

A Simplified Thermodynamic Modeling Method for Predicting Energy Systems Performance at Steady State

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ABSTRACT

This paper describes a highly flexible method which models the thermal performance of any energy system at steady state. A steam power plant (Libya-Derna 65 MW) is mathematically represented by a system of algebraic equations. The method outlines the steps taken in the development of energy systems general model including the mass and energy balances and exergy loss. A computer program was written based on the mathematical model of the selected steam plant. The results show good agreement with the actual data. The necessary instructions are provided for the application of the method to a large variety of energy systems types. The implantation of the method is discussed in detail and example of application is given.

Keywords: Steady State Modeling, Simulation, Exergy loss, Steam Power Plant.

NOMENCLATUR

ex	specific exergy of the flowing stream, kJ/kg
Ex	total exergy of the flowing stream, kW
Ex_f	exergy in fuel, kW
CV_f	calorific value of flue, kJ/kg
h_i	specific enthalpy of flow i in balance node n , kJ/kg
k_m	set of mass streams in balance node n .
k_q	set of energy streams balance node n .
m	mass of flowing stream, kg/s
m_i	stream of mass flow i in balance node n , kg/s
m_f	mass of fuel, kg/s
m_s	mass of steam, kg/s
P_i	shaft work or electric energy, kW
Q_i	stream of energy i in balance node n , kW
$s.f.c$	Specific fuel consumption
$s.s.c$	Specific steam consumption

Greek letters

η_{Ex}	exergy efficiency, %
$\delta\pi_n$	exergy losses in component n , kW

π_n	relative exergy losses of component n to exergy in fuel,.
Π	relative exergy losses of the whole power plant to exergy

1. INTRODUCTION

As emissions regulations grow tighter and the prospects of increased energy costs loom, the need for modeling and simulation of energy systems will increase. Modeling and simulation play a key role in the design and performance optimization of complex energy processes. Modeling is used by academic researchers and engineers to improve their knowledge of existing or future types of energy systems verify the design accuracy and understand important transients. The energy system engineer or researcher is often faced with the problem of assessing the change in operating costs due the deterioration of performance of individual pieces of equipment in the system and of predicting the effect upon performance due to changes of equipment or operation procedures. When presented with such tasks the engineer has a number of techniques from which to choose to perform his evaluation as: an energy balance (first law analysis), exergy analysis (second law analysis), rules-of-thumb and heat rate test [9]. Numerous program packages have been developed for energy systems calculations [1, 3, 6, 10]. The complexity of these programs covers a wide range that allows the modeling of any system configuration. These packages, however, lack the flexibility that is required for many advanced investigations [4, 8]. Therefore, a detailed simple method for power cycle calculation was developed based on the first and second law analysis. In this paper, a method has been developed that enables users to perform detailed analysis and design of complete thermal-fluid systems such as complete power plants, industrial and commercial energy systems and thermal-fluid networks. This paper demonstrates the usage of the method. Finally, a simple energy system will be examined for clarity.

2. PHYSICAL MODEL

The system cycle studied in the ensuing analysis is a fairly typical 65 MW steam power plant under operating in Libya, with three stages extraction to the feedwater heaters. This unit is shown schematically in Fig. 1. Table 1 presents the thermodynamics parameters at various points in the cycle at design condition. It considered including components that strongly effect the operation of the system under the study. Thus, the real structure is simplified by omitting some of its insignificant flows and components such as steam seals, air ejectors, flue gases drought system, air heater and stand by flows and components.

3. CONCEPT DEFINITIONS AND BASIC ASSUMPTIONS

We define energy system any set of components such as turbines, pumps, heat exchangers, control valves with a stream of mass and energy links between them. These sets of components compose the thermodynamic processes of the system and directly influence in its performance.

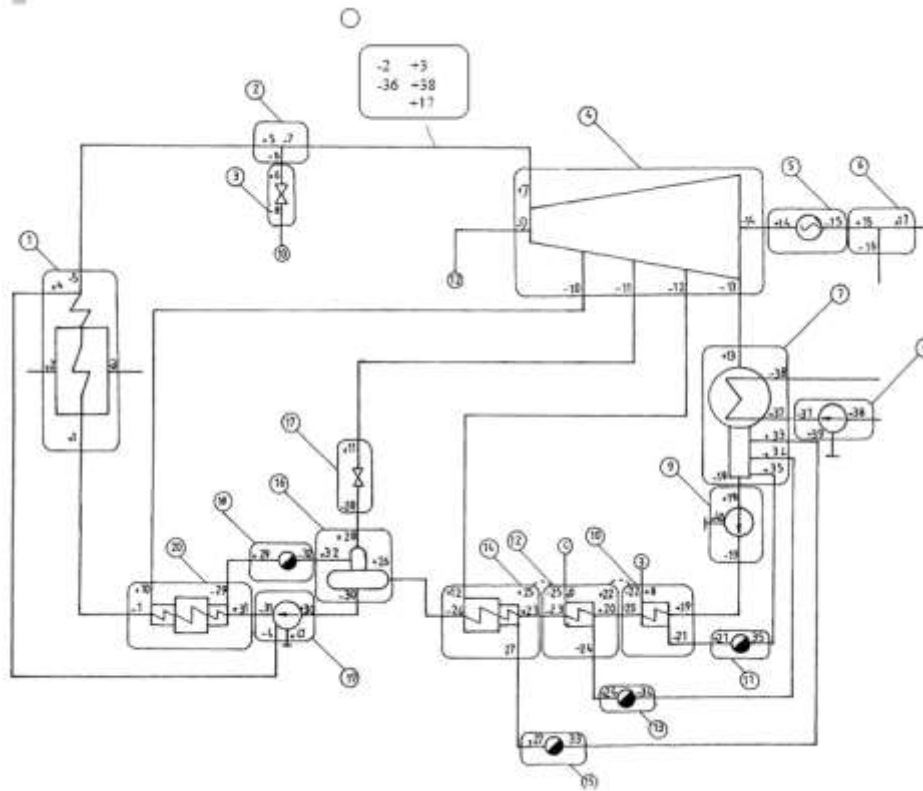


Figure 1. Schematic diagram of the typical Physical Model

Description of the Power Components		
1-steam boiler	8-cooling water pump	15-steam trap
2-steam distributor	9-condensation extraction pump	16-de-aerator
3-steam expansion valve	10-steam cooler	17-steam
4-steam turbine	11-steam trap	18-steam trap
5-generator	12-steam gland	19-feed water
6-energy distributor	13-steam trap	20-high pressure
7-condenser	14-low pressure heater	21-environment

The operation of each component in the system is thermodynamically and economically dependent upon the operation of other one. For a suitable symbolic representation may will be found in all cases of different and large energy systems, each component in the structure of the power plant is surrounded by balance shield and called node and each node is connected with existing and entering flows. The entering flows is marked with a(+), where the existing flows is marked with a(-).

Figure 1. Shows the structure of the power plant analyzed herein and the balance nodes are used for the balance problem calculations. There are 20 nodes with 30 mass flows and 11 energy flows. The thermodynamic transformations take place only within the nodes surrounded by balance shields. There are two kinds of nodes: mass nodes which are connected with mass and energy flows, and energy nodes which are connected with energy flows only. The node number corresponds to the number placed outside the balance shield where the mass and energy flows are numbered within the balance shield of a particular component.

4. SYSTEM MODELING

System modeling provides the set of governing equations to be solved simultaneously for the calculations and simulation of an energy system. These equations come from thermodynamic properties, mass and energy balances and performance characteristics. Mathematically this means to put all equations together into a system of linear equations. This system must be solved to obtain all states including the performance of the energy system. The system can have 1000 unknowns or even more, the task of a computer-aided to set up and solve this system. After the process is given a flow diagram representation as shown in Fig.1, i.e, each one of the N components is properly defined, and the connecting M streams completely identified, the modeling of a process with the method proposed in this paper is performed according to the following steps:

i- Thermodynamic properties

The first step in the system modeling of any energy system is to perform the thermodynamic properties of each mass stream. The properties for water and steam shown were computed from polynomial defined by the international standard IAPWS-IF97 [1] and given in Table1. Usually it is not possible to calculate thermodynamic data independently from mass stream. Mixing points needs mass stream data to calculate thermodynamic properties. The enthalpy behind a mixing point is calculated from the feed streams as follows [1]:

$$h[20] = \frac{Q[22]}{m[20]} \quad (1)$$

$$h[23] = \frac{Q[25]}{m[23]} \quad (2)$$

This means the additional energy flows numbered 22 and 25 have been assumed, thus the mass and energy balances form a system of linear equations.

ii Mass and Energy Balances

The next is to perform the required mass and energy balances around each node (system component). The mass and energy balances are in the form [2]:

$$\sum_{i=1}^N a_i m_i = 0.0 \quad (3)$$

Where, a_i coefficient that determines the mass flows entering and leaving the balance node.

And for energy balances:

$$\sum_{i=1}^N a_i m_i h_i \pm Q_i = 0.0 \quad (4)$$

where x is the coefficient that determines the flows entering and leaving the balance node. x=+1 for entering condition, and x=-1 for leaving condition.

iii The last of governing equations come from the performance characteristics of the cycle's equipment and thermodynamic relations [9]. The following performance equations can be considered:

$$\text{Overall efficiency } \eta_{net} = \frac{P_{net}}{m_f \times C.V_f} \quad (5)$$

$$\text{Net heat rate } HR_{net} = \frac{Q_B \times 3600}{P_{net}} = \frac{3600}{\eta_{net}}, kJ/kWh \quad (6)$$

Specific fuel consumption $s.f.c_{net} = \frac{3600 \times m_f}{P_{net}}, kg/kWh$ (7)

Specific steam consumption $s.s.c_{net} = \frac{3600 \times m_s}{P_{net}}, kg/kWh$ (8)

Exergy losses

The exergy balance applied to the considered power plant follows:

Turbines, pump shaft work and electrical energy are full transfers of exergy. They are taken as:

$$Ex_i = P_i \quad (9)$$

It is assumed that the specific fuel exergy is equal (in real conditions 2÷5 % [1]) to its calorific value (CV_f) and thus the total fuel exergy can be expressed as:

$$Ex_f = m_f CV_f \quad (10)$$

The energy flow carried away from the system in a useless form and is not recovered by any method not further used in the power plant, (e.g. exhaust gases from boiler) is taken as:

$$Ex_i = 0.0 \quad (11)$$

The exergy balance used to determine exergy losses in the component n, takes the form:

$$\delta\pi_n = \sum_{i \in \Omega_e} Ex_i - \sum_{j \in \Omega_0} Ex_j = \sum_{i \in \Omega_e} ex_i m_i - \sum_{j \in \Omega_0} ex_j m_j \pm Q_z \quad (12)$$

Where, $ex_i = (h_i - h_o) - T_o(s_i - s_o)$ (13)

Relative exergy losses in n th component to exergy in fuel are:

$$\pi_n = \left(\frac{\delta\pi_n}{B_f} \right) \times 100\% \quad (14)$$

Relative exergy losses of the whole power plant to exergy in fuel are:

$$\Pi = \sum_{n \in \Omega_i} \pi_n \quad (15)$$

the exergy efficiency is calculated using:

$$\eta_{Ex} = \left(1 - \frac{\sum_{n \in \Omega_i} \delta\pi_n}{Ex_f} \right) \times 100\% \quad (16)$$

5. SOLUTION ALGORITHM

The algorithm of the system leads to a calculation process as shown schematically in Fig. 2. At the beginning the input data are supplied (net electric power generated and properties at the outlet of the condenser). With this data all thermodynamic properties are calculated. By setting up and solving the mass and energy balance equations values for mass flow rates and energy flows are obtained. The mass and energy balances form a system of linear equations. This can easily be solved with standard algorithms for linear equation system solution like Gauss-Jordan Elimination or Lower-Upper decomposition [7]. The

unknown enthalpies (20, 23) after solving the mathematical model are now calculated using equations (1, 2). The residual for each equation and the norm residual is calculated [6,7]. Finally, the power plant performances are determined.

6. EXAMPLE SYSTEM ANALYSIS

Consider the steam cycle depicted in Fig. 1. The process can be described by a network of 21 nodes and 41 flows. The mass and energy balances equations and the performance equations form the basis for analyzing the energy system. The following section will show the set of governing equations that will be solved. The energy system here is a simple steam power plant. This will serve as an example of larger and more complicated systems which can be modeled with this method.

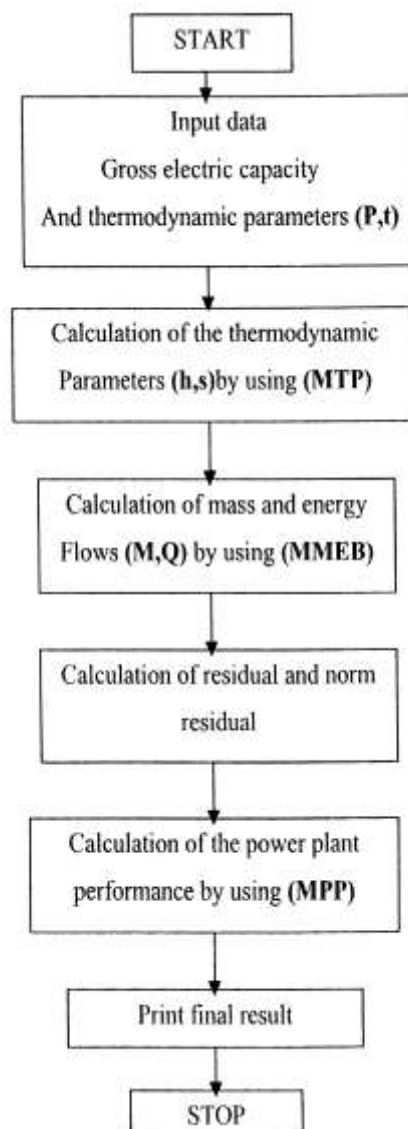


Fig.2 General Flow Diagram of the Solution Method

The equations for various components of the system are given below (see Table 2.). Performance relations will be used for the boiler, electrical generator and condenser. This will add 7 more equations (eq no.).

The computer now has 41 equations and 41 unknowns. Upon receiving initial guesses for each variable, it will attempt to find a solution. Table 3. show the results.

Table 1. The mathematical model of the balance problem

Stream	Nodes	Eq. Type	Equations	Remarks
1	6	1d	$Q[17]=VGF$	
2	1	1m	$M[1]+M[4]-M[5]=0$	Determines heat losses in boiler
3	1	1q	$M[1]h[1]+Q[2]-Q[3]+M[4]h[4]-M[5]h[5]=0$	
4	1	2d	$Q[3] - (1 - \eta_b)Q[2]= 0$	
5	1	3d	$M[4]-\alpha M[5]= 0$	
6	2	2m	$M[5]-M[6]-M[7]=0$	
7	2	4d	$\alpha 2M[5]-M[6]=0$	Determines flow [6] in node 2
8	3	3m	$M[6]-M[8]=0$	
9	4	5d	$\alpha 3M[7]-M[9]=0$	Determines losses from seals in node 4
10	4	2q	$M[7]h[7]-M[9]h[9]-M[10]h[10]-M[11]h[11]-M[12]h[12]-M[13]h[13]-Q[14]=0$	
11	5	6d	$\eta_g Q[14]-Q[15]=0$	Determines gross electrical power in node 5
12	6	7d	$Q[16]-\alpha 4Q[15]=0$	Determines own need in node 6
13	6	3q	$Q[15]-Q[16]-Q[17]=0$	
14	7	4m	$M[13]+M[18]+M[33]+M[34]+M[35]+M[37]-M[38]=0$	
15	7	5m	$M[37]-M[38]=0$	
16	7	4q	$M[13]h[13]-M[18]h[18]+M[33]h[33]+M[34]h[34]+M[35]h[35]+M[37]h[37]-M[38]h[38]=0$	
17	8	6m	$M[36]-M[37]=0$	
18	8	5q	$M[36]h[36]-M[37]h[37]+Q[39]=0$	
19	9	7m	$M[18]-M[19]=0$	
20	9	6q	$M[18]h[18]-M[19]h[19]+Q[40]=0$	
21	10	8m	$M[19]-M[20]=0$	
22	10	9m	$M[8]+M[19]-M[20]-M[21]=0$	
23	10	7q	$M[8]h[8]+M[19]h[19]-M[21]h[21]-Q[22]=0$	$h[20]=0.0$
24	11	10m	$M[21]-M[35]=0$	
25	12	11 m	$M[20]-M[23]=0$	
26	12	12m	$M[9]+M[20]-M[23]-M[24]=0$	

27	1 2	8q	$M[9]h[9]+Q[22]-M[24]h[24]-Q[25]=0$	$h[23]=0.0$
28	1 3	13m	$M[24]-M[34]=0$	
29	14	14m	$M[23]-M[26]=0$	
30	1 4	15m	$M[22]+M[23]-M[26]-M[27]=0$	
31	1 4	9q	$M[12]h[12]+Q[25]-M[26]h[26]-M[27]h[27]=0$	
32	1 5	16m	$M[27]-M[33]=0$	
33	1 6	17m	$M[26]+M[28]-M[30]+M[32]=0$	
34	1 6	10q	$M[26]h[26]+M[30]h[30]+M[32]h[32]=0$	$M[28]h[28]-$
35	17	18m	$M[11]-M[28]=0$	
36	1 8	19m	$M[29]-M[32]=0$	
37	1 9	20m	$-M[4]+M[30]-M[31]=0$	
38	1 9	11 q	$-M[4]h[4]+M[30]h[30]-M[31]h[31]+ Q[41]=0$	
39	20	21m	$-M[1]+M[31]=0$	
40	20	22m	$-M[1]+M[10]-M[29]+M[31]=0$	
41	20	12q	$-M[1]h[1]+M[10]h[10]-M[29]h[29] + M[31]h[31]=0$	

Table 2. Comparison between model results and Plant data

Streams	Value of mass flow	
	Model results	Plant data
1	67.461	70.299
6	.166	.166
7	67.301	69.363
9	.045	.046
10	6.9	7.238
11	5.933	5.978
12	5.800	5.936
13	48.615	48.696
19	54.621	57.014

7. CONCLUSION

A simplify method for industrial and commercial energy systems calculation at steady state has been demonstrated. The concepts presented provide a fundamental tool for the academic researcher and practicing engineer. Knowing when and where to use simulation and modeling technology is fundamental to successful design and operation of an energy systems. Correct application of simulation and modeling technology improves design accuracy, and saves time and money by clarifying many projects details early in the design cycle.

Modeling gives many opportunities to reduce energy consumption exists in supply (system), there also are measures to take within the system's components to ensure that the energy losses gets where it is required in required quality and quantity.

This method accurately predicts steady state performance of a wide range of type and rating energy systems. The procedure is applicable to any type of energy system. The method has been demonstrated by example of real steam power plant. The results comparison with manufacturer catalog information has been performed with reasonable accuracy.

The conclusions of this research can be summarized as following:

1. Good accuracy has been achieved which is confirmed by observing the residual for each equation and the norm residual for the set of equations.
2. The results obtained show a class agreement with manufacture results.
3. By using the indicated method, the designer can make the wise decision for the economic and optimum plant components such as size, cost and performance of component, in an easy way to get maximum system efficiency.

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The Input Data to the Main Program ONA'PM:

Net Electric Energy Sent Out=61100.0 kW

Calorific Value of Fuel Used=44719.2 kJ/kg

Inlet Cooling Water Temperature=20.00 C

ALFA1=.000

ALFA2= .002387

ALFA3= .000663

ALFA4=.060

The output Results of Mass and Energy Flows from the Main Program

ONA'PM

Flow NO.	p [bar]	t [C]	h [kJ/kg]	s [kJ/kg.K]	X [-----]	M or Q [kg/s or kW]
1	118.000	214.200	920.254	2.447	.00	67.462 kg/s
2	=====	=====	=====	=====	.00	195363.400 kW
3	=====	=====	=====	=====	.00	25397.250 kW
4	100.000	157.800	671.562	1.910	.00	.000 kg/s
5	87.000	520.000	3439.679	6.742	1.00	67.462 kg/s
6	87.000	520.000	3439.679	6.742	1.00	.161 kg/s
7	87.000	520.000	3439.679	6.742	1.00	67.301 kg/s
8	10.000	482.088	3439.679	7.712	1.00	.161 kg/s
9	1.200	177.890	2830.431	7.654	1.00	.045 kg/s
10	21.810	334.816	3100.503	6.859	1.00	6.909 kg/s
11	6.023	192.773	2833.521	6.930	1.00	5.933 kg/s
12	1.150	103.584	2573.114	7.025	.95	5.800 kg/s
13	.062	36.783	2287.416	7.413	.88	48.615 kg/s
14	=====	=====	=====	=====	.00	67010.300 kW
15	=====	=====	=====	=====	.00	65000.000 kW
16	=====	=====	=====	=====	.00	3900.000 kW
17	=====	=====	=====	=====	.00	61100.000 kW
18	.062	36.800	154.042	.529	.00	54.621 kg/s
19	9.000	36.871	155.167	.530	.00	54.621 kg/s
20	8.000	38.552	162.102	.550	.00	54.621 kg/s
21	10.000	250.300	1087.401	2.804	.00	.161 kg/s
22	=====	=====	=====	=====	.00	8854.197 kW
23	7.500	38.969	163.799	.552	.00	54.621 kg/s
24	1.200	177.700	752.535	2.118	.00	.045 kg/s
25	=====	=====	=====	=====	.00	8946.914 kW
26	5.541	99.500	417.297	1.301	.00	54.621 kg/s
27	1.093	44.400	185.930	.630	.00	5.800 kg/s
28	5.541	191.503	2833.521	6.967	1.00	5.933 kg/s
29	21.800	162.100	685.497	1.962	.00	6.909 kg/s
30	5.541	155.800	657.242	1.900	.00	67.462 kg/s
31	120.000	157.835	672.942	1.908	.00	67.462 kg/s
32	5.541	155.755	685.497	1.966	.00	6.909 kg/s
33	.065	37.652	185.930	.155	.00	5.800 kg/s

34	.065	37.652	752.535	.155	.00	.045 kg/s
35	.065	37.652	1087.401	.155	.00	.161 kg/s
36	1.000	20.000	83.954	.296	.00	1780.254 kg/s
37	1.750	20.016	84.048	.296	.00	1780.254 kg/s
38	1.500	34.000	142.509	.491	.00	1780.254 kg/s
39	=====	=====	=====	=====	.00	167.184 kW
40	=====	=====	=====	=====	.00	61.428 kW
41	=====	=====	=====	=====	.00	1059.154 kW

Power Plant Performance :

- Thermal Efficiency = 39.43 %
- Gross Efficiency = 33.27 %
- Net(Overall) Efficiency = 31.28 %
- Boiler Efficiency = 87.00 %
- Generator Efficiency = 97.00 %
- Gross Heat Rate = 10820.13 kJ/kWh
- Net Heat Rate = 11510.78 kJ/kWh
- Mass of Fuel Consumed Per Day = 375.71 Ton
- Gross Specific Steam Consumption = 3.73 kg/kWh
- Net Specific Steam Consumption = 3.97 kg/kWh
- Gross Specific Fuel Consumption = 240.84 g/kWh
- Net Specific Fuel Consumption = 256.21 g/kWh
- Cooling Water Pump Electric Power = 167.18kW
- Extraction Pump Electric Power = 61.43kW
- Boiler Feed Water Pump Electric Power = 1059.15kW
- Electric Power Consumption by Power Plant(Own Needs)=1287.77 kW
- Energy transferred in the Boiler = 169966.20kW
- Ratio of Boiler Energy to the Energy Supply = 87.00%
- Energy available in the Turbin = 67034.58kW
- Ratio of Turbine Energy to The Energy Supply = 34.31%
- Energy transferred through the Condenser = 104076.50kW
- Ratio of Condenser Energy to The Energy Supply = 53.27%
- Energy transferred in the Low Pressure Heater = 13846.35kW
- Ratio of Low-Pressure Heater Energy to The Energy Supply = 7.09%
- Energy transferred in the High Pressure Heater = 16684.22kW
- Ratio of High Pressure Heater Energy to The Energy Supply = 8.54%

Residual of each Equation and Norm Residual for the Set of Equations of the Mathematical Model:

Equation No.	Residual
1	.000000E+00
2	.000000E+00

3 .133398E-02
4 .150315E-03
5 .000000E+00
6 .000000E+00
7 -.736573E-08
8 -.596046E-07
9 -.211997E-08
10 .315826E-02
11 -.253594E-02
12 .871718E-04
13 .000000E+00
14 .000000E+00
15 .000000E+00
16 .330615E-02
17 .000000E+00
18 .139561E-02
19 .000000E+00
20 .349135E-03
21 .000000E+00
22 .327826E-06
23 .273107E-03
24 .000000E+00
25 .000000E+00
26 -.208616E-06
27 .451686E-03
28 .000000E+00
29 .000000E+00
30 .238419E-05
31 -.122571E-02
32 .000000E+00
33 .000000E+00
34 .402880E-03
35 .000000E+00
36 .000000E+00
37 .000000E+00
38 -.163983E-02
39 .000000E+00
40 -.476837E-06
41 -.461460E-02
Norm Residual= .571425E-04