ERROR=0
C
ERROR = ETF — ETI — DQF + DQCY + DQCR + DWORKA + DWORKE + DQCV
DERIV = 0.0
DO 24 I = 1, 4
24 DERIV = DERIV + WNF (I) * 8.3143 * ((COEFFA (I) — 1.0 + 2.0 * COEFFB (I) * TF
1 + 3.0 * COEFFC (I) * TF**2 + 4.0 * COEFFD (I) * TF**3)
C
SET NEW VALUE OF FINAL TEMPERATURE
ERROR = ERROR / DERIV

102
TF = TF - ERROR
C TEST FOR ACCURACY OF ESTIMATE OF TF. IF NOT ACCURATE ENOUGH
C RETURN TO LABEL 22 WITH BETTER ESTIMATE OF TF AND REPEAT
C CALCULATION
IF (ABS (ERROR) .GT. 0.01) GOTO 22
C
Rgas = 8.3143 * (WN(1) + WN(2) + WN(3) + WN(4)) / WM
GE = CPT / (CPT - RGAS)
TEXH = TF
PRESS = 14.5 * PCF
TRAN = 1.8 * TEXH
VOL = 61032.7 * VCYLA (K)
PERCNT = 100. * FUELS / WFUEL
WRITE (3, 1020) PRANG(K), PRESS, TRAN, GE, VOL
1020 FORMAT (5(1X, E11.5))

XSTIN = XST * 39.372
C ANSWER
WORKA = WORKA + DWORKA
WORKE = WORKE + DWORKE
HEATRF = HEATRF + DQCY + DQCR
C
QSLEV1 = QSLEV1 + DQCY1 + DQCR1
QPIST1 = QPIST1 + DQCY2 + DQCR2
QHEAD1 = QHEAD1 + DQCY3 + DQCR3
QEXH1 = QEXH1 + DQCY4 + DQCR4
QTOT1 = QSLEV1 + QPIST1 + QHEAD1 + QEXH1
C
SUM CREVICE VOLUME HEAT TRANSFER (KJ)
C
QCV = QCV + DQCV
C
SUM INTEGRALS USED IN CALCULATING EFFECTIVE GAS TEMPERATURES
C
HC1 = HC1 + (H + HR1) * SURFC
HC2 = HC2 + (H + HR2) * SURFP
HC3 = HC3 + (H + HR3) * SURFH
HC4 = HC4 + (H + HR4) * SURFE
HCT1 = HCT1 + (H + HR1) * SURFC * IM
HCT2 = HCT2 + (H + HR2) * SURFP * IM
HCT3 = HCT3 + (H + HR3) * SURFH * IM
HCT4 = HCT4 + (H + HR4) * SURFE * IM
C
TCP(K) = TF
CALL UNITT (IUNITT, 2, TCP(K))
PCP(K) = PCF
CALL UNITP (IUNITP, 2, PCP(K), PBARAB)
C ********************************************
C TEST IF POWER CYCLE IS COMPLETE. IF NOT RETURN TO LABEL 23
C ********************************************
IF (ANGLC LT (ANGLP - 0.1)) GO TO 23
C
FINISH POWER CYCLE. STORE RELEASE PRESSURE AND TEMPERATURE
C AND CALCULATE INDICATED POWER
C ********************************************
PCF = PCR
TF = TCR
WORKA = WORKP + WORKG + WORKE
WORKG = WORKP + WORKG + WORKGE
HEATRF = HEATG + HEATRF
CYCLE = RPS * 2.0 / CYCLE
POWERA = WORKA * CYCLES
POWERG = WORKG * CYCLES
POWERGE = WORKGE * CYCLES
VSWP = XSTA + FCYL + VREF
PM = (WORKT / VSWP) * 0.01

HEATFL = WFUEL * CALVAL

C CHECK OVERALL ENERGY BALANCE (FOR COMPRESSION, COMB, EXPANSION)

BALANCE = UNINITL - HEATRF - WORKP - HEATFL + QCVC
PCBAL = BALANCE / HEATFL * 100.

WRITE (6, 30) PCBAL
30 FORMAT (2X, 'COMP--EXP ENERGY BALANCE = ', F8.4, ' % OF FUEL ENERGY')

C PRINT OUT ANSWERS
WRITE (4, 116) PRANG(1), PCP(1), TCP(1)
116 FORMAT (6H ANGLE, F6.1, 23H TRAPPED PRESSURE, F7.1,
1 26H TRAPPED TEMPERATURE, F7.1)
WRITE (4, 117) PRANG(KC), PCP(KC), TCP(KC)
117 FORMAT (6H ANGLE, F6.1, 23H COMPRESSION PRESSURE, F7.1,
1 26H COMPRESSION TEMPERATURE, F7.1)

I = 0
C I = I + 1
C IF (PCP(I) - PCP(I + 1)) 33, 33, 34
C 34 WRITE (4, 118) PRANG(I), PCP(I), TCP(I)
TMAX = 0.
Pmax = 0.
DO 33 I = 1, K
Pmax = AMAX1 (Pmax, PCP(I))
33 TMAX = AMAX1 (TMAX, TCP(I))
WRITE (4, 118) PRANG(I), PCP(I), TCP(I)
118 FORMAT (6H ANGLE, F6.1, 23H MAXIMUM PRESSURE, F7.1,
1 ' MAXIMUM TEMPERATURE', F7.1)
WRITE (4, 119) PRANG(K), PCP(K), TCP(K)
119 FORMAT (6H ANGLE, F6.1, 23H RELEASE PRESSURE, F7.1,
1 26H RELEASE TEMPERATURE, F7.1)
WRITE (4, 105) TRAF, EAFR, ACBB
105 FORMAT (17H AIR--FUEL RATIO = , F6.2,
1 30H EFFECTIVE AIR--FUEL RATIO = , F6.2,
1 24H START OF COMBUSTION = , F7.2)
X = VCYLP / VMIN
XX = X
Y = VCYLP(K) / VMIN
WRITE (4, 106) X, Y
106 FORMAT (30H EFFECTIVE COMPRESSION RATIO = , F6.2,
EFFECTIVE EXPANSION RATIO =, F6.2)
IF (IUNITK.EQ.2) GO TO 38
WRITE(4,107)
107 FORMAT (20H INDICATED POWER KW)
X=POWERA+POWEGA
WRITE(4,108) POWERA,POWEGA,X
108 FORMAT (20HAIR POWER CYCLE =,F8.2,17H GAS EXCHANGE =,F8.2,
1 10H TOTAL =,F8.2)
39 WRITE(4,111) POWERT,PMIP
111 FORMAT (16HCOMBINED POWER =,F8.2,
1 36H MEAN INDICATED PRESSURE (BARS) =,F8.2)
GO TO 40
38 WRITE(4,112)
112 FORMAT (23H INDICATED HORSE POWER)
A=POWERA*1.34
B=POWEGA*1.34
X=A+B
WRITE(4,108) A,B,X
41 A=POWERT*1.34
B=PMIP*14.5
AMEP=B
IF (ALPHAT.LE.540.) GOTO 50

CALCULATE EXHAUST TEMPERATURE FROM ENERGY BALANCE

FUEL=FUEL*CYCLES*2.205
FZA = FUEL/AIRFL
YY = HEATF/HEATFL
DEH/(FZA*CALVAL* (I. --YY-WORKT/HEATFL) +HAIR-HREF)/(1.+FZA)
CALL BAL(CARBON, FZA, TREF, DELH, TEXHC, GAM, DUM)
TEXHC'=TEXHC*1.8

YY = YY*100.
SHP = A
IF (ISTOP.NE.1) WRITE(2,1000) FUEL,SCASW,TREFF,SCAEFF,TEXHC,
+ SHP,PURE,AIRFL,EQUIV,PMAX,TMAX,YY
1000 FORMAT (FI0.7,T13,F8.5,T25,F7.3,T37,F7.3,T47,F8.2,T56,F7.2,T65,
+ F7.4,T77,F8.5,T86,F7.4,T96,F7.1,T107,F7.1,T116,F7.2)

WRITE(4,113) A,B
113 FORMAT (17H COMBINED POWER =,F8.2,
1 38H MEAN INDICATED PRESSURE (P.S.I.) =,F8.2)

40 A=100.0*HEATRF/HEATFL
B=100.0*HEATG/HEATFL
X=100.0*HEATI/HEATFL
WRITE(4,114) A,B,X
114 FORMAT (35H PERCENT HEAT LOSS POWER CYCLE =,F6.2,
1 17H GAS EXCHANGE =,F6.2,10H TOTAL =,F6.2)

Y=100.0*WORKT/HEATFL
WRITE (4,115) Y
115 FORMAT(31H INDICATED THERMAL EFFICIENCY = ,F6.2)
CALL HTRANS

C
C
C ********** CONVERGENCE TEST **************
C
IF (ABS(SHIP-SHPS) GT SHP*.001) GO TO 45
IF (ABS(TEXH-TEXHS) GT TEXH*.001) GO TO 45
IF (EQUIV-GT.0..AND.ABS(EQUIV-EQUIVD) GT .001) GO TO 45
C
IF (ISTOP.EQ.1) RETURN
ISTOP=1
C
APIST=.7854*(3.281*DCYL*REF)**2*144.
AIRVMX = AIRVMX*1550.15*REF
EXHVMX = EXHVMX*1550.15*REF
EXHAP = EXHVMX/APIST
AIRAP = AIRVMX/APIST
WRITE (2,2900) XX, EXHAP, AIRAP, GAM
2900 FORMAT (1X,28HEFFECTIVE COMPRESSION RATIO ,F8.4,5X,
+16HEXHVMX/APONST= ,F9.4,5X,16HAIRVMX/APONST= ,F9.4,5X,4HGE= ,
+F7.4/)
WRITE(2,1010) AMEP, GA, BLBACK, Y
1010 FORMAT (1X,39HINDICATED MEAN EFFECTIVE PRESSURE (PSI) ,F11.4,4X,
+39HGA= ,F8.5,4X, 18HBLLOWBACK FRACTION= ,F9.5,4X,
+20HTERM EFF= ,F6.2)
C
C ******************************************
C ENGINE FRICTION CALCULATION
C ******************************************
C
VPSTN=PVEL*3.281*60.
FMEP1=12.964
FMEP2=0.0030476
FMEP3=0.65476E-6
FMEP=FMEP1+VPSTN*(FMEP2+VPSTN*FMEP3)
FMEP=FMEP+FMEP2+FMEP3
FHP=FMEP*XSTA*XREF*3.281*APIST*REVREF*2./(550.*CYCLE)
BHP=SHIP-FHP
BSFC=3600.*FUELF/BHP
C
WRITE(2,1012) VPSTN, FMEP, BHP, BSFC
1012 FORMAT (1X, 'PISTON MEAN VELOCITY (FPM)' ,F9.2,4X,
+'FRICTION MEAN EFFECTIVE PRESSURE (PSI)' ,F9.4,4X,
+'BRAKE HP=' ,F7.2,4X, 'BSFC=' ,F8.5/)
45 CONTINUE
SHPS = SHP
TEXHS = TEXHC
50 CONTINUE
RETURN
END
C
SUBROUTINE MASSFL(FHOLE, RUP, RDP, A0, GR, GWFLOW)
C
IMPLICIT REAL(A-H, O-Z), INTEGER(I-N)
C
SUBROUTINE TO CALCULATE MASS FLOW RATE OF A COMPRESSIBLE
C
FLUID THROUGH A PASSAGE
FHOIZ = RATIO OF UPSTREAM PRESSURE TO REFERENCE PRESSURE
RUP = RATIO OF DOWNSTREAM PRESSURE TO REFERENCE PRESSURE
A0 = RATIO OF SPEED OF SOUND OF FLUID TO REFERENCE SPEED OF
SOUND
GR = REFERENCE VALUE OF GAMMA, THE RATIO OF SPECIFIC HEATS
G = GAMMA, THE RATIO OF SPECIFIC HEATS
WFLOW = MASS FLOW RATE OF FLUID THROUGH PASSAGE (NON–DIMENSIONALIZED)

CALCULATE MACH NUMBER OF FLOW THROUGH PASSAGE TO DETERMINE
WHETHER FLOW IS CHOKE

UM=SQRT((2.0/(G-1.0))*(((RUP/RDP)**((G-1.0)/G))-1.0))
IF(UM.LT.1.0) GO TO 1

FLOW IS CHOKE

FM=G*SQRT((2.0/(G+1.0))**(G+1.0)/(G-1.0))
GO TO 2

FLOW IS NOT CHOKE

1 FM=G*UM/(1.0+((G-1.0)/2.0)*UM**2)**(G+1.0)/(2.0*(G-1.0))

CALCULATE MASS FLOW RATE

2 WFLOW=FHOIZ*RUP*FM/(G*A0)
RETURN
END

SUBROUTINE HTRANS

HEAT TRANSFER CALCULATIONS

COMMON/XXX/ EQUVD, RPM, PEXH, PAIR, TAIR,
1 CR, BORE, STROKE, CONROD, FPISTE, FPISTA,
2 EVO, EVC, AVO, AVC,
3 TWALL, WFUEL,
4 ACB, ACF,
5 ANNA, FMEMP,
6 NPCWF, DEL1, DEL2, DEL3, AAN(2),
7 VALEXH, CDE, NTEXH, WIDTHE, ALPHEX(50), FEXH(50),
8 VALAIR, CDA, NTAIR, WIDIHA, ALPAIR(50), FAIR(50)
COMMON/GEN/ALPHAT, ANGEND, ANGRES, AIRP0, EXHP0, IMOLS,
1 APAIR, APEXH, AREF, AP(2),
1 APN(2), CYCLE, DALPHA,
1 DREF, DZ, FREF,
1 IPower, IREV, GA, GE, GREF, IUNITL,
1 IUNITP, IUNITT, IUNITK, IUNITW, IUNITQ,
1 WAR, PBARAB,
1 PI, PREF, REVENG, REVREF, RPAIR, RPEXH, RP(2),
1 RPN(2), STEP2, TEXH, TREF, VREF, WREF, XREF,
1 Z, ZREF, HAIR, HREF, SCHULT, NC
CALCULATE EFFECTIVE GAS TEMPERATURES

\[
\begin{align*}
\text{TEG1} &= \frac{\text{HCT1}}{\text{HC1}} \\
\text{TEG2} &= \frac{\text{HCT2}}{\text{HC2}} \\
\text{TEG3} &= \frac{\text{HCT3}}{\text{HC3}} \\
\text{TEG4} &= \frac{\text{HCT4}}{\text{HC4}} \\
\text{TEG5} &= \frac{\text{HCT5}}{\text{HC5}} \\
\text{TEG6} &= \frac{\text{HCT6}}{\text{HC6}} \\
\text{TEG7} &= \frac{\text{HCT7}}{\text{HC7}} \\
\text{TEG8} &= \frac{\text{HCT8}}{\text{HC8}}
\end{align*}
\]

\[
\begin{align*}
\text{HTOT1} &= \text{HC1} + \text{HC5} \\
\text{HTOT2} &= \text{HC2} + \text{HC6} \\
\text{HTOT3} &= \text{HC3} + \text{HC7} \\
\text{HTOT4} &= \text{HC4} + \text{HC8} \\
\text{HTOT5} &= \text{HC1} + \text{HC6} \\
\text{HTOT6} &= \text{HC2} + \text{HC7} \\
\text{HTOT7} &= \text{HC3} + \text{HC8} \\
\text{HTOT8} &= \text{HC4} + \text{HC5}
\end{align*}
\]
HTI2 = HCT2 + HCT6
HTI3 = HCT3 + HCT7
HTI4 = HCT4 + HCT8

TTEG1 = HTT1 / HTOT1
TTEG2 = HTT2 / HTOT2
TTEG3 = HTT3 / HTOT3
TTEG4 = HTT4 / HTOT4

CALCULATE RESISTANCES FROM NETWORK MODEL

R1 = XXEVG / (AEXVS * CEXV)
R2 = 1 / (HEXHP * AEXV)
R3 = XXEVEH / (AEXST * CEXV)
R4 = XXHED / (AHEAD * CHEAD)
R5 = 1 / (HCED * CHEAD)
R6 = XXPIS / (APIST1 * CPIST)
R7 = 1 / (HTOILP * APIST2)
R8 = XXPISL / (ASLEEV * CPIST)
R9 = XXPCR / (APISTR * CPIST)
R10 = XXRPL / (ARING1 * CRING)
R11 = XXSLV / (ASLEEV * ASLEEV)
R12 = XXPRG / (ARING2 * CRING)
R13 = 1 / (HCIL * ASLEEV)

WRITE (6, *) 'R(S)' , R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R11, R12, R13

RX1 = 360 / HTOT1
RX2 = 360 / HTOT2
RX3 = 360 / HTOT3
RX4 = 360 / HTOT4

QX1 = (TTEG1 - TWALL) / RX1
QX2 = (TTEG2 - TPIST) / RX2
QX3 = (TTEG3 - THEAD) / RX3
QX4 = (TTEG4 - TEXV) / RX4
QY1 = (TTEG5 - TWALL) / RY1
QY2 = (TTEG6 - TPIST) / RY2
QY3 = (TTEG7 - THEAD) / RY3
QY4 = (TTEG8 - TEXV) / RY4

WRITE (6, *) QX1, QY1, QSLEV1, QSLEV2
WRITE (6, *) QX2, QY2, QPIST1, QPIST2
WRITE (6, *) QX3, QY3, QHEAD1, QHEAD2
WRITE (6, *) QX4, QY4, QEXHV1, QEXHV2
HEAT TRANSFER IN KJ/CYCLE

QCYL1=QSLEV1-QSLEV2
QCYL2=QPIST1-QPIST2
QCYL3=QHEAD1-QHEAD2
QCYL4=QEXHV1-QEXHV2

QTOT1=QSLEV1+QPIST1+QHEAD1+QEXHV1
QTOT2=QSLEV2+QPIST2+QHEAD2+QEXHV2

CHECK CALCULATIONS

QC1=(TTEG1-4WALL)/R14/RPS
QC2=(TTEG2-TPIST)/R15/RPS
QC3=(TTEG3-4HEAD)/R16/RPS
QC4=(TTEG4-TEXV)/R17/RPS

WRITE (6,*) 'QCYL1, QC1', QCYL1, QC1
WRITE (6,*) 'QCYL2, QC2', QCYL2, QC2
WRITE (6,*) 'QCYL3, QC3', QCYL3, QC3
WRITE (6,*) 'QCYL4, QC4', QCYL4, QC4

QTOT=QCYL1+QCYL2+QCYL3+QCYL4
QTOT2=QCYL1+QCYL2+QCYL3+QCYL4

WRITE (6,*) 'QTOT, QTOT', QTOT, QTOT

QPC=QTOT/WFUEL/CALVAL*100.
WRITE (6,*) 'HEAT LOSS AS A PERCENTAGE OF FUEL:', QPC

**** CALCULATE HEAT GENERATION DUE TO FRICTION ****

PISTON/RING FMEP FROM BISHOP'S EQUATION
BISHOP, J.N. "EFFECTS OF DESIGN VARIABLES ON FRICTION AND ECONOMY," SAE PAPER 812A, (1964)

MEAN PISTON SPEED (M/S)
STROKE=XSTA
BORE=DCYL
CM=2.*STROKE*RPS

OIL DENSITY (KG/M**3)
DENOI=55.31*16.018

OIL VISCOSITY (KG/M-SEC) AT 200 DEG F
VISOI=250.E-5*1.4878

REYNOLDS NUMBER
RE=CM*DENOI*BORE/VISOIL

FMEP, FROM BISHOP (PA)
FMEPB=(6.2E4*CM**0.2/RE)*DENOI*CM**2

WRITE (6,*) 'FMEPB, RE, CM', FMEPB, RE, CM

FRICTION TORQUE (N-M)
FRICT=FMEPB*BORE*BORE*STROKE/8.

FRICTION POWER LOSS (KW)
FRICP=FRICT*2.*3.1415926*RPS/1000.
FRICHP=FRICP/0.7456

WRITE (6,*) 'PISTON/RING FRICTION HP', FRICHP

FRICTION HEAT GENERATION TERMS (KW)
CFRIC1=0.5
CFRIC2=0.5
QFRIC1=CFRIC1*CFRIC2*FRICP
QFRIC2=(1.-CFRIC2)*FRICP
QFRIC3=(1.-CFRIC1)*CFRIC2*FRICP

***** CREVICE VOLUME CALCULATIONS ******

CREVICE VOLUME HEAT TRANSFER IN KW

QCV1=QCV*(ARR+ASS+APP)*RPS
QCV2=QCV*ASS/(ARR+ASS+APP)*RPS
QCV3=QCV*APP/(ARR+ASS+APP)*RPS

GENERATE COEFFICIENT MATRIX FOR SOLUTION OF SYSTEM OF EQUATIONS

DO 100 I=1,9
DO 100 J=1,10
100 A(I,J)=0.

A(1,1)=-1./R11
A(1,8)=1./R11
A(1,10)=TC2/R13

A(2,2)=-1./R6
A(2,6)=1./R6
A(2,10)=TC1/R7

A(3,3)=-1./R4
A(3,5)=1./R4
A(3,10)=-TC3/R5

A(4,4)=-1./R17
A(4,5)=1./R3
A(4,10)=QWEVG/R1-TEXHP/R2-TTEG4/R17

A(5,5)=-1./R16
A(5,3)=1./R4
A(5,4)=1./R3
A(5,10)=TTEG3/R16

A(6,6)=-1./R15
A(6,8)=1./R8
A(6,7)=1./R9
A(6,2)=1./R6
A(6,10)=-QFRIC3-TTEG2/R15

A(7,7)=-1./R12
A(7,6)=1./R9
A(7,9)=1./R12
A(7,10)=-QCV3

A(8,8)=-1./R14
A(8,10)=-QCV3
A(8,1)=1./R11
A(8,9) = 1./R10
A(8,6) = 1./R8
A(8,10) = -QCVC2 - QFRIC2 - TTEG1/R14

A(9,9) = 1./R10 - 1./R12
A(9,8) = 1./R10
A(9,7) = 1./R12
A(9,10) = -QCVC1 - QFRIC1

SOLVE SYSTEM OF EQUATIONS TO GET METAL TEMPERATURES
SOLUTION VECTOR IS LOCATED IN COLUMN 10 OF COEFFICIENT MATRIX
TEMPERATURES ARE IN KELVIN

CALL ELIM(A,9,10,9)

TWC = A(1,10)
TWCP = A(2,10)
TWCH = A(3,10)
TWEG = A(4,10)
TWGH = A(5,10)
TWGP = A(6,10)
TWPR = A(7,10)
TWGC = A(8,10)
TWCR = A(9,10)

DO 200 I = 1,9
200 AFAHR(I) = A(I,10) * 1.8 - 460.

WRITE(6,1000) (A(I,10), AFAHR(I), I = 1, 9)
1000 FORMAT (2X, 'COOLANT SIDE SLEEVE TEMPERATURE', F9.1, ' K', F11.1, ' F'/
    1 2X, 'OIL SIDE PISTON TEMPERATURE', 5X, F8.1, ' K', F11.1, ' F'/
    2 2X, 'COOLANT SIDE HEAD TEMPERATURE', 3X, F8.1, ' K', F11.1, ' F'/
    3 2X, 'EXHAUST VALVE TEMPERATURE', 7X, F8.1, ' K', F11.1, ' F'/
    4 2X, 'GAS SIDE HEAD TEMPERATURE', 7X, F8.1, ' K', F11.1, ' F'/
    5 2X, 'GAS SIDE PISTON CROWN TEMPERATURE', F7.1, ' K', F11.1, ' F'/
    6 2X, 'PISTON RIM TEMPERATURE', 10X, F8.1, ' K', F11.1, ' F'/
    7 2X, 'GAS SIDE SLEEVE TEMPERATURE', 5X, F8.1, ' K', F11.1, ' F'/
    8 2X, 'COMPRESSION RING TEMPERATURE', 4X, F8.1, ' K', F11.1, ' F'/)

CHECK ENERGY BALANCE ON HEAT TRANSFER NETWORK

ENERGY IN
QF = QFRIC1 + QFRIC2 + QFRIC3
QC = QCVC1 + QCVC2 + QCVC3
A1 = (TTEG1 - TWGC)/R14
A2 = (TTEG2 - TWGP)/R15
A3 = (TTEG3 - TWGH)/R16
A4 = (TTEG4 - TWEG)/R17
QCYL = QF + QC + A1 + A2 + A3 + A4
QFPC = QF/ QCYL*100.
QCPC = QC/ QCYL*100.
A1PC = A1/ QCYL*100.
A2PC = A2/ QCYL*100.
A3PC = A3/ QCYL*100.
A4PC = A4/ QCYL*100.
QCYLPC=100.

C — ENERGY OUT —
QEVG=(TWEV-TWEVG)/R1
QEXHP=(TWEV-TEXHP)/R2
QTC1=(TWC1-TC1)/R7
QTC2=(TWC2-TC2)/R13
QTC3=(TWC3-TC3)/R5
QOUT=QEVG+QEXHP+QTC1+QTC2+QTC3
QEVGPC=QEVG/QOUT*100.
QEXHPC=QEXHP/QOUT*100.
QTC1PC=QTC1/QOUT*100.
QTC2PC=QTC2/QOUT*100.
QTC3PC=QTC3/QOUT*100.
QOUTPC=100.

C PRINT OUT HEAT TRANSFER SUMMARY
C
C WRITE(6,*) 'HEAT TRANSFER SUMMARY —KW'
C WRITE(6,1001) QF, QFPC, QC, QCPC, AI, AIPC, A2, A2PC, A3, A3PC, A4, A4PC, QCYL, QCYLPC
1001 FORMAT(2X,'FRICCTION GENERATED HEAT TRANSFER',3X,F10.3,F11.2,'%'/
  1 2X,'CREASE VOLUME HEAT TRANSFER',F17.3,F11.2,'%'/
  2 2X,'HEAT TRANSFER TO CYLINDER WALL',F15.3,F11.2,'%'/
  3 2X,'HEAT TRANSFER TO PISTON',4X,F18.3,F11.2,'%'/
  4 2X,'HEAT TRANSFER TO HEAD',6X,F18.3,F11.2,'%'/
  5 2X,'HEAT TRANSFER TO EXHAUST VALVE',F15.3,F11.2,'%'/
  6 2X,'TOTAL HEAT INPUT TO NETWORK',3X,F15.3,F11.2,'%')
C WRITE(6,1002) QEVG, QEVGPC, QEXHP, QEXHPC,
C 1 QTC1, QTC1PC, QTC2, QTC2PC, QTC3, QTC3PC, QOUT, QOUTPC
1002 FORMAT(2X,'HEAT TRANSFER TO EXH VALVE GUIDE',3X,F10.3,F11.2,'%'/
  1 2X,'HEAT TRANSFER TO EXHAUST PORT GASES',F10.3,F11.2,'%'/
  2 2X,'HEAT TRANSFER TO PISTON COOLING OIL',F10.3,F11.2,'%'/
  3 2X,'HEAT TRANSFER TO SLEEVE COOLING OIL',F10.3,F11.2,'%'/
  4 2X,'HEAT TRANSFER TO HEAD COOLING OIL ',F10.3,F11.2,'%'/
  5 2X,'TOTAL HEAT TRANSFER FROM NETWORK ',F10.3,F11.2,'%')
C
RETURN
END
C
SUBROUTINE INPUT2
COMMON/INPUT2/
1 XXEVG, XXEVH, XXPSL, XXPIS, XXPRG, XXHED, XXPCR, XXRSL, XXSLV,
2 AEXVS, AEXV, AEXST, AHEAD, ASLEEVE, APIST1, APIST2, APISTR, ARING1, ARING2,
3 CEXV, CHEAD, CSLEEVE, CPIST, CRING,
4 HEXHP, HOILP, HCSL, HCHD, NEXHV, DEXHV,
5 D1, D2, D3, D4, D5, D6, VCV, APP, ARR, ASS
COMMON/XXEV/ EQUVD, RPM, PEXH, PAIR, TAIR,
1 CR, BORE, STROKE, CONROD, FPISTE, FPISTA,
2 EVO, EVC, AVO, AVC,
3 TWALL, WFOIL,
4 ACP, ACF,
5 ANNA, FMEPM,
6 NPCWF, DEL1, DEL2, DEL3, AAN(2),
7 VALEXH, CDE, NTEXH, WIDTHE, ALPHEX(50), FEXH(50),
8 VALAIR, CDA, NTAIR, WIDTHA, ALPAIR(50), FAIR(50)
COMMON/GEN/ALPHAT, ANGEND, ANGRES, AIRPO, EXHP0, IMOLS,
1 APAIR, APEXH, AREF, AP(2),
1 APN(2), CYCLE, DALPHA,
1 DREF, DZ, FREF,
1 IPOWER, IREV, GA, GE, GREF, IUNITL,
1 IUNITPP, IUNITTT, IUNITK, IUNITW, IUNITQ,
1 WAR, PBARAB,
1 PI, PREF, REVENG, REVREF, RPAIR, RPEXH, RP(2),
1 RPN(2), STEP2, TEXH, TREF, VREF, WREF, XREF,
1 Z, ZREF, HAIR, HREF, SCMULT, NC
COMMON/CYL/ACSB, ALPHA, ALPHAE, ANN, ANNC, AC,
1 ACN, ACR, ALPHAC,
1 CALVAL, CARBON,
1 COEFFA(4), COEFFB(4), COEFFC(4), COEFFD(4),
1 COEFFE(4), COEFFZ(4), CRANK, DCYL, DHEAT,
1 DRC, DCYL, DWCIN, DWCP(2), DWCYL,
1 FCYL, HEATG,
1 PURITY, PVEL, PCR, PCYL,
1 PORTS, RC, RCN, RCR, SURFC,
1 TCR, TCYL, VSWEPT,
1 VCYL, WCAIR, WCIN,
1 WCOUT, WCYL, WMW(4), WPCNT(4), WCYL,
1 WN(4), WORKGA, WORKGE, XCR, XSTA,
1 NCD, WCYLT, DMCINT,
1 TPIST, THEAD, TEXV, CID
COMMON/COMB/AIRFL, EQUIV, TEXHS, SHPS, FZA, HRD, SCASW, TREFF, SCoeff,
+ AIRVMX, EXHVMX, PORTED, STOIC, WCO, BLCBL, FUEL, EHP
COMMON/TEMP/TWEG, TWG, TWGC, TWCR, TWPR, TWCP, TWCC, TWCH, TEXHP,
1 TWEG, TC1, TC2, TC3
PI=3.141592654
C BORE AND STROKE IN FEET
BORE=DCYL
STROKE=XSTA
C
C OPEN DATA FILE FOR HEAT TRANSFER INPUT
C OPEN (10, FILE=’DIESEL10.INP’, STATUS=’OLD’)
C
C READ IN INITIAL ESTIMATES OF METAL TEMPERATURES (DEG F)
C
C READ(10, *) TWEG, TWG, TWGC, TWV
TWEG=1000.
TWG=1000.
TWGC=1000.
TWV=1000.

C READ IN OIL AND COOLANT TEMPERATURES (DEG F)
C
C READ(10, *) TC1, TC2, TC3
TC1=200.
TC2=200.
TC3=200.
CONVERT FROM FAHRENHEIT TO KELVIN

TWEV=(TWEV+460.)/1.8
TWGH=(TWGH+460.)/1.8
TWGP=(TWGP+460.)/1.8
TWGC=(TWGC+460.)/1.8
TWEVG=(TWEVG+460.)/1.8
TC1=(TC1+460.)/1.8
TC2=(TC2+460.)/1.8
TC3=(TC3+460.)/1.8

READ IN EXHAUST VALVE PARAMETERS AND CALCULATE EXHAUST VALVE AREA

DEXHV in inches, AEXV in square inches

READ(10, *) NEXHV, DEXHV
NEXHV=4
DEXHV=1.
AEXV=FLOAT(NEXHV)*0.785398*DEXHV**2

READ IN PISTON RING/GROOVE DIMENSIONS (INCHES)

READ(10, *) D1, D2, D3, D4, D5, D6
D1=0.375
D2=0.130
D3=0.130
D4=0.005
D5=0.125
D6=0.125

READ IN CONDUCTION PATH LENGTHS (INCHES)

READ(10, *) XXEVG, XXEVH, XXPSL
READ(10, *) XXPIS, XXPRG, XXHED
READ(10, *) XXPCR, XXRSL, XXSLV
XXEVG=0.
XXEVH=0.
XXPSL=0.
XXPIS=0.
XXPRG=0.
XXHED=0.
XXPCR=0.
XXRSL=0.
XXSLV=0.2

XXEVH=0.93
XXPIS=2.00
XXHED=0.800
XXSLV=0.750

CHECK FOR ZEROS, IF SO, USE DEFAULTS

IF(XXEVG.LE.1.E-6) XXEVG=3.
IF(XXEVH.LE.1.E-6) XXEVH=DEXHV/3.
IF(XXPSL.LE.1.E-6) XXPSL=(BORE*12.)/3.
IF(XXPIS.LE.1.E-6) XXPIS=0.5
IF (XXPRG . LE. 1. E-6) XXPRG = D5
IF (XXHED . LE. 1. E-6) XXHED = 0.25
IF (XXPCR . LE. 1. E-6) XXPCR = 0.25
IF (XXRSL . LE. 1. E-6) XXRSL = D6
IF (XXSLV . LE. 1. E-6) XXSLV = 0.25

CONVERT FROM INCHES TO METERS

XXEVG = XXEVG / 39.372
XXEVH = XXEVH / 39.372
XXPSL = XXPSL / 39.372
XXPIS = XXPIS / 39.372
XXPRG = XXPRG / 39.372
XXHED = XXHED / 39.372
XXPCR = XXPCR / 39.372
XXRSL = XXRSL / 39.372
XXSLV = XXSLV / 39.372

READ IN HEAT TRANSFER AREAS (SQUARE INCHES)

READ (10, *) AEXVS, AEXST
READ (10, *) ASLEEV, APIST2
READ (10, *) APISTR, ARING1, ARING2

AEXVS = 0.
AEXST = 0.
ASLEEV = 0.
APIST2 = 0.
APISTR = 0.
ARING1 = 0.
ARING2 = 0.

CHECK FOR ZEROS, IF SO, USE DEFAULTS

IF (AEXVS . LE. 1. E-9) AEXVS = FLOAT (NEXHV) * PI / 4. * (0.25) ** 2
IF (AEXST . LE. 1. E-9) AEXST = FLOAT (NEXHV) * PI * DEXHV * 0.050
IF (ASLEEV . LE. 1. E-9) ASLEEV = PI * BORE * (STROKE / 4.) * 144.
IF (APIST2 . LE. 1. E-9) APIST2 = APIST1
IF (APISTR . LE. 1. E-9) APISTR = PI * BORE * 12. * 0.5
IF (ARING1 . LE. 1. E-9) ARING1 = PI * BORE * 12. * D5
1 - (BORE * 12. - 2. * D6) ** 2)

CONVERT FROM SQUARE INCHES TO SQUARE METERS

AEXVS = AEXVS / 39.372 ** 2
AEXV = AEXV / 39.372 ** 2
AEXST = AEXST / 39.372 ** 2
ASLEEV = ASLEEV / 39.372 ** 2
APIST1 = APIST1 / 39.372 ** 2
APIST2 = APIST2 / 39.372 ** 2
APISTR = APISTR / 39.372 ** 2
ARING1 = ARING1 / 39.372 ** 2
ARING2 = ARING2 / 39.372**2
AHEAD = AHEAD / 39.372**2

C
C READ IN THERMAL CONDUCTIVITIES — BTU/(HR–FT–R)
C
C READ(10,*) CEXV, CHEAD, CSLEEV, CPIST, CRING
CEXV = 24.
CHEAD = 22.
CSLEEV = 22.
CPIST = 60.
CRING = 24.8

C
C CONVERT FROM BTU/(HR–FT–R) TO KW/(M–K)
C
TT = 1.054 * 3.281 * 1.8 / 3600.
CEXV = CEXV * TT
CHEAD = CHEAD * TT
CSLEEV = CSLEEV * TT
CPIST = CPIST * TT
CRING = CRING * TT

C
C READ IN CONVECTIVE COEFFICIENTS — BTU/(HR–FT**2–R)
C
C READ(10,*) HEXHP, HOILP, HCSL, HCHD

C
C CONVERT FROM BTU/(HR–FT**2–R) TO KW/(M**2–K)
C
HEXHP = 10.
HOILP = 900.
HCSL = 200.
HCHD = 200.
HEXHP = HEXHP * TT
HOILP = HOILP * TT
HCSL = HCSL * TT
HCHD = HCHD * TT

C
C CONVERT FROM INCHES TO METERS
C
D1 = D1 / 39.372
D2 = D2 / 39.372
D3 = D3 / 39.372
D4 = D4 / 39.372
D5 = D5 / 39.372
D6 = D6 / 39.372

C
C CALCULATE CREVICE VOLUME CHARACTERISTICS
C
BORE=DCYL/3.281
VCV=PI/4.*((BORE**2-(BORE-2.*D4)**2)*D1
1 + PI/4.(*(BORE-2.*D6)**2-(BORE-2.*D4-2.*D2)**2)*(D3-D5)
2 + PI/4.*((BORE-2.*D6)**2-(BORE-2.*D4-2.*D2)**2)*D5
APP=PI*(BORE-2.*D4)*D1
1 + PI/4.(*(BORE-2.*D4)**2-(BORE-2.*D4-2.*D2)**2)
ARR=PI/4.*((BORE-2.*D6)**2-(BORE-2.*D4-2.*D2)**2)+PI*(BORE-2.*D6)*D5
ASS=PI*BORE*(D1+D3-D5)

CLOSE (10, STATUS='KEEP')
RETURN
END

SUBROUTINE BURNRT(ANGLA, ACB, ACF, WFUEL, DWFUEL)

C MODIFIED BURNING RATE MODEL — SAWTOOTH SHAPE

ACF1=ACF+360.
ACB1=ACB+0.8*(ACF1-ACB)
IF(ANGLA.LT.ACB) DWFUEL=0.
IF(ANGLA.GT.ACB .AND. ANGLA.LE.ACBI) DWFUEL
1 =WFUEL*2./(ACF1-ACB))*(ANGLA-ACB)/(ACB1-ACB)
IF(ANGLA.GT.ACBI .AND. ANGLA.LE.ACFI) DWFUEL
1 =WFUEL*2./(ACF1-ACB))*(ACFI-ANGIA)/(ACFI-ACBI)
IF (ANGLA.GE.ACFI) DWFUEL=0.
RETURN
END

SUBROUTINE SPLFIT(JJ, IJ, NP, OPT, ANGROT, XXX, IXLGR, FY, IYLGR, X, Y, ITRP)

C—— SUBROUTINE SPLFIT IS A GENERALIZED SPLINE CURVE FIT PROGRAM
C—— THE INPUT PARAMETERS ARE
C JJ — OVERALL FLOW ITERATION NUMBER
C IJ — INTERVAL NUMBER
C NP — THE NUMBER OF POINTS DESCRIBING THE CURVE
C (A MINIMUM OF 3 POINTS ARE REQUIRED)
C OPT — OPTION FOR COORDINATE SYSTEM ROTATION (INTEGER)
C (USE ONLY FOR REGULAR CARTESIAN COORDINATE SYSTEM)
C 0 — NO ROTATION
C 1 — ROTATION (MUST SPECIFY ANGROT)
C ANGROT — COORDINATE ROTATION ANGLE (DEGREES)
C (DUMMY VALUE IF OPT=0)
C XXX(I) — THE NP X—VALUES DEFINING THE CURVE (25 MAX)
C (MUST BE IN ASCENDING ORDER)
C IXLGR — LOGARITHMIC X—AXIS INDICATOR
C 0 — CARTESIAN COORDINATE AXIS
C 1 — LOGARITHMIC COORDINATE AXIS
C FY(I) — THE NP Y—VALUES DEFINING THE CURVE
C (CORRESPONDING TO THE X—VALUES)
C IYLGR — LOGARITHMIC Y—AXIS INDICATOR
C 0 — CARTESIAN COORDINATE AXIS
C 1 — LOGARITHMIC COORDINATE AXIS
C—— NOTE: THE FUNCTION SLOPES AT THE END POINTS ARE EVALUATED FROM THE FIRST
C TWO AND LAST TWO DATA INPUT POINTS. THESE POINTS MUST THUS BE

119
SELECTED TO GIVE A GOOD SLOPE REPRESENTATION

X -- THE X VALUE WHERE THE FUNCTION VALUE IS DESIRED

THE OUTPUT PARAMETERS ARE

Y -- THE FUNCTION VALUE AT THE DESIRED X--VALUE

ITRP -- TRAP FOR NON--CONVERGENCE

REAL MAT(25,51), L(25), FCT(25), MK1, MK, LK, LR(25)
DIMENSION XX(25), XK(25), FY(25), F(25)
DIMENSION XKR(25), FR(25)
INTEGER OPT

ITRP=0
N=NP-1
NP1=N+1
NP2=N+2
NP3=N+3
NM1=N-1
NT(X(NPI+NP2)
DO 5 I=1,NP
XK(I)=XX(I)
F(I)=FY(I)
5 CONTINUE

CHANGE COORDINATES FOR LOGARITHMIC AXES

IF(IXLGR .EQ. 0) GOTO 210
DO 200 I=1,NP
IF(XK(I) .GT. 0.0) GOTO 198
ITRP=1
WRITE(6,606)
GO TO 1010
198 CONTINUE
XK(I)=ALOG10(XK(I))
200 CONTINUE
IF(X .LE. 0.0) X=1.E-5
X=ALOG10(X)
210 CONTINUE
IF(IYLGR .EQ. 0) GOTO 230
DO 220 I=1,NP
IF(F(I) .GT. 0.0) GOTO 202
ITRP=1
WRITE(6,608)
GO TO 1010
202 CONTINUE
F(I)=ALOG10(F(I))
220 CONTINUE
230 CONTINUE

IF(OPT .EQ. 0) GO TO 15
ANGROT=ANGROT*3.141593/180.
CAN=COS(ANGROT)
SAN=SIN(ANGROT)

DO 10 I=1,NP1
XKR(I)=XK(I)*CAN + F(I)*SAN
120
FR(I) = F(I) * CAN -- XK(I) * SAN
10 CONTINUE
15 CONTINUE
C
DO 20 I=1,N
IF(OPT .EQ. 0) GO TO 20
LR(I) = XK(I+1) -- XK(I)
20 L(I) = XK(I+1) -- XK(I)
C—SET SLOPES AT THE END POINTS
YPFST = (F(2) -- F(1)) / (XK(2) -- XK(1))
YPFST = (F(NP1) -- F(N)) / (XK(NP1) -- XK(N))
IF(OPT .EQ. 1) YPFRST = (FR(2) -- FR(1)) / (XKR(2) -- XK(1))
IF(OPT .EQ. 1) YPFRST = (FR(NP1) -- FR(N)) / (XKR(NP1) -- XK(N))
C—INITIALIZE THE MATRIX TO ZERO
DO 30 I=1,NP1
DO 30 J=1,NP2
30 MAT(I,J) = 0.
C—ADD THE IDENTITY MATRIX TO GET THE OVERALL MATRIX
DO 40 J=NP3,NTOT
DO 40 I=1,NP1
MAT(I,J) = 0.
IF((J-I) .EQ. (NP1 + 1)) GO TO 35
GO TO 40
35 MAT(I,J) = 1.
40 CONTINUE
C
MAT(1,1) = L(1)/3.
MAT(1,2) = L(1)/6.
MAT(1,NP2) = (F(2) -- F(1)) / L(1) -- YPFST
MAT(NP1,N) = L(N) / 6.
MAT(NP1,NP1) = L(N) / 3.
MAT(NP1,NP2) = YPFST -- (F(NP1) -- F(N)) / L(N)
IF(OPT .EQ. 1) MAT(1,1) = LR(1) / 3.
IF(OPT .EQ. 1) MAT(1,2) = LR(1) / 6.
IF(OPT .EQ. 1) MAT(1,NP2) = (FR(2) -- FR(1)) / LR(1) -- YPFST
IF(OPT .EQ. 1) MAT(NP1,N) = LR(N) / 6.
IF(OPT .EQ. 1) MAT(NP1,NP1) = LR(N) / 3.
IF(OPT .EQ. 1) MAT(NP1,NP2) = YPFST -- (FR(NP1) -- FR(N)) / LR(N)
C
DO 50 I=2,N
IM1 = I-1
IM2 = I-2
IPI = I+1
MAT(I,IM1) = L(IM1) / 6.
MAT(I,I) = (L(IM1) + L(I)) / 3.
MAT(I,IPI) = L(I) / 6.
MAT(I,NP2) = (F(IPI) -- F(I)) / L(I) -- (F(I) -- F(IM1)) / L(IM1)
IF(OPT .EQ. 1) MAT(I,IM1) = LR(IM1) / 6.
IF(OPT .EQ. 1) MAT(I,I) = LR(IM1) + LR(I) / 3.
IF(OPT .EQ. 1) MAT(I,IPI) = LR(I) / 6.
50 IF(OPT .EQ. 1) MAT(I,NP2) = (FR(IPI) -- FR(I)) / LR(I) -- (FR(I) -- FR(IM1)) / LR(IM1)
C—MAKE THE PIVOT ELEMENT THE LARGEST ELEMENT
NSW = 0
DO 70 J=I,NPI
    IF(J.EQ.NPI)GO TO 75
    DO 70 I=J,NPI
        IP=I+1
        IF(ABS(MAT(IP,J)).LT.ABS(MAT(J,J)))GO TO 70
        NSW=NSW+1
        DO 60 JS=1,NTOT
            STOR=MAT(J,JS)
            MAT(J,JS)=MAT(IP,JS)
            MAT(IP,JS)=STOR
        60 CONTINUE
    70 CONTINUE
75 CONTINUE

C------REDUCE ELEMENTS IN PIVOT COLUMN TO ZERO, EXCEPT PIVOT

    DO 110 J=1,NPI
    DO 80 IR=1,NPI
        FCT(IR)=MAT(IR,J)/MAT(J,J)
        FCT(J)=0.
        DO 100 IZER=1,NPI
            DO 90 JZER=J,NTOT
                MAT(IZER,JZER)=MAT(IZER,JZER) - FCT(IZER)*MAT(J,JZER)
            90 CONTINUE
        100 CONTINUE
    110 CONTINUE

C------GET THE DETERMINANT

    DET=1.0
    DO 120 K=1,NPI
    120 DET=DET*MAT(K,K)

C------TRAP SINGULARITY

    IF(ABS(MAT(NPI,NPI)).LT.1.E-7.AND.ABS(DET).LT.1.E-7)GO TO 122

    DO 125 IJ,JJ
    ITRP=1
    GO TO 1010
    125 CONTINUE

C------DIVIDE EACH ROW BY IT'S PIVOT

    DO 130 IPIV=1,NPI
    DIV=MAT(IPIV,IPIV)
    DO 130 JPIV=1,NTOT
        MAT(IPIV,JPIV)=MAT(IPIV,JPIV)/DIV
    130 CONTINUE

C------FOR A GIVEN X, FIND THE XK THAT BRACKET IT AND CALCULATE GENERATED F

    ND=0
    IF(X.LE.XK(1))IND=1
    IF(IND.EQ.1)Y=F(1)
    IF(IND.EQ.1)GO TO 1000
    IF(X.GE.XK(NPI))IND=2
    IF(IND.EQ.2)Y=F(NPI)
    IF(IND.EQ.2)GO TO 1000

C

    DO 140 I=2,NPI
    IND=0
    IF(X.EQ.XK(I))Y=F(I)

122
IF(X .EQ. XK(I)) GO TO 1000
IF(XK(I-1) .LT. X .AND. XK(I) .GT. X) GO TO 135
GO TO 140
135 CONTINUE
IM1=I-1
MKM1=MAT(IM1, NP2)
MK=MAT(I, NP2)
XXM=XK(I-1)
XX=XK(I)
FK=F(I)
FKM1=F(I-1)
LK=XX(I)-XXK(I-1)
IF(OPT .EQ. I) XXM=XKR(I-1)
IF(OPT .EQ. I) XX=XKR(I)
IF(OPT .EQ. I) FK=FR(I)
IF(OPT .EQ. I) FKMI=FR(I-1)
IF(OPT .EQ. I) LK=XKR(I)-XKR(I-1)
GO TO 142
140 CONTINUE
142 CONTINUE
C IF(OPT .EQ. 0) GO TO 160
ANGRT1=ANGROT
ANGRT2=ANGROT
ANGRT3=ANGROT
ANGRT4=ANGROT
Y1=(MKM1* (XX-XXM) **3)/(6.*LK) + (FKM1/LK-LK*MKM1/6.)*(XX-XXM)
Y2=(1.0/TAN(ANGRT1)) *XXM-X/SIN(ANGR2)
IF(Y1.GT. Y2L) INDC=I
IF(Y2L.GT. Y1L) INDC=-I
INDCP=INDC
INDCPI=-INDCP
DELXR=(XX-XXM)/10.
XR=XXM
C DO 150 I=1,30
XR=XR+DELXR
IF(XR.GT. XX) GO TO 152
TERM1=(MKM1* (XX-XR) **3)/(6.*LK)
TERM2=(MK* (XR-XXM) **3)/(6.*LK)
TERM3=(FK/LK-MK/LK/6.)*(XR-XXM)
TERM4=(FKM1/LK-LK*MKM1/6.)* (XX-XR)
Y1=TERM1+TERM2+TERM3+TERM4
Y2=(1.0/TAN(ANGRT3)) *XR-X/SIN(ANGRT4)
IF(Y1.GT. Y2) INDC=I
IF(Y2.GT. Y1) INDC=-I
CRIT=ABS(Y1-Y2)/ABS(Y1)
IF(CRIT.LE. 1.E-4) GO TO 155
IF(INDC.EQ. INDCP) DELXR=-DELXR/10.
IF(INDC.EQ. INDCP) INDCP=INDCPI
IF(INDC.EQ. INDCP) INDCP=-INDCP
150 CONTINUE
C GO TO 155
152 WRITE(6,604)I,IJ,JJ
   ITRP=1
   GO TO 1010
155 CONTINUE
   ANGINV=ANGROT
   SANI=SIN(ANGINV)
   CANI=COS(ANGINV)
   Y=Y1*CANI-XR*SANI
   X=XR*CANI+Y1*SANI
   GO TO 1000
160 CONTINUE
   TERM1=(MKM1*(XX-X)**3)/(6.*LK)
   TERM2=(MK*(X-XXM)**3)/(6.*LK)
   TERM3=(FK/LK-MK*LK/6.)*(X-XXM)
   TERM4=(FKM1/LK-LK*MKM1/6.)*(XX-X)
   Y=TERM1+TERM2+TERM3+TERM4
C——FORMAT STATEMENTS
602 FORMAT(/,1X,44HABORT—SINGULAR MATRIX IN SUBROUTINE SPLFIT,/, —
*1X,11HIN INTERVAL,13,24H, OVERALL FLOW ITERATION,13,/) 
604 FORMAT(/,1X,64HABORT—COORDINATE ROTATION CALCULATIONS HAVE NOT C—
*ONVERGED IN,14,1X,31HITERATIONS IN SUBROUTINE SPLFIT,/, —
*1X,11HIN INTERVAL,13,24H, OVERALL FLOW ITERATION,13,/) 
606 FORMAT(/,1X,61HABORT—NEGATIVE NUMBER SPECIFIED IN LOGARITHMIC X—
*AXIS ARRAY,/) 
608 FORMAT(/,1X,61HABORT—NEGATIVE NUMBER SPECIFIED IN LOGARITHMIC Y—
*AXIS ARRAY,/) 
1000 CONTINUE
   IF(IXLGR.EQ.1)X=(10.0)**(X)
   IF(IYLGR.EQ.1)Y=(10.0)**(Y)
1010 CONTINUE
   RETURN
   END
C
SUBROUTINE UNITP(IA,IB,PP,PPB)
C IMPLICIT REAL(A-H,O-Z),INTEGER(I-N)
   IF(IB.EQ.2) GO TO 1
   IF(IA.EQ.1) GO TO 2
   IF(IA.EQ.2) GO TO 3
   PP=(PP+PPB)/14.5
   GO TO 2
   3 PP=PP/14.5
   2 RETURN
   1 IF(IA.EQ.1) GO TO 4
   IF(IA.EQ.2) GO TO 5
   PP=(PP+PPB)*14.5
   GO TO 4
   5 PP=PP*14.5
   4 RETURN
   END
C
SUBROUTINE UNITT(IA,IB,TT)
C IMPLICIT REAL(A-H,O-Z),INTEGER(I-N)
   IF(IB.EQ.2) GO TO 1
   IF(IA.EQ.1) GO TO 2
IF(IA.EQ.2) GO TO 3
IF(IA.EQ.3) GO TO 4

TT=(TT+460.0)/1.8
GO TO 2
3 TT=TT+273.0
GO TO 2
4 TT=TT/1.8
2 RETURN

1 IF(IA.EQ.1) GO TO 5
IF(IA.EQ.2) GO TO 6
IF(IA.EQ.3) GO TO 7
TT=1.8*TT-460.0
GO TO 5
6 TT=TT-273.0
GO TO 5
7 TT=1.8*TT
5 RETURN

END

SUBROUTINE UNITW(IA, IB, WW)

IMPLICIT REAL(A-H, O-E), INTEGER(I-N)

IF(IB.EQ.2) GO TO 1
IF(IA.EQ.1) GO TO 2
WW=WW/2.205
2 RETURN
1 IF(IA.EQ.1) GO TO 3
WW=WW*2.205
3 RETURN

END

SUBROUTINE STROK(XSTROK, DSTROK, THETA, STROKE, CONROD, RPS, ZR)

IMPLICIT REAL(A-H, O-E), INTEGER(I-N)

CONRAT=2.0*CONROD/STROKE
PI=3.14159
THETA=THETA*PI/180.0
FNN=SQR(T( CONRAT**2-SIN(THETA)**2))
IF(DSTROK.EQ.0.0) GO TO 1
DSTROK=(PI/360.0)*ZR*RPS*STROKE*(SIN(THETA)+SIN(2.0*THETA))/
(2.0*FNN)
1 XSTROK=0.5*STROKE*(1.0+CONRAT*COS(THETA)-FNN)
RETURN

END

SUBROUTINE CYLVOL(FCYLG, XSTROK, STROKE, CRR, DSTROK, VCYLG, DVCYL)

IMPLICIT REAL(A-H, O-E), INTEGER(I-N)

VCYLG=FCYLG*(XSTROK+STROKE/(CRR-1.0))
DVCYLG=FCYLG*DSTROK
RETURN

END

SUBROUTINE SREA(SAREA, VCYLL, FCYLL, DCYLL, XR, DR, F1, F2)

IMPLICIT REAL(A-H, O-E), INTEGER(I-N)

SAREA=4.0*VCYLL*XR/(DCYLL*DR)+(F1+F2)*FCYLL
RETURN
SUBROUTINE BAL(CARBON, FZA, T1, DELH, T2, GAM, H3)
OVERALL ENERGY BALANCE
FZA=OVERALL FUEL/AIR RATIO
T=TEMPERATURE, K
DELH=ENTHALPY CHANGE, KJ/KG
DIMENSION X(4)
COMMON/JANAF/ A(4), B(4), C(4), D(4)
X(1) = .79
X(3) = FZA*CARBON*28.85/12.01
X(4) = FZA*(1.-CARBON)*28.85/2.016
X(2) = .21 - 5*X(4)
SUM = X(1)+X(2)+X(3)+X(4)
X(1) = X(1)/SUM
X(2) = X(2)/SUM
X(3) = X(3)/SUM
X(4) = X(4)/SUM
IF (DELH.EQ.0.) GO TO 15
H1 = 0.
DO 5 I = 1, 4
5 H1 = H1 + X(I)*8.3143*(A(I)*T1+B(I)*T1**2+C(I)*T1**3+D(I)*T1**4)
H2 = H1 + DELH*(FZA+1.)*28.85/SUM
T2 = T1 + 100.
15 H2C = 0.
DO 10 I = 1, 4
10 H2C = H2C + X(I)*8.3143*(A(I)*T2+B(I)*T2**2+C(I)*T2**3+D(I)*T2**4)
H3 = H2C*SUM/(28.85*(1.+FZA))
CP = 0.
DO 20 I = 1, 4
20 CP = CP + X(I)*8.3143*(A(I)+2.*B(I)*T2+3.*C(I)*T2**2+4.*D(I)*T2**3)
GAM = CP/(CP-8.3143)
IF (DELH.EQ.0.) RETURN
IF (ABS(H2C-H2).LE.H2*.0001) GO TO 25
T2 = T2 + (H2-H2C)/CP
GO TO 15
25 RETURN
END

SUBROUTINE FOPEN
CHARACTER*16 FNAME1, FNAME2, FNAME3, FNAME4
COMMON/OPEN/ FNAME1, FNAME2, FNAME3, FNAME4
OPEN (1, FILE='DIESEL1.INP', STATUS='OLD')
OPEN (2, FILE=FNAME1, STATUS='NEW')
OPEN (3, FILE=FNAME2, STATUS='NEW')
OPEN (4, FILE=FNAME3, STATUS='NEW')
RETURN
END

SUBROUTINE FCLOSE
CLOSE (1, STATUS='KEEP')
CLOSE (2, STATUS='KEEP')
CLOSE (3, STATUS='KEEP')
126
CLOSE (4, STATUS=’KEEP’)
RETURN
END

C SUBROUTINE INPUT
C
C IMPLICIT REAL(A-H,O-Z), INTEGER(I-N)
DIMENSION TITLE(20)
COMMON/XXX/EQUIVD,RPM, PEXH, PAIR, TAIR,
1 CR, BORE, STROKE, CONROD, FPSTE, FPISTA,
2 EVO, EVC, AVO, AVC,
3 TVALI, WDFUL,
4 ACO, ACF,
5 ANNA, FMEPM,
6 NPCWF, DEL1, DEL2, DEL3, AAN(2),
7 VALEXH, CDE, NTEXH, WIDTHE, ALPHEX(50), FEXH(50),
8 VAIR, CDA, NTAIR, WIDTHA, ALPAIR(50), FAIR(50),
COMMON/GEN/ALPHAT, ANGEND, ANGRES, AIRP0, EXHPO, IMOLS,
1 APAIR, APEXH, AREF, AP(2),
1 APN(2), CYCLE, DALPHA,
1 DREF, DZ, FREF,
1 IPOWER, IREV, GA, GE, GREF, IUNITL,
1 IUNITP, IUNITT, IUNITK, IUNITW, IUNITQ,
1 WAR, PBARAB,
1 PI, FREF, REVENG, REVREF, RPAIR, RPEXH, RP(2),
1 RPN(2), STEP2, TExH, TREF, VREF, WREF, XREF,
1 Z, ZREF, HAIR, HREF, SCMULT, NC
COMMON/CYL/ACSB, ALPHA, ALPHAE, ANNB, ANNC, AC,
1 ACN, ACR, ALPHAC,
1 CALVAL, CARBON,
1 COEFFA(4), COEFFB(4), COEFFC(4), COEFFD(4),
1 COEFFE(4), COEFFZ(4), CRANK, DCYL, DHEAT,
1 DRC, DWCYL, DWCIN, DWCP(2), DWCYL,
1 FCYL, HEATG,
1 PURITY, PVEL, PCR, CYLTL,
1 PORTS, RC, RCN, RCR, SURFC,
1 TCR, TCYLT, VSWEPT,
1 VCYLT, WCAIL, WCIN,
1 WCO, WCYL, WMM(4), WCINT(4), WCYL,
1 WN(4), WORKGA, WORKGE, XCRA, XSTA,
1 NCD, WCYLT, WCINT,
1 TPIST, THEAD, TExV, CID
COMMON/COMB/AIRFL, EQUIV, EXHVS, SHPS, FZA, HRD, SCASW, TREFF, SCAEFF,
+ AIRVMAX, EXHVMAX, PORTED, STOIC, WCO, BLBACK, FUEL, BHP
COMMON/CPURE/WCA, WCHG, IMIX
WRITE (4,10)
WRITE (2,10)
10 FORMAT (’BENSON DIESEL ENGINE MODEL’/)
C
C READ(1,20) TITLE
C WRITE(4,21) TITLE
C WRITE(2,21) TITLE
C 20 FORMAT(20A4)
C 21 FORMAT (1X,20A4)
C
IPOWER=10
CYCLE=2.
ANGEND=7200.
PORTED=2.
COOLED=2.
IF (PORTED.EQ.0.) PORTED = 1.

C
IUNITP=2
IUNITT=3
IUNITL=2
IUNITW=2
IUNITK=2
IUNITQ=3

C
READ(1,*) EQUVID, RPM, PEXH, PAIR, TAIR
WRITE(2,*) EQUVID, RPM, PEXH, PAIR, TAIR
REVENG=RPM/60.
PBARAB=14.7
PREF=14.7
TREF=518.7
GREF=1.4
REVREF=REVENG

C
TEXH=2100.
GE=1.33
GA=1.4
WAR=0.

C
STEP2=2.

C
READ(1,*) CR, BORE, STROKE, CONROD, FPISTA
WRITE(2,*) CR, BORE, STROKE, CONROD, FPISTA
DCYL=BORE/12.
XSTA=STROKE/12.
XCRA=CONROD/12.

C
READ(1,*) EVO, EVC, AVO, AVC
WRITE(2,*) EVO, EVC, AVO, AVC
ACSB=EVC
IF (AVC.GT. EVC) ACSB=AVC

C
READ(1,*) TWALL, WFUEL
WRITE(2,*) TWALL, WFUEL
PURITY=0.9
PCYLT=185.
TCYLT=1290.
CRANK=0.
NCD=0

C
READ(1,*) ACB, ACF
WRITE(2,*) ACB, ACF
TPIST=TWALL
THEAD=TWALL
TEXV=TWALL

C
CALVAL=42515.
C READ(1,*), ANNA, FMEPM
C WRITE(2,*), ANNA, FMEPM
SMULT=1.1
ANNB=0.7
ANNC=0.327E-10
C WOSCHI HEAT LOSS MODEL ASSUMED WHEN ANNB=0.8 AND ANNC=0.
   IF(SMULT.EQ.0.) SMULT=1.
   IF(FMEPM.EQ.0.) FMEPM=1.
C
CARBON=0.85561
C READ(1,*), NPCWF, DEL1, DEL2, DEL3, AAN(1), AAN(2)
C WRITE(2,*), NPCWF, DEL1, DEL2, DEL3, AAN(1), AAN(2)
C AAN(1), AAN(2) FUEL INJECTION CONSTANTS FOR WHITEHOUSE-WAY MODEL
   IF(AAN(1).EQ.0.) AAN(1)=1.
   IF(AAN(2).EQ.0.) AAN(2)=1.
   IF(DEL1.EQ.0.) DEL1=6.9
   IF(DEL2.EQ.0.) DEL2=2.1
STOIC=1./((CARBON/12.01+(1.-CARBON)/(1.008*4.))*(32.0+3.76*28.0))
C AVL HEAT RELEASE MODEL USED WHEN NPCWF = 0, DEL3=0.
C WIEBE HEAT RELEASE MODEL USED WHEN NPCWF=0, DEL3 .GT. 0.
C WHITEHOUSE-WAY MODEL USED WHEN NPCWF .LT. 0
C WATSON MODEL USED WHEN NPCWF.GT.0
   IF (NPCWF.GT.0) HRD=125.0
   IF (NPCWF.EQ.0) HRD=DEL3
C
C READ(1,*), VALEXH
C WRITE(2,*), VALEXH
   IF(VALEXH.EQ.0.0) GOTO S
C READ(I,*) (ALPHEX(N), FEXH(N), N=1,NTEXH)
C WRITE(2,191) (ALPHEX(N), FEXH(N), N=1,NTEXH)
191 FORMAT (IX, 2El0.3)
   DO 192 N=1,NTEXH
       ALPHEX(N) =_(N) +EVO
   GOTO 9
C
CONTINUE
C READ(1,*), CDE, NTEXH
C WRITE(2,*), CDE, NTEXH
C READ(1,*), (ALPAIR(N), FAIR(N), N=1,NTAIR)
C WRITE(2,*), (ALPAIR(N), FAIR(N), N=1,NTAIR)
192 ALPHEX(N)=ALPHEX(N)+EVO
   GO TO 9
C
8 CONTINUE
C READ(1,*), CDE, WIDTHE
C WRITE(2,*), CDE, WIDTHE
C
9 CONTINUE
C READ(1,*), VALAIR
C WRITE(2,*), VALAIR
   IF(VALAIR.EQ.0.0) GOTO 200
C READ(1,*), CDA, NTAIR
C WRITE(2,*), CDA, NTAIR
C READ(1,*), (ALPAIR(N), FAIR(N), N=1,NTAIR)
C WRITE(2,*), (ALPAIR(N), FAIR(N), N=1,NTAIR)
DO 193 N=1,NTAIR
193 ALPAIR(N)=ALPAIR(N)+AVO
   GO TO 201
C 200 CONTINUE
C READ(1,*) CDA,WIDTHA
C WRITE(2,*) CDA,WIDTHA
C 201 RETURN
END
C SUBROUTINE HEADER
COMMON/XXX/ EQUVD, RPM, PEXH, PAIR, TAIR,
   1  CR, BORE, STROKE, CONROD, FPISTE, FPISTA,
   1  EVO, EVC, AVO, AVC,
   1  TWALL, WFCUL
   1  ACB, ACF,
   1  ANNA, FMFM
   1  NPWF, DEL1, DEL2, DEL3, AAN(2),
   1  VALEXH, CDUE, NTEXH, WIDTHA, ALPaha(50), FEYHY(50),
   1  VALAIR, TWA, NTAIR, WIDTHA, ALPAIR(50), FAIR(50)
COMMON/GEN/ALPHA, ANGI, ANGRES, AIRP0, EXH0, IMOLS
   1  APAIR, APEXH, AREF, AP(2),
   1  APN(2), CYCLE, DALPA, WIDZ_A,
   1  DREF, DZ, FREF,
   1  IPOWER, IREV, GA, GE, GREF, IUNITL,
   1  IUNITP, IUNITT, IUNITK, IUNITW, IUNITQ,
   1  WAR, PEARAB,
   1  PI, PREF, REVENG, REVREF, RPAIR, RPEXH, RP(2),
   1  RPN(2), STEP2, TEXH, TREF, VREF, WREF, XREF,
   1  Z, ZREF, HAIR, HREF, SCMUL, NC
COMMON/CYL/ACSB, ALPHA, ALPHAE, ANNB, ANNC, AC,
   1  ACN, ACR, ALPHAC,
   1  CALVAL, CARBON,
   1  COEFFA(4), COEFFB(4), COEFFC(4), COEFFD(4),
   1  COEFFE(4), COEFFZ(4), CRANK, DCYL, DHEAT,
   1  DRC, DCYL, DWCIN, DWCP(2), DWCYL,
   1  FCYL, HEATG,
   1  PURITY, PVEL, PCR, PCYLT,
   1  PORTS, RC, RON, RCR, SURFC,
   1  TCR, TCYLT, TSWEFT,
   1  VCUL, WCALR, WCIN,
   1  WOUT, WCYL, WNN(4), WPCNT(4), WCYLR,
   1  WN(4), WORKGA, WORKGE, XCR, XSTA,
   1  NCD, WCYLT, DWCINT,
   1  TPIST, HEAD, TEKV, CID
COMMON/COMB/AIRFL, EQUVD, TEXH, SHPS, FZA, HRD, SCASW, TREF, SCAEFF,
  + AIRVMX, EXHVMX, PORTED, STOIC, WCO, BLBACK, FUEL, BHP
COMMON/CFA/RC, WCA, WC, IMIX
WRITE(3,2048)
2048 FORMAT(4X,'ANGLE',5X,'PRESSURE',3X,'TEMPERATURE',4X,
  1 'GAMMA',5X,'VOLUME',5X,'MEAN TEMP'/)
C NC=1
WRITE(2, 1027)
WRITE(2, 1028) TWALL, WFUEL, ACB, ACF, TPIST, THEAD, WAR
1027 FORMAT (4X, 'WALL', 7X, 'FUEL', 8X, 'COMBUSTION', 5X, 'PISTON', 4X,
+ 'CHAMB', /11X, 13X, 13X, 6X, 'TEMP', 5X,
+ 'PER CYCLE', 4X, 'START FINISH', 5X, 'TEMP TEMP', 5X, 'WAR/')
1028 FORMAT (9X, F9.1, E13.3, F9.1, F7.1, F10.1, F9.1, 3X, F6.4)
1035 FORMAT (14H CYLINDER BORE, F8.4/7H STROKE, F9.4/
  1      50H SURFACE AREA PISTON / CYLINDER CROSS SECTION AREA, F8.4
  2      /22H CONNECTING ROD LENGTH, F9.4)
DCYL12=DCYL1*12
XSTA12=XSTA*12
XCRA12=XCRA*12
CID=.7854*DCYL12**2*XSTA12
WRITE(2, 1035) DCYL12, XSTA12, FPISTA, XCRA12
WRITE(2, 1038) CR, CID
1038 FORMAT (26H NOMINAL COMPRESSION RATIO, F8.4, 5X, 'SWEPT VOLUME (IN3)' +, F8.3)
WRITE(2, 1040) EVO, EVC, AVO, AVC, ACSB, AAN(1), AAN(2)
1040 FORMAT (/12H PORT TIMING//4H EVO, F7.1/4H EVC, F7.1/4H AVO, F7.1/
  1     4H AVC, F7.1/32H ANGLE COMPRESSION STROKE BEGINS, F7.1, 5X,
1'AAN(1) = ', F6.3, 5X, 'AAN(2) = ', F6.3)
IF (VALEXH.GT.5.) GO TO 85
WRITE(2, 1042) WIDTHHE
1042 FORMAT (28H PERCENTAGE PORT WIDTH (EXH), F9.4)
GO TO 86
85 WRITE(2, 1043) CDE
1043 FORMAT (26HCOEFFICIENT CD (EXH) VALVE, F7.4)
86 IF (VALAIR.GT.5.) GO TO 87
WRITE(2, 1044) WIDTHHA
1044 FORMAT (27H PERCENTAGE PORT WIDTH (AIR), F9.4)
GO TO 88
87 WRITE(2, 1045) CDA
1045 FORMAT (25HCOEFFICIENT CD (AIR) PORT, F7.4)
88 SPEED=REVENG*60.
WRITE(2, 2047) SPEED, PAIR, TAIR, PEXH
2047 FORMAT (11HSPEED (RPM), F10.2, 5X, 26HSUPPLY AIR PRESSURE (PSIa), + F8.2, 5X, 19HSUPPLY AIR TEMP (R), F8.2, 5X, 23HEXHAUST PRESSURE (PSIa) +, F8.2/)
WRITE(2, 1049) CALVAL, CARBON, DEL1, DEL2, DEL3
1049 FORMAT (22H CALORIFIC VALUE (KJ/KG), F10.2, 4X,
  1     15HCARBON FRACTION, F8.5, 4X, 5HDEl1 , F6.4, 4X, 5HDEl2, F6.4, +4X, 5HDEl3, F6.4)
WRITE(2, 1051) ANNA, FMEPM, ANN
1051 FORMAT (1H, 8HANNAND A, F7.4, 49X,
  + 5X, 'FMEPM= ', F5.3, /9H ANNAND B, F7.4)
WRITE(2, 1052) ANNAN
WRITE(2, 3000)
3000 FORMAT (/1X, 8HFUEL FLOW, 2X, 9HSCAV RAT., 3X, 8HTRAPPING, 3X,
+ 8HSCAVENGE, 2X, 8HTEMl OUT, 3X, 5HPower, 5X, 4HTRUe, 5X, 8HAIR FLOW,
+ 3X, 5HEQUIV, 5X, 5HP MAX, 6X, 5HT MAX, 4X, 7HPERCent)
WRITE(2, 3010)
3010 FORMAT (2X, 6HLB/SEC, 5X, 6HWSW VOL, 7X, 3HEFF, 8X, 3HEFF, 9X, 1HR, 8X,
+ 2HEP, 5X, 6HPURITY, 5X, 6HLB/SEC, 15X, 4HPSSA, 8X, 1HR, 5X,
+ 9HHEAT LOSS/)
FOURTH ORDER POLYNOMIAL CURVE FIT TO JANAF TABLE DATA

IN THE RANGE 400 K TO 2400 K

THIS DATA CAN BE USED TO FIND ENTHALPY, INTERNAL ENERGY, AND SPECIFIC HEAT USING THE FOLLOWING EQUATIONS

\[
H(I) = R (A(I) * T + B(I) * T^2 + C(I) * T^3 + D(I) * T^4)
\]

\[
U(I) = R ((A(I) - 1) * T + B(I) * T^2 + C(I) * T^3 + D(I) * T^4)
\]

\[
CP(I) = R (A(I) + 2B(I) * T + 3C(I) * T^2 + 4D(I) * T^3)
\]

WHERE \( H(I) \) IS THE SENSIBLE MOLAR ENTHALPY OF SPECIES I, J/GMOL

\( U(I) \) IS THE SENSIBLE MOLAR ENTHALPY OF SPECIES I, J/GMOL

\( CP(I) \) IS THE MOLAR SPECIFIC HEAT AT CONSTANT PRESSURE, J/GMOL−K

COMMON/JANAF/ A(4), B(4), C(4), D(4)
DATA A/3.00845, 2.94628, 3.29003, 3.50953/
DATA B/6.15041E−4, 1.03617E−3, 2.69417E−3, 6.54488E−4/
DATA C/−1.09800E−7, −3.39775E−7, −8.66074E−7, 9.41722E−8/
DATA D/5.68186E−12, 4.75627E−11, 1.11529E−10, −3.43661E−11/
END
**Abstract**

This report documents the Benson Diesel Engine Simulation Program and explains how it can be used to predict the performance of diesel engines. This program was obtained from the Garrett Turbine Engine Company but has been extensively modified since that time. The program is a thermodynamic simulation of the diesel engine cycle which uses a single zone combustion model. It can be used to predict the effect of changes in engine design and operating parameters such as valve timing, speed and boost pressure. The most significant change made to this program is the addition of a more detailed heat transfer model to predict metal part temperatures. This report contains a description of the sub-models used in the Benson program, a description of the input parameters and sample program runs.

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

Diesel; Cycle; Simulation; Parameters; Efficiency

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