A Computer Program for Energy and Availability Analyses of Thermal Power Plants (*)

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ABSTRACT

A computer program, written in Turbo Pascal, was developed for performing both the energy find availability analyses of thermal power plants. Computing equations used for the energy analysis were drawn from ASME Power Test Codes for steam generating units and steam turbines, while the equations for the availability analysis were adapted from those compiled by Moran and Ahern. Physical property data were stored in equation form and were extracted mainly from such sources as the German VDI and ASME-PTC's.

A case study was carried out for EGAT's lignite - fired Mae Mae Power Plant Unit 1 using, as the program input, measurement data obtained for EGAT's performance evaluation tests. The results showed that, under 100% load conditions, the first-and second-law efficiencies were 88.5 %, 42,7 % respectively for the steam generator. The adiabatic efficiency of the steam turbine was 98.3%, the corresponding second-low efficiency being 69.8%. The main sources of availability destruction for the steam generator were identified to be heat transfer irreversibility (34.7%) and combustion irreversibility (13.5%) with only 2.7% availability loss through flue gas, 0.3% through unburnt fuel, 0.2% through radiation and 5.8% unaccounted for. For the steam turbine, irreversibility accounted for only 7.1% whereas, losses associated

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with steam flow were : 16.9% to the feedwater heaters and 6.2% to the condenser. The first-and second-law cycle efficiencies were 34.5% and 32.6% respectively.

1. INTRODUCTION

In fiscal year 1989, the Electricity Generating Authority of Thailand (EGAT) produced about 36,000 GWh of electricity. About 85% of this was generated from thermal power plants using natural gas, lignite and fuel oil as the main sources of fuel. With the rapid increase in electricity demand in the past few years, and more recently with increasing fuel prices prompted by the Gulf crisis, the importance of operating the thermal power plants at their best efficiencies is apparent.

The performance of EGAT's various plants are evaluated firstly, immediately after the commissioning of the plant (known as the "acceptance test") and thereafter upon each major overhaul which is carried out on a regular basis. The tests and computations are performed in accordance with relevant standards-usually the ASME Power Test Codes, and such other conditions as may be agreed between EGAT and its contractors. In all cases the concept of the second -law analysis, although increasingly recognised as being particularly suited for furthering the goal of more efficient energy use, is never applied in actual calculations. However even with the application of the first law analysis the task can be a very tedious and time-consuming one, for it involves the handling of a large number of measured physical data (temperature, pressure and flow), the determination of property values from charts and tables, and repeated number crunching.

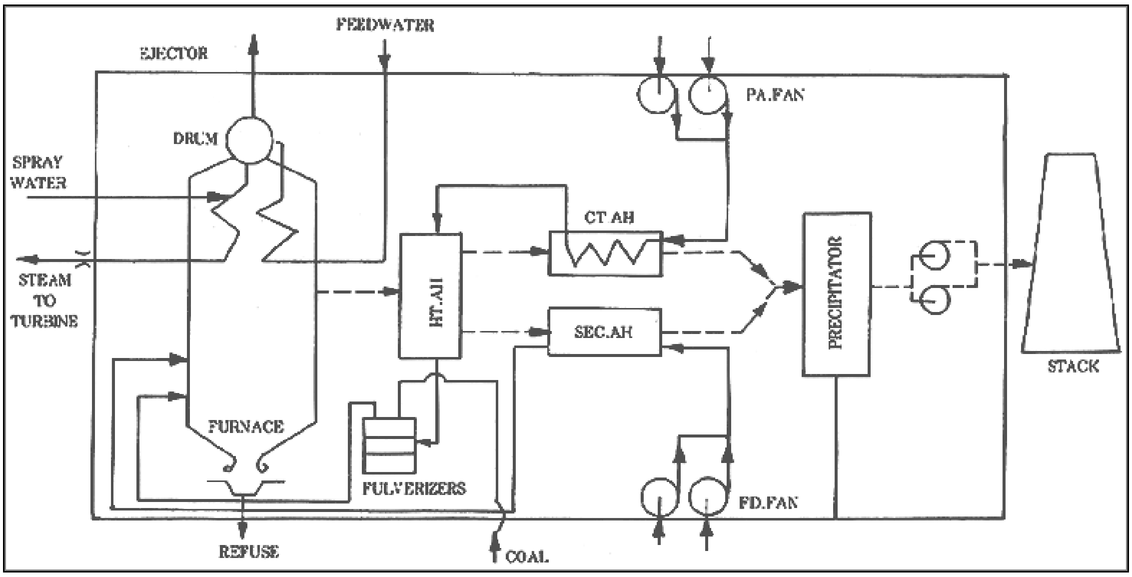
Against this background a computer program has been developed for the IBM-PC with the objectives of expediting the performance evaluation process and of encouraging the use of the first law together with the second law to guide steps taken to reduce inefficiencies. The program is capable of performing both the energy and availability analyses for steam generators, steam turbines and for their associated air and water heaters of a thermal power plant. In this paper the methods of analysis and the program structure are described, and application examples are presented using test data for EGAT's Lignitefired Mae Moh Power Plant Unit 1.

2. ANALYSES

The performance of a thermal power plant is characterised by the performance of two major components, namely, the steam generating unit and the steam turbine. The performance tests and the analyses there-of are conducted, separately for each component, in accordance with their respective ASME Power test Codes (PTC) (1, 2) and with other conditions mutually agreed between EGAT and its contractors.

2.1 Steam Gencraing Unit

The thermodynamic boundary for the performance analysis of a typical steam generating unit is shown in Fig. 1. Such a unit may include the boiler, furnace, superheater, economizer, air heater, and fuel burning equipment.



HT.AH = HOT TUBULAR AIR HEATER
CT.AH = COLD TUBULAR AIR HEATER
SEC.AH = SECONDARY AIR HEATER
PA = PRIMARY AIR
ID = INDUCED DRAFT

Fig. 1 Control volume of steam generating unit.

2. 1.1 Energy Analysis

The "heat loss method" of analysis (1), which requires the determination of losses, "heat credits" and ultimate analysis and higher heating value of the fuel, is employed. The major loss! items (L) generally include losses due to unburnt carbon in refuse, energy in dry flue gas, moisture in air, moisture in fuel, moisture from burning hydrogen, radiation and others. The heat credits (B) are the energy associated with mass flow into the control volume, which may include sensible heat in fuel, and energy in entering air and in atomizing steam, and the work input to pumps, fans and pulverizer. Thus the energy input can be expressed as

$$\text{INPUT} = B + H_f \qquad (1)$$

where H_f = chemical energy in fuel or higher heating value (HHV), and the and the output as

$$\text{OUTPUT} = \text{INPUT} - L \qquad (2)$$

The first law efficiency (η_b) of the unit is defined as

$$\eta_b = \frac{\text{OUTPUT}}{\text{INPUT}} \qquad (3a)$$

or

$$\eta_b = 1 - \frac{L}{B + H_f} \qquad (3b)$$

2.1.2 Availability Analysis

The purpose of performing an availability analysis for a steam plant is to identify and evaluate the primary sources of availability losses and destructions associated with the various plant components and the overall second law efficiency. This requires the determination of the input availability, exiting availability and irreversibilities. The input availability includes the chemical availability of the fuel and the availability associated with shaft work. The exiting availability comprises the availability with exiting steam, gaeous combustion products and unburnt fuel. The irreversibilities include those associated with fuel combustion, heat transfer in the steam generator and air heaters, radiative heat transfer from the generator surface, and others. Under steady flow conditions and assuming that changes in kinetic and potential energies are negligible, the various availability and irreversibility terms can be expressed as follows.

Input Availability

Chemical availability of fuel at reference (ambient) condition a_f can be approximated as (3)

$$a_f = (LHV)_d[1.0438 + 0.0013\frac{H}{C} + 0.1083\frac{O}{C} + 0.0549\frac{N}{C}] + 6.740S \qquad (4)$$

where H/C, O/C, and N/C denote, respectively, the mass ratio of hydrogen to carbon, oxygen to carbon, and hitrogen to carbon. S is the mass fraction of sulfur in kg per kg of fuel, and $(LHV)_d$ the lower heating value for the fuel.

Availability with shaft work, a_{sh}, is

$$a_{sh} = \frac{\text{fan power} + \text{pump power} + \text{pulverizer power}}{\overset{o}{m}_f} \qquad (5)$$

where m_f is the fuel feed rate.

Exiting Availability

Availability exiting with refuse (assumed to be: unburnt fuel) a_{uc} , is approximated as

$$a_{uc} = (\dot{m}_{uc} / \dot{m}_f) \times (LHV)_{uc} \qquad (6)$$

where $\dot{m}_{uc}$ and $(LHV)_{uc}$ are the mass flow rate \and lower heating value of the unburnt fuel. Availability out with stack gases, a_{ge} , can be estimated by [4]

$$a_{ge} = (\dot{m}_a / \dot{m}_f + 1 - H)\, C_{pg} [T_{ge} - T_o - T_o \ln (T_{ge} / T_o)] + 9H [(h_{ve} - h_{wo}) - T_o (s_{ve} - s_{wo})] \qquad (7)$$

where $\dot{m}_a$ = mass flow rate of air,

H = mass of hydrogen in 1 kg of fuel,

C_{pg} = average specific heat of dry flue gas,

T_{ge} = exit flue gas temperature,

T_o = dead state or environment temperature,

h_{ve} = specific enthalpy of water vapor at T_{ge} ,

h_{wo} = specific enthalpy of water at T_o ,

s_{ve} = specific entropy of water vapor at T_{ge} ,

s_{wo} = specific entropy of water at T_o.

Availability out with steam flow, a_{se}, is given by

$$a_{se} = (\dot{m}_{se} / \dot{m}_f) [(h_{se} - h_{wo}) - T_o (s_{se} - s_{wo})] \qquad (8)$$

where the subscript se denotes exiting steam condition.

Irreversibilities

Irreversibility due to the conversion of chemical energy to heat in the combustion process, i_c , is estimated by [5]

$$i_c = (\dot{m}_s / \dot{m}_f) (h_{se} - h_{wi}) (T_o / T_{ac}) \qquad (9)$$

where T_{ac} is the adiabatic combustion temperature and h_{wi} is the enthalpy of entering feedwater.

Irreversibility due to beat transfer from combustion gas to working fluid (water) in the boiler, i_b, is given by

$$i_b = (\dot{m}_s / \dot{m}_f) T_o [(s_{se} - s_{wi}) - (h_{se} - h_{wi}) / T_{ac}] \qquad (10)$$

Irreversibility due to heat transfer in the air heaters (Fig.2) [6]

$$i_{bh} = (1/\dot{m}_f) [\dot{m}_g (a_{gi} - a_{ge}) - \dot{m}_g (a_{ai} - a_{ae})] \qquad (11)$$

where $a = (h - h_o) - T_o (s - s_o)$ is the flow availability per unit mass of the individual streams. The subscripts i and e refer to the inlet and exiting streams respectively, and a to air, g to gas.

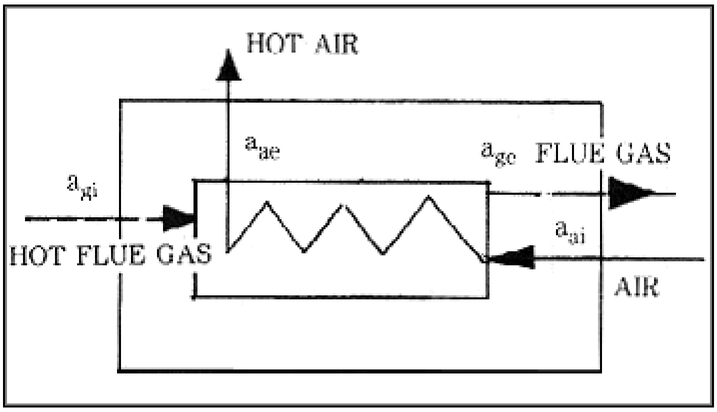


Fig. 2 Control volume of air heater (adiabatic)

Irreversibility (or loss) due to heat transfer to the surrounding, i_l, is given by

$$i_l = (1 - T_o / T_s)\, q_l \tag{12}$$

where q_l is the estimated heat loss from the generator surface in kJ per kg of fuel, and T_s is average surface temperature.

Second-law Efficiency

The second-law efficiency for the steam generator, ε_b, can be defined as

$$\varepsilon_b = (a_{se} - a_{wi})/(a_f + a_{sh}) \tag{13}$$

where

$$a_{wi} = (\dot{m}_{se} / \dot{m}_f)\,[(h_{wi} - h_{wo}) - T_o\,(s_{wi} - s_{wo})]$$

is the flow availability of the entering feedwater.

2.2 Steam Turbines

The control volume of a typical steam turbine is shown in Fig.3. It encompasses the turbine it self and the generator, with superheated steam as the inlet stream, steam extraction at various points for feedwater heating and deaerating, and steam exhaust to the condenser.

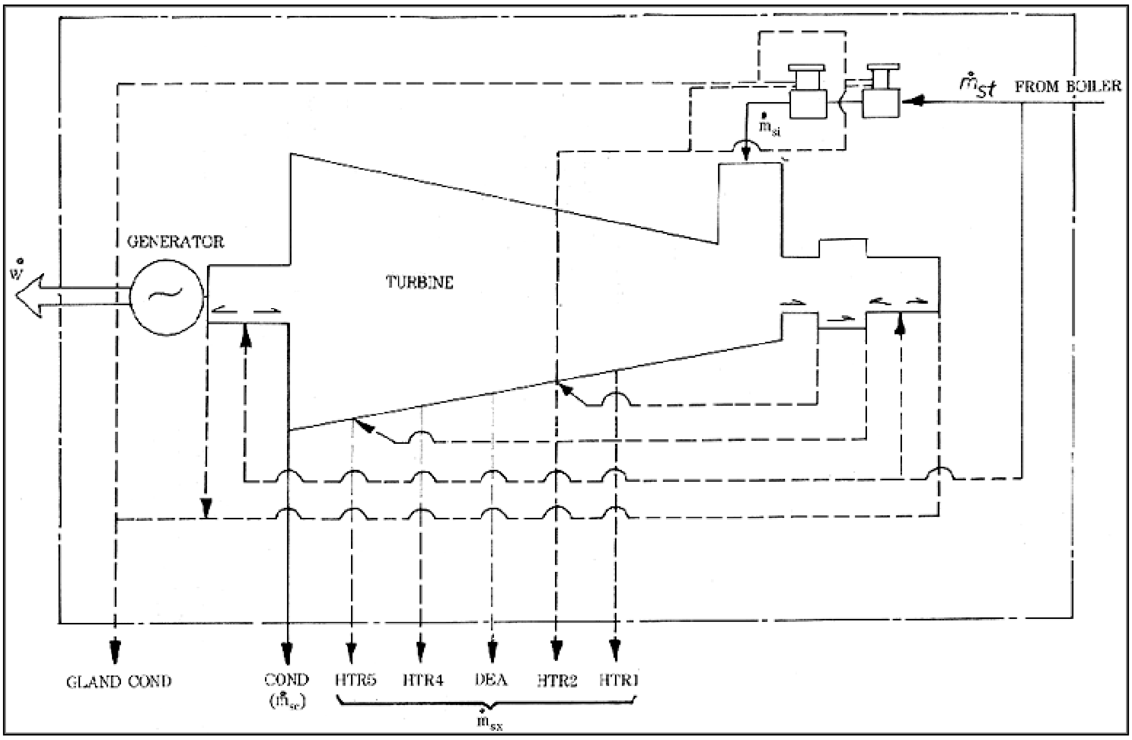


Fig. 3 Control volume of steam turbine

(HTR = Heater, DEA = Deaerator, COND = Condenser)

2.2.1 Energy Analysis

The "heat rate" of a steam turbine [2], hr_t, is defined as the "heat" consumption per hour per unit output, and is expressed in kJ/kWh as

$$hr_t = (\dot{m}_{st} h_{st} + \dot{m}_{sej} h_{sej} - \dot{m}_{wi} h_{wi}) / W \tag{14}$$

where the subscripts st, sej, wi denote, respectively, the steam entering the turbine unit, steam to ejector, feedwater entering the boiler. W is the power output of the generator.

2.2.2 Availability Analysis

Availability analysis of the steam turbine requires the determination of intet steam flow availability, availability exiting (losses) with steam extracted to heaters and that exhausted to the condenser, and irreversibilities within the turbo-generator.

Inlet Steam Flow Availability, a_{si}

$$a_{si} = (\dot{m}_{si} / \dot{m}_f) [(h_{si} - h_{wo}) - T_o (s_{si} - s_{wo})] \tag{15}$$

where the subscript si denotes the condition of the steam at the turbine inlet.

Exiting Availability

Availability out with steam exhaust to the condenser, a_{sc},

$$a_{sc} = (\dot{m}_{sc} / \dot{m}_f) [(h_{sc} - h_{wo}) - T_o (s_{sc} - s_{wo})] \tag{16}$$

Availability out with steam extracted to feedwater heaters and deaerators, a_{sx},

$$a_{sx} = (1 / \dot{m}_f) \, \dot{m}_{sx} [(h_{sx} - h_{wo}) - T_o (s_{sx} - s_{wo})] \tag{17}$$

Irreversibility, i_t

$$i_t = a_{si} - (a_{sc} + a_{sx}) - \dot{W}/\dot{m}_f \tag{18}$$

where $\dot{W}/\dot{m}_f$ is the work output.

Second-law efficiencies

Adiabatic turbine efficiency, η_t

$$\eta_t = (h_{si} - h_{sc}) / (h_{si} - h_{sc}) \tag{19}$$

where sc' refers to the turbine exit condition for an isentropic process.

Second-law efficiency based on availability, ε_t

$$\varepsilon_t = \frac{\text{work output}}{\text{input flow availability}} = \frac{\dot{W}/\dot{m}_f}{a_{si}} \tag{20}$$

2.3 Overall Plant Performance

First-law cycle efficiency, η_p

$$\eta_p = \frac{3600}{(hr_t / \eta_b)} \tag{21}$$

Second-law cycle efficiency, ε_p

$$\varepsilon_p = \frac{\text{work output}}{\text{input availability}} = \frac{\dot{W}/\dot{m}_f}{a_f + a_{sh}} \tag{22}$$

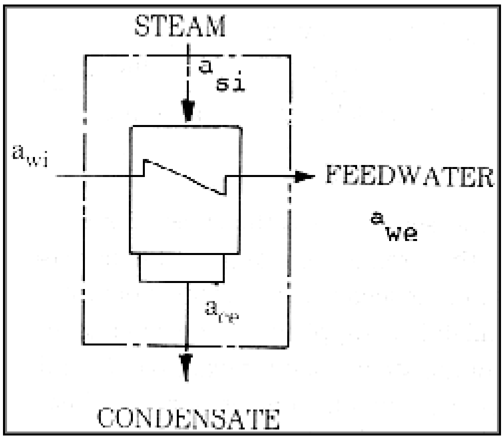
2.4 Heat Exchangers

In defining the second-law efficiencies for heat exchangers, the product is taken as the increase in availability of the feedwater and for condensate and the availability supplied as the change in availability of the steam (see for example [5] and [6].

The second-law efficiencies for the heat exchanges shown in Fig. 4 which are commonly encountered as auxiliary equipment for steam turbines can then be expressed as follows.

Non-mixing heat exchangers (Fig. 4 (a)) :

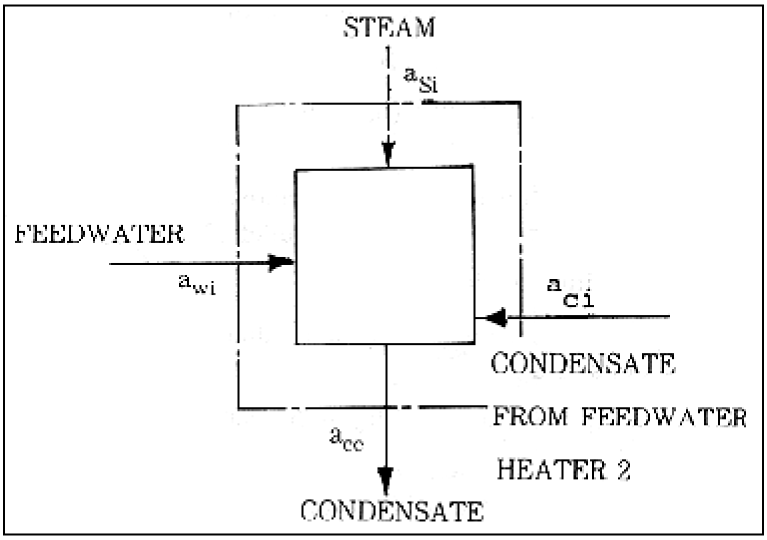
$$\varepsilon_{nx} = \frac{\dot{m}_w (a_{we} - a_{wi})}{\dot{m}_s (a_{si} - a_{ce})} \tag{23}$$



(a) Feedwater heaters 1 & 4

Mixing heat exchangers (deaerator) (Fig. 4 (b))

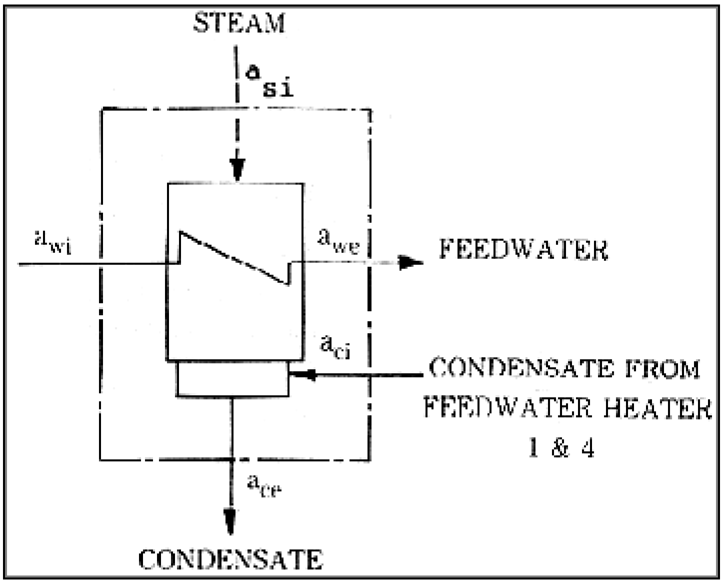
$$\varepsilon_{mx} = \frac{\dot{m}_w (a_{ce} - a_{wi}) + \dot{m}_c (a_{ce} - a_{ci})}{\dot{m}_s (a_{si} - a_{ce})} \qquad (24)$$



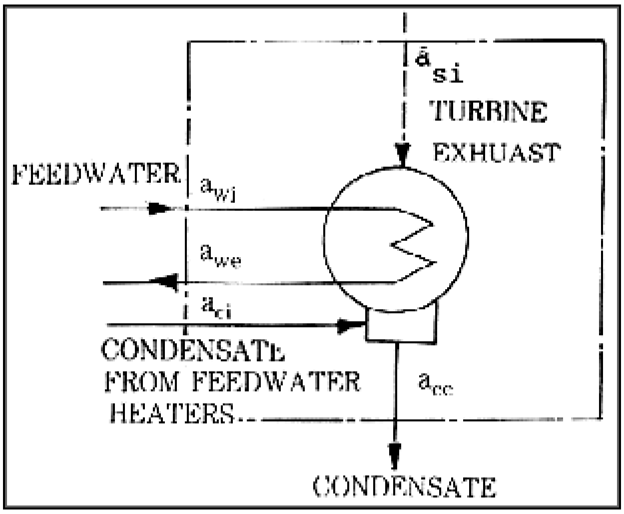
(b) Deaerator

For combined heat exchangers (both mixing and non-mixing streams present)(Fig .4 (c) and (d)):

$$\varepsilon_{cx} = \frac{\dot{m}_w (a_{we} - a_{wi}) + \dot{m}_c (a_{ce} - a_{ci})}{\dot{m}_s (a_{si} - a_{ce})} \qquad (25)$$



(c) Feedwater heaters 2 & 5



(d) Condenser

3. PROGRAM STRUCTURE

The program is written in Turbo Pascal Version 5.0 171 and can be run on any IBM-PC or compatible. It is divided into two main programs one for steam generator ('BCAL') and the other for steam turbine ('TCAL'), which can be run separately with data being transferable between them. For each program there is a choice for performing either energy analysis only or combined energy and availability analyses. The general Organisation of the programs are shown in Fig. 5.

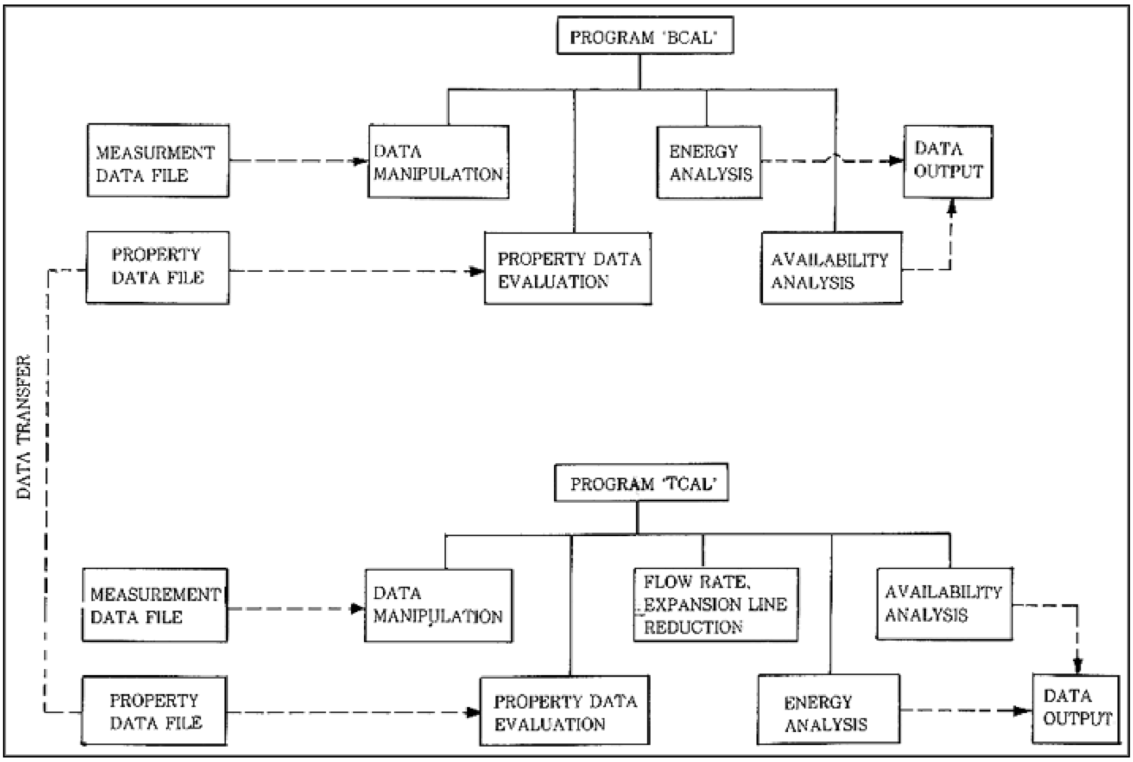


Fig. 5 Program organisation

Program BCAL consists of four major 'modules' (or 'units'), each with its own 'procedures' and 'functions'. A data manipulation module accepts data entries from the keyboard and stores them in a data file. A data editing option is also provided. A very important feature of the program is the facility to evalute all the property data in the temperature and pressure ranges required for the performance analysis of thermal power plants. These data, which include the steam table [8], specific heat of air and flue gas [5], and moisture content in air [9], are stored in equation form in the property data file. Energy and availability analyses are carried out in separate modules with the results printed out on a hard copy. Procedures are also provided for adjusting the calculated results back to the base line operating conditions under which the performances are gauranteed by the contractors. Program TCAL operates in much the same fashion as BCAL except for two additional major features, one for steam and condensate flow rates reduction and the other for determining the expansion line of the steam in passing through the turbine.

4. APPLICATION

A case study was carried out to validate the program by using the measurement data obtained for EGAT's Mae Moh Power Plant Unit I during one of its performance evaluation tests. The steam generator unit, manufactured by Babcock & Wilcox Canada Ltd., is designed primarily for burning pulverized lignite. The unit is of the one drum, natural circulation, radiant type, with a fully water-cooled furnace, two stage superheater, convection section and air heaters (Fig. 1). The steam turbine is of the combination impulse and reaction type with a rated capacity of 75 MW at 3000 rpm. At design conditions, the steam inlet pressure is 100 bar, the temperature 510 °C, and exhaust steam pressure is 0. 1 bar. Steam is extracted for five stages of feedwater heating (Fig. 3).

The results of the calculations for 100% plant load conditions are summarized in Table 1. for the steam generating unit, the energy efficiency is 88.6%. The energy losses are due mainly to the energy carried out with flue gas (8.4%). These figures are in exact agreement with those obtained by EGAT's consultants [10]. The second- law efficiency of the unit is 42.7%, with irreversibilities in the combustion unit as the main source of availability destruction (45. 1 %). Based on an estimated adiabatic combustion temperature, these irreversibilities could be attributed to the combustion process (13.5%) and the heat transfer from the hot combustion gas to the working fluid in the generator. Irreversibility in the air preheaters accounts for 3. 1 %. Availability losses are considered minor with 2.7% loss through flue gas, 0.3% through unburnt fuel, 0.2% through heat loss from the generator surface, and 5.8% unaccounted for.

For the steam turbine, the "heat rate" or energy consumption per unit output is 9,226.8 kJ/kWh. The adiabatic efficiency (not shown in the table) is 98.3%. The second-law efficiency based on availability analysis is found to be 69.8%. Availability losses accounted for 23.1%, 16.9% being the availability associated with the steam extracted to the feedwater heaters and 6.2% with the steam exhausted to the condenser. The over all cycle efficiencies based on the first and second laws are, respectively, 34.5% and 32.6%. The above figures are considered typical for thermal power plants (see for example [6]).

Analyses was also carried out for the various feed- water heaters and the condenser. The results in Table I indicate very high first-law efficiencies. Availability destruction is obviously due to heat transfer irreversibility in the heat exchangers, with that in the condenser being the most significant.

Table 1 Summary of Energy and Availability Analyses

STEAM GENERATOR		
	KJ/kg fuel	% Input
Energy Input	12,955.0	100.0
Chemical energy in fuel	12,854.1	99.2
Sensible energy in fuel	100.9	0.8
Energy Loss	1,476.4	11.4
Unburnt fuel	38.6	0.3
Moisture in air	39.6	0.3
Moisture in fuel	128.6	1.0
Flue gas	1,094.4	8.4
Hydrogen in fuel	78.6	0.6
Heat loss in from surface	32.2	0.3
Others	64.4	0.5
Energy Efficiency	-	88.6

	KJ/kg fuel	% Input
A vailability Input	14,584.3	100.0
Chemical availability in fuel	14,486.6	99.3
Electrical work input	94.7	0.7
A vailability increase in steam	6,232.3	42.7
A vailability Losses	478.3	3.2
Flue gas	398.8	2.7
Unburnt fuel	43.4	0.3
Heat loss	36.2	0.2
Irreversibilities	7,033.9	48.2
Combustion process	1,973.5	13.5
Heat transfer in generator	4,606.2	31.6
Heat transfer in air heaters	454.2	3.1
Unaccounted	844.4	5.8

STEAM TURBINE

Heat Rate (kJ / kWh)	9,226.8	
A vailability in with Steam	6,810.6	100.0
Power Developed	4,756.7	69.8
A vailability	1,573.3	23.1
Exiting to condenser	424.5	6.2
Extracted to feedwater heaters	1,148.8	16.9
Irreversibility	480.6	7.1

PLANT CYCLE

First-law cycle efficiency	34.5
Second-low cycle Efficiency	32.6

HEATERS (HTR)

	HTR 1	HTR 2	HTR 4	HTR 5	Condenser
First-law Efficiency (%)	99.3	97.1	98.9	98.1	97.0
Second-low efficiency (%)	89.4	87.6	81.3	71.7	38.2

5. CONCLUSIONS

A computer program written in Turbo Pascal V. 5 for the IBM-PC can be used to expedite the performance evaluation process of a thermal power plant based on the first and second law analyses. The addition of second law analysis to this process enables the program user to assess more accurately the performance of the major plant components relative to the results of previous tests and to that of Re devices in other, similar or otherwise, plant units. This turn will enable an accurate evaluation to be made on the measures taken to improve plant efficiency. Although the present program still contains a number of the specificities of the Mae Moh plants, it can be applied to other plants with minor modifications.

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