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Effect of varying dead-state properties on energy and exergy analyses of thermal systems

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Abstract

This study deals with the effects on the results of energy and exergy analyses of variations in dead-state properties, and involves two main tasks: (i) examination of the sensitivities of energy and exergy values to the choice of the dead-state properties and (ii) analysis of the sensitivities of the results of energy and exergy analyses of complex systems to the choice of dead-state properties. A case study of a coal-fired electrical generating station is considered to illustrate the actual influences. The results indicate that the sensitivities of energy and exergy values and the results of energy and exergy analyses to reasonable variations in dead-state properties are sufficiently small that the findings, conclusions and recommendations based on such analyses usually are not significantly affected by the property variations.

Keywords: Dead state; Energy; Exergy; Thermal system

1. Introduction

Exergy analysis is a methodology for the evaluation of the performance of devices and processes, and involves examining the exergy at different points in a series of energy conversion steps. With this information, efficiencies which are a measure of an approach to the ideal can be evaluated, and the process steps having the largest losses (i.e., the greatest margin for improvement) can be identified. Exergy is defined as the maximum work which could be produced by a stream or system in a specified environment, or with respect to a dead state. Although the basic concepts related to exergy analysis were formulated around the mid-to-late 1800s, most developments in the area of practical application have occurred during the past few decades [1–9]. At present, exergy analysis is gaining widespread acceptance in many communities. In the last decade, many researchers, e.g., [10–16] have recommended that exergy analysis be used to aid decision making regarding the allocation of resources (capital, research and development effort, optimization, life cycle analysis, materials, etc.) in place of or in addition to energy analysis.

Exergy is a measure of the maximum capacity of a system to perform useful work as it proceeds to a specified final state in equilibrium with its surroundings. The available work that can be extracted from an energy source depends on the state of the source's surroundings. The greater the difference between the energy source and its surroundings, the greater the capacity to extract work from the system.

Some energy and exergy values are dependent on the intensive properties of the dead state. Consequently the results of energy and exergy analyses generally are sensitive to variations in these properties. Before energy and exergy analyses can be applied with confidence to engineering systems, the significance of the sensitivities of energy- and exergy-analysis results to reasonable variations in dead-state properties must be assessed. Only very brief discussions of these sensitivities have been reported. For example, Wepfer and Gaggioli [11] have pointed out that exergy analyses of chemical plants are often relatively insensitive to variations in T_o and P_o. Many have assumed that small and reasonable changes in dead-state properties have little effect on the performance of a given system. In a study focussed on aerospace applications, one of the authors examined the impact on exergy analysis results of variations in dead-state properties at increasing altitudes in the atmosphere [17].

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Nomenclature

c_p	specific heat at constant pressure
h	specific enthalpy; specific base enthalpy
H	enthalpy; base enthalpy
I	irreversibility or exergy consumption
KE	kinetic energy
N	moles
NGS	Nanticoke Generating Station
P	absolute pressure
PE	potential energy
Q	heat interaction
R	universal gas constant
R_{energy}	net station condenser energy (heat) rejection rate
R_{exergy}	net station condenser exergy rejection rate
s	specific entropy
S	entropy
t	time
T	temperature
V	volume
W	total work done by a system
W_{NET}	net useful work done by a system due to change in its volume
W_x	shaft work
X	a variable in Eq. (10) representing a dead-state property
Y	a variable in Eq. (10) representing either energy or exergy

Greek symbols

B	exergy function, $= H - T_0 S$
ε	exergy
ε^Q	thermal exergy transfer
η	energy efficiency
μ	chemical potential
Π	entropy production
σ	sensitivity
ψ	exergy efficiency

Subscripts

i	ith constituent
kin	kinetic component
o	environmental state; chemical exergy
oo	dead state
ph	physical component
pot	potential component

Superscript

$\cdot$	rate with respect to time

To the best of the authors' knowledge, however, no other detailed examinations of these sensitivities have appeared in the literature. The authors believe that one requirement for continued acceptance of exergy analysis is that the effects on the results of exergy analyses of variations in dead-state properties be fully examined and understood.

Recall that the exergy of a system is the maximum amount of work that can be obtained from the system. In order to quantify the exergy of a system, we must specify both the system and the surroundings. The *exergy reference environment* is used to standardize the quantification of exergy. The exergy reference environment or simply the environment is assumed to be a large, simple compressible system. The temperature of the environment is assumed to be uniform at T_o, and the pressure is assumed to be uniform at P_o. Also, it is assumed that the intensive properties of the environment are not significantly changed by any process.

The dead state is normally selected to be as similar to the accessible natural environment as possible. Usually P_o and T_o are selected to be 100 kPa and $273.15\ \text{K} \leqslant T_o \leqslant 323.15\ \text{K}$, and the chemical composition is taken to be similar to that of the accessible region of the crust of the earth.

The primary objective of this paper is to examine the sensitivities to reasonable variations in dead-state properties of several energy and exergy values, and the results of energy and exergy analyses of a complex device. Through this work, it is demonstrated that the main results of energy and exergy analyses are usually not significantly sensitive to reasonable variations in dead-state properties, even though energy and exergy values are dependent on these properties.

2. Modeling

A key discussion of the relevant theory of exergy analysis is presented here. Further information and discussion may be found elsewhere, e.g., [18,19].

Exergy is evaluated with respect to a reference environment. The reference environment acts as an infinite system, and is a sink and source for heat and materials. It experiences only internally reversible processes in which its intensive state remains unaltered (i.e., its temperature T_o, pressure P_o and the chemical potentials, μ_{ioo}, for each of the i components present remain constant).

The dead state is a state of a system in which it is at equilibrium with its surroundings. When a system is at the same temperature, pressure, elevation, velocity and chemical composition as its surroundings, there is no opportunity to construct a heat engine or other device to extract work, to operate a piston, to raise a weight or turn a turbine. No potential differences exist in such instances that would allow the extraction of useful work.

The exergy of a stream or system is zero when it is in equilibrium with the reference environment. The reference environment is in stable equilibrium. All parts are at rest relative to one another. The exergy associated with shaft work W_x is by definition W_x. The term “shaft work” includes all forms of work that can be used to raise a weight (i.e., mechanical work, electrical work, etc.) net of any work done by a system due to change its volume. The exergy transfer associated with work done by a system due to volume change is the net usable work due to the volume change, and is denoted by W_{NET}. Thus for a process in time interval t_1 to t_2,

$$W_{\mathrm{NET}} = W - P_o(V_2 - V_1) \tag{1}$$

where W is the work done by the system due to volume change $(V_2 - V_1)$. $P_o(V_2 - V_1)$ is the displacement work necessary to change the volume against the constant pressure P_o exerted by the environment.

The flow of exergy associated with heat transfer Q at a constant temperature T is

$$\varepsilon^{\mathrm{Q}} = (1 - T_o/T)Q \tag{2}$$

The exergy of a flowing stream of matter, ε, is

$$\varepsilon = \varepsilon_{\mathrm{ph}} + \varepsilon_o + \varepsilon_{\mathrm{kin}} + \varepsilon_{\mathrm{pot}} \tag{3}$$

where

$$\varepsilon_{\mathrm{pot}} = PE \tag{4}$$

$$\varepsilon_{\mathrm{kin}} = KE \tag{5}$$

$$\varepsilon_o = \Xi_o = \sum_i (\mu_{io} - \mu_{ioo})N_i \tag{6}$$

$$\varepsilon_{\mathrm{ph}} = B - B_o \tag{7}$$

and where the flow exergy function, B, is defined as

$$B = H - T_oS \tag{8}$$

The terms on the right side of Eq. (3) represent respectively the physical, chemical, kinetic and potential components of the exergy of a flowing stream of matter.

The exergy consumption, I, is the difference between the useful work obtainable from reversible and irreversible processes, and is given by

$$I = T_o\Pi \tag{9}$$

2.1. *Sensitivities of several energy and exergy values to variations in dead-state properties*

For the present investigations, the authors define the sensitivity σ of a general quantity Y to a variation ΔX in a quantity X as follows:

$$\sigma = \frac{Y(X + \Delta X) - Y(X)}{Y(X)} \tag{10}$$

where σ is a non-dimensional measure of the fractional change in Y due to a perturbation ΔX in X. For the present discussions, Y represents energy or exergy, and X a dead-state property.

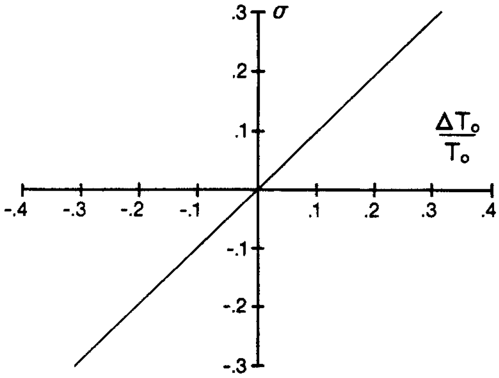

Fig. 1. Variation of sensitivity of exergy consumption (irreversibility), I, with T_o.

Exergy consumption

The only dead-state property on which exergy consumption, I $(= T_o\Pi)$, and exergy-consumption rate $\dot{I}$ $(= T_o\dot{\Pi})$, are dependent is T_o. The sensitivity of I to a variation in T_o is given by Eq. (10) with $Y = I$ and $X = T_o$:

$$\sigma = \frac{(T_o + \Delta T_o)\Pi - T_o\Pi}{T_o\Pi} = \frac{\Delta T_o}{T_o} \tag{11}$$

Similarly for $\dot{I}$, $\sigma = \Delta T_o/T_o$. Fig. 1 plots σ for I against $\Delta T_o/T_o$. A variation in T_o causes a proportional variation in I. For the narrow range of T_o values normally used, the sensitivity of I to variations in T_o is relatively insignificant.

Energy and exergy of work

The energy and exergy values associated with shaft work, W_x and the work done by a system due to volume change, W, are independent of dead-state properties. (The net usable work, W_{NET}, due to volume change is dependent on P_o.)

Thermal energy and thermal exergy

Values of thermal energy, Q, are independent of the dead state, while values of thermal exergy, $\varepsilon^{\mathrm{Q}} = (1 - T_o/T)Q$, and thermal exergy flow rate, $\dot{\varepsilon}^{\mathrm{Q}} = (1 - T_o/T)\dot{Q}$, are dependent only on T_o. The sensitivity of ε^{Q} to a variation in T_o is given by Eq. (10) with $Y = \varepsilon^{\mathrm{Q}}$ and $X = T_o$:

$$\sigma = \frac{Q[1 - (T_o + \Delta T_o)/T] - Q[1 - T_o/T]}{Q[1 - T_o/T]} = \frac{\Delta T_o}{T_o - T} \tag{12}$$

Similarly for $\dot{\varepsilon}^{\mathrm{Q}}$, $\sigma = \Delta T_o/(T_o - T)$. Fig. 2 plots σ for ε^{Q} against $\Delta T_o/T_o$ for a range of T/T_o values. σ is small when ε^{Q} is large (i.e., $T \ll T_o$ or $T \gg T_o$), and large when ε^{Q} is small (i.e., T is near T_o). However the large sensitivity when $T \cong T_o$ is normally not significant because of the small magnitude of ε^{Q}.

Physical energy and physical exergy

The physical energy and exergy associated with flowing streams of matter are generally dependent on T_o and P_o. The sensitivities are examined here for two common flows: an ideal gas and water.

For an ideal gas,

$$h - h_o = c_p(T - T_o) \tag{13}$$

and

$$s - s_o = c_p \ln(T/T_o) - R \ln(P/P_o) \tag{14}$$

where specific heats are assumed to be constant. Thus,

$$\begin{aligned} \varepsilon_{ph} &= h - h_o - T_o(s - s_o) \\ &= c_p\big[T - T_o - T_o \ln(T/T_o)\big] - R\ln(P/P_o) \end{aligned} \tag{15}$$

The term $h - h_o$ can be thought of as the specific physical energy associated with a flowing stream of matter. For an ideal gas, $h - h_o$ is dependent only on T_o, and the sensitivity of $h - h_o$ to a variation in T_o is given by Eq. (10) with $Y = h - h_o$ and $X = T_o$:

$$\sigma = \frac{c_p(T - T_o - \Delta T_o) - c_p(T - T_o)}{c_p(T - T_o)} = \frac{\Delta T_o}{T_o - T} \tag{16}$$

A comparison of Eqs. (16) and (12) reveals that $h - h_o$ for an ideal gas and ε^Q are equally sensitive to variations in T_o.

The sensitivity of ε_{ph}, for $P = P_o$, to a variation in T_o is given by Eq. (10) with $Y = \varepsilon_{ph}$ and $X = T_o$:

$$\begin{aligned} \sigma &= \big\{c_p\big[T - T_o - \Delta T_o - (T_o + \Delta T_o)\ln\big(T/(T_o + \Delta T_o)\big)\big] \\ &\quad - c_p\big[T - T_o - T_o\ln(T/T_o)\big]\big\} \\ &\quad \times \big\{c_p\big[T - T_o - T_o\ln(T/T_o)\big]\big\}^{-1} \\ &= \frac{T_o \ln(1 + \Delta T_o/T_o) - \Delta T_o(1 + \ln(T/T_o + \Delta T_o))}{T - T_o - T_o\ln(T/T_o)} \\ &= \frac{\ln(1 + \Delta T_o') - \Delta T_o'[1 + \ln(T'/(1 + \Delta T_o'))]}{T' - 1 - \ln T'} \end{aligned} \tag{17}$$

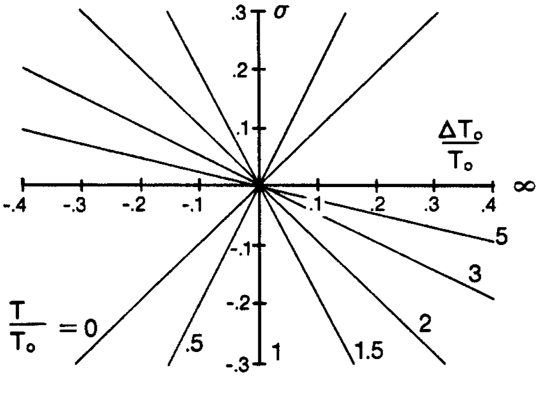

Fig. 2. Variation of thermal exergy, ε^Q, with T_o for a range of T/T_o values.

where $\Delta T_o' \equiv \Delta T_o/T_o$ and $T' \equiv T/T_o$. The sensitivity of ε_{ph}, for $T = T_o$, to a variation in P_o is given by Eq. (10) with $Y = \varepsilon_{ph}$ and $X = P_o$:

$$\begin{aligned} \sigma &= \frac{-R\ln P/(P_o + \Delta P_o) + R\ln(P/P_o)}{-R\ln(P/P_o)} \\ &= \frac{\ln(1 + \Delta P_o/P_o)}{\ln(P_o/P)} \end{aligned} \tag{18}$$

Eqs. (17) and (18) indicate that the sensitivity of ε_{ph} to variations in T_o and P_o is small when ε_{ph} is large, and large when ε_{ph} is small.

For flowing streams of liquid and vapor water, the values of $h - h_o$ and ε_{ph} depend on both T_o and P_o. The values of $h - h_o$ and ε_{ph} for several conditions for reasonable variations in T_o and P_o are presented in Table 1. The values were generated with the EXCEM code, a code for the simulation and analysis of engineering systems [18,20,21]. The values generated by the code for the present analysis were based on properties of water contained in the ASME Steam Tables. The reference values used for T_o and P_o were 298.15 K and 101 kPa, respectively, and variations considered were ±10 K and ±20 K for T_o, and ±5 kPa and ±10 kPa for P_o. Water in the liquid phase was taken to be the stable form in the environment. The sensitivities of $h - h_o$ and ε_{ph} to the larger variations in T_o and P_o were evaluated using Eq. (10) with $Y = h - h_o$ and $Y = \varepsilon_{ph}$, and $X = T_o$ or $X = P_o$, and are plotted for selected cases in Fig. 3. The sensitivities are small except when the magnitudes of $h - h_o$ and ε_{ph} are small (i.e., the stream is near T_o and P_o).

Chemical exergy and base enthalpy

The sensitivities of values of chemical exergy and base enthalpy to variations in dead-state properties are not examined in depth in this paper. However, in order to provide some insights into these sensitivities and to indicate the need for further examination of them, several points are discussed.

For several chemical species, Table 2 lists specific chemical exergies evaluated by several researchers relative to the range of chemical reference environments they propose. For

Table 1
Values of ε_{ph} (in kJ·kg^{-1}) for water at several states for a range of T_o values and for $P_o = 0.101$ MPa

State of water			T_o [°C]				
T [°C]	P [MPa]	Phase	5.0	15.0	25.0	35.0	45.0
25.0	0.101	liquid	2.87	0.71	0.0	0.69	2.74
25.0	0.0032	vapor	166.5	82.4	−0.19	−81.4	−161.3
99.9	0.101	vapor	629.6	557.6	487.0	417.8	349.9
5.0	0.101	liquid	0.0	0.75	2.94	6.54	11.50
300.0	8.00	vapor	1175.0	1119.0	1064.0	1010.0	958.0
500.0	5.00	vapor	1493.0	1425.0	1358.0	1293.0	1228.0
600.0	10.0	vapor	1703.0	1636.0	1569.0	1505.0	1442.0
1000.0	100.0	liquid	1667.0	1617.0	1659.0	1523.0	1478.0

Table 1(b)
Values of ε_{ph} (in kJ·kg^{-1}) for water at several states for a range of P_o values and for $T_o = 25.0\,^\circ$C

State of water			P_o [MPa]				
T [°C]	P [MPa]	Phase	0.091	0.096	0.101	0.106	0.111
25.0	0.101	liquid	0.013	0.006	0.0	−0.006	−0.013
25.0	0.0032	vapor	−0.180	−0.187	−0.193	−0.199	−0.206
99.9	0.101	vapor	486.98	486.97	486.96	486.96	486.95
5.0	0.101	liquid	2.96	2.95	2.94	2.94	2.93
300.0	8.00	vapor	1063.74	1063.73	1063.73	1063.72	1063.71
500.0	5.00	vapor	1357.92	1357.90	1357.90	1357.89	1357.89
600.0	10.0	vapor	1569.49	1569.48	1569.48	1569.47	1569.46
1000.0	100.0	liquid	1569.26	1569.25	1569.24	1569.24	1569.23

Table 1(c)
Values of $h - h_o$ (in kJ·kg^{-1}) for water at several states for a range of T_o values and for $P_o = 0.101$ MPa

State of water			T_o [°C]				
T [°C]	P [MPa]	Phase	5.0	15.0	25.0	35.0	45.0
25.0	0.101	liquid	83.7	41.8	0.0	−41.8	−83.2
25.0	0.0032	vapor	2526.0	2484.0	2442.0	2400.0	2358.0
99.9	0.101	vapor	2654.0	2612.0	2571.0	2529.0	2487.0
5.0	0.101	liquid	0.0	−41.9	−83.7	−125.5	−167.3
300.0	8.00	vapor	2765.0	2723.0	2681.0	2640.0	2598.0
500.0	5.00	vapor	3412.0	3370.0	3328.0	3327.0	3245.0
600.0	10.0	vapor	3601.0	3559.0	3517.0	3475.0	3434.0
1000.0	100.0	liquid	3060.0	3018.0	2977.0	2935.0	2893.0

Table 1(d)
Values of $h - h_o$ (in kJ·kg^{-1}) for water at several states for a range of P_o values and for $T_o = 25.0\,^\circ$C

State of water			P_o [MPa]				
T [°C]	P [MPa]	Phase	0.091	0.096	0.101	0.106	0.111
25.0	0.101	liquid	0.009	0.005	0.0	−0.005	0.009
25.0	0.0032	vapor	2442.02	2442.01	2442.01	2442.00	2442.00
99.9	0.101	vapor	2570.56	2570.56	2570.55	2570.55	2570.54
5.0	0.101	liquid	−83.73	−83.73	−83.74	−83.74	−83.75
300.0	8.00	vapor	2681.46	2681.46	2681.45	2681.45	2681.44
500.0	5.00	vapor	3328.24	3328.24	3328.23	3328.23	3328.23
600.0	10.0	vapor	3517.24	3517.24	3517.23	3517.23	3517.22
1000.0	100.0	liquid	2976.69	2976.68	2976.68	2976.67	2976.67

Table 2
Specific chemical exergies (in kJ·g^{-1}·mol^{-1}) proposed by various researchers for selected species[*]

Species	Gaggioli and Petit	Baehr and Schmidt	Szargut	Wadsley	Ahrendts	Sussman
O_2 (g)	3.947	3.953	3.973	3.914	3.951	0.0
N_2 (g)	0.691	0.692	0.718	0.6524	0.639	0.0
CO_2 (g)	20.108	20.108	20.189	19.91	14.174	0.0
H_2O (g)	8.668	8.595	11.758	10.31	8.636	8.593
H_2O (l)	0.0	0.0	3.168	1.716	0.045	0.0
SO_2(g)	287.6	–	304.3	301.5	240.633	0.0
C (s)	411	411	411	41.04	405	394.4
H_2 (g)	235	235	238	237	235	237.2
H_2S (g)	795	–	805	801.5	800	–
CH_4 (g)	830	830	837	833.5	824	818
C_7H_{16} (g)	4759	4757	4783	4776	4716	4667
CH_3OH (l)	717	717	723	720	711	702.2
NH_3 (g)	337	336	340	339.3	337	339.4

[*] Compiled from data in Wadsley [37]. Values are for $T_o = 298.15$ K and $P_o = 0.101$ MPa.

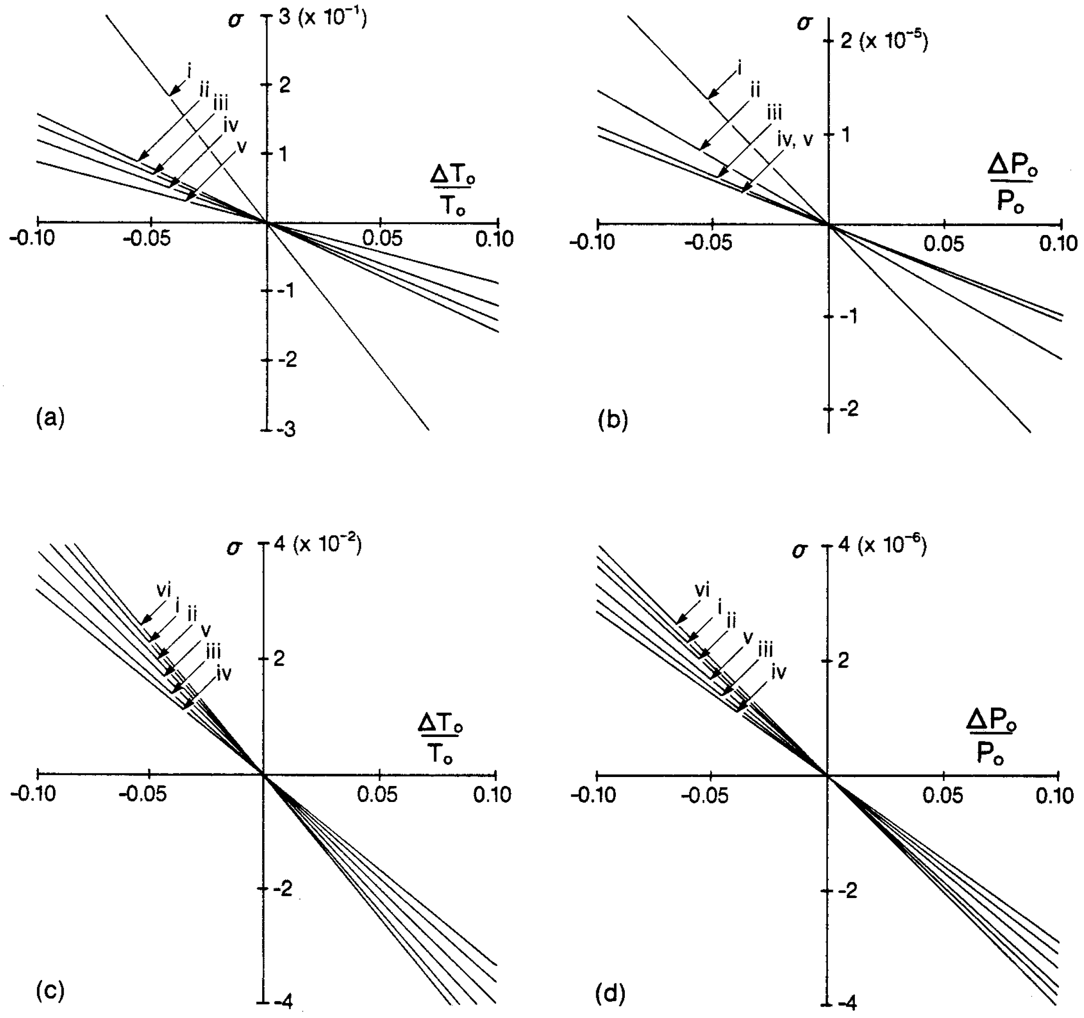

Fig. 3. Variations of sensitivities of specific physical energy and exergy values for water at several states with T_0 and P_0 values. States of water considered are: 0.101 MPa and saturated as indicated by (i), 300 °C and 8 MPa (ii), 500 °C and 5 MPa (iii), 600 °C and 10 MPa (iv), 1000 °C and 100 MPa (v), and 25.0 °C and 0.101 MPa (vi). (a) For $Y = \varepsilon_{\text{ph}}$ and $X = T_0$; (b) for $Y = \varepsilon_{\text{ph}}$ and $X = P_0$; (c) for $Y = h - h_0$ and $X = T_0$; and (d) for $Y = h - h_0$ and $X = P_0$.

reference environments which approximately simulate the "accessible" natural environment (those of Gaggioli and Petit, Baehr and Schmidt, Szargut, and Wadsley), chemical exergies normally vary by less than 10% for any species. For reference environments which do not simulate the environment (those of Ahrendts and Sussman), chemical exergies can vary significantly.

When simulating different natural environments, chemical exergies for most substances normally do not vary greatly. For a gaseous mixture of N_2, O_2, CO_2, CO, H_2O and SO_2, for example, the chemical exergy evaluated by Wepfer [22] relative to a reference environment having $T_0 = 298.15$, $P_0 = 101$ kPa and a composition typical of a desert region was shown to be 6.7% higher than that evaluated to a reference environment having the same temperature and pressure and a composition typical of a moderate-climate region. The effects of such a difference on plant performance mayor may not be significant.

Enthalpies evaluated relative to the stable components of the exergy-analysis reference environment are referred to here as "base enthalpies". Base enthalpies are often used so that the results from energy and exergy analyses can be logically compared. Since values of base enthalpy are similar to values of chemical exergy for many species, it can be expected that, like chemical exergies, base enthalpies are not strongly sensitive to reasonable variations in the reference chemical environment.

3. Case study

3.1. Sensitivities of energy- and exergy-analysis results for a coal-fired electrical generating station to variations in dead-state temperature

Since energy and exergy values normally are not significantly sensitive to reasonable variations in dead-state properties (except when the values are small), it is expected that the main results (i.e., findings, conclusions and recommendations) of energy and exergy analyses generally are not sig-

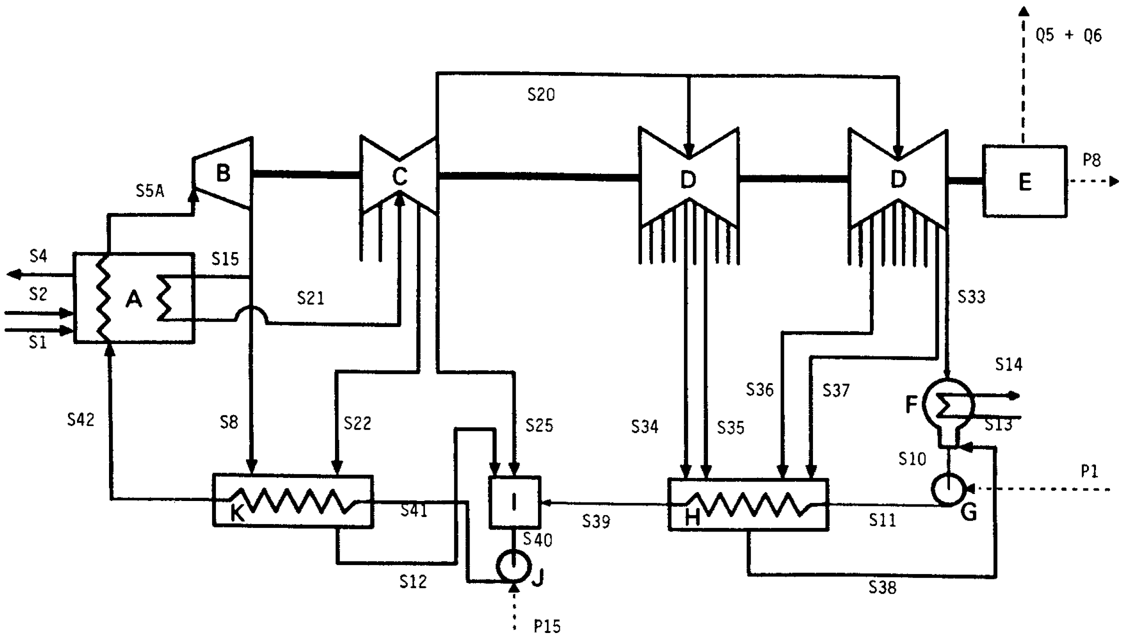

Fig. 4. Process flowsheet for a single unit of NGS. Lines exiting turbines represent flows of extraction steam. Devices are identified as A: steam generator and reheater, B: high-pressure turbine, C: intermediate-pressure turbine, D: low-pressure turbines, E: generator and transformer, F: condenser, G: hot well pump, H: low-pressure heat exchangers, I: open deaerating heat exchanger, J: boiler feed pump, K: high-pressure heat exchangers.

nificantly sensitive to variations in these properties. This idea is demonstrated by the authors for a complex device, the coal-fired Nanticoke Generating Station (NGS).

Process description

The individual units of NGS each have net outputs of approximately 500 MWe. A substantial base of operating data has been obtained for NGS, which has been operating since 1981. A detailed flow diagram for a single unit of NGS is shown in Fig. 4. The symbols identifying the streams are described in Table 3. The main process data are summarized below, and were compiled from data in Refs. [23–25].

Steam generators. Eight pulverized-coal-fired natural circulation steam generators each produce 453.6 kg·s^{-1} steam at 16.89 MPa and 538 °C, and 411.3 kg·s^{-1} of reheat steam at 4.00 MPa and 538 °C. Coal is consumed at full load at a rate of 47.9 kg·s^{-1}. Air is supplied to the furnace by two 1080 kW 600-rpm motor-driven forced draft fans. Regenerative air preheaters are used. The flue gas passes through an electrostatic precipitator rated at 99.5% collection efficiency, and exits the plant at 1200 °C through two multi-flued, 198 m high chimneys.

Turbine generators and transformers. The steam produced in the steam generators is passed through a series of turbine generators and a transformer. The net power output is 505 MW. Each unit has a 3600-rpm, tandem-compound, impulse-reaction turbine generator containing one single-flow high-pressure cylinder, one double-flow intermediate-pressure cylinder and two double-flow low-pressure cylinders. Steam exhausted from the high-pressure cylinder is reheated in the combustor. Extraction steam from several points on the turbines preheats feedwater in several low- and high-pressure heat exchangers and one spray-type open deaerating heat exchanger. The low-pressure turbines exhaust to the condenser at 5 kPa.

Condensers. Cooling water condenses the steam exhausted from the turbines. A flow rate of cooling water of 18.9 m^3·s^{-1} is used to achieve a temperature rise of 8.3 °C in the cooling water across the condenser.

Preheating heat exchangers and pumps. The temperature and pressure of the condensed steam are increased to 253 °C and 16.89 MPa in a series of pumps and heat exchangers.

Modelling, simulation and analysis

To simplify the modelling, simulation and analysis procedures, coal was modelled as pure graphite (C) and air as 79% nitrogen and 21% oxygen by volume. In addition, it was assumed that (i) the turbines have isentropic and mechanical efficiencies of 80% and 95%, respectively, and (ii) the generators and transformers are each 99% efficient and heat losses from the surfaces occur at 15 °C (i.e., T_0).

The EXCEM analysis code was developed by the authors for the simulation and analysis of engineering systems. The code is based on the EXCEM analysis methodology, which is described in Refs. [18,20,26]. EXCEM is an acronym for exergy, cost, energy and mass. The basic rationale underlying an EXCEM analysis is that an understanding of the performance of a system requires an examination of the flows of each of the quantities represented by EXCEM into, out of and at all points within a system. Of the quantities

Table 3
Stream data for unit in Nanticoke Generating Station

Stream	Flow rate* [kg·s^{-1}]	Temperature [°C]	Pressure [N·m^{-2}]	Vapor fraction	Energy (MW)	Exergy (MW)
S1	41.74*	15.00	1.01×10^5	SOLID	1367.58	1426.73
S2	668.41*	15.00	1.01×10^5	1.0	0.00	0.00
S3**	710.15*	1673.59	1.01×10^5	1.0	1368.00	982.85
S4	710.15*	119.44	1.01×10^5	1.0	74.39	62.27
S5A	453.59	538.00	1.62×10^7	1.0	1585.28	718.74
S8	42.84	323.36	3.65×10^6	1.0	135.44	51.81
S10	367.85	35.63	4.50×10^3	0.0	36.52	1.20
S11	367.85	35.73	1.00×10^6	0.0	37.09	1.70
S12	58.82	188.33	1.21×10^6	0.0	50.28	11.11
S13	18636.00	15.00	1.01×10^5	0.0	0.00	0.00
S14	18636.00	23.30	1.01×10^5	0.0	745.95	10.54
S15	410.75	323.36	3.65×10^6	1.0	1298.59	496.81
S20	367.85	360.50	1.03×10^6	1.0	1211.05	411.16
S21	410.75	538.00	4.00×10^6	1.0	1494.16	616.42
S22	15.98	423.23	1.72×10^6	1.0	54.54	20.02
S25	26.92	360.5	1.03×10^6	1.0	88.64	30.09
S33	309.62	35.63	4.50×10^3	0.93	774.70	54.07
S34	10.47	253.22	3.79×10^5	1.0	32.31	9.24
S35	23.88	209.93	2.41×10^5	1.0	71.73	18.82
S36	12.72	108.32	6.89×10^4	1.0	35.77	7.12
S37	11.16	60.47	3.45×10^4	1.0	30.40	5.03
S38	58.23	55.56	1.33×10^4	0.0	11.37	0.73
S39	367.85	124.86	1.00×10^6	0.0	195.94	30.41
S40	453.59	165.86	1.00×10^6	0.0	334.86	66.52
S41	453.59	169.28	1.62×10^7	0.0	347.05	77.57
S42	453.59	228.24	1.62×10^7	0.0	486.75	131.93
Q5					5.34	0.00
Q6					5.29	0.00
P1					0.57	0.57
P8					523.68	523.68
P15					12.19	12.19

* The composition of all streams is 100% H_2O, except for indicated streams. On a volume basis, the composition of S1 is 100% carbon, of S2 is 79% N_2 and 21% O_2, and of both S3 and S4 are 79% N_2, 6% O_2, 15% CO_2.

** S3 is not shown in Fig. 4. It represents the hot product gases for adiabatic combustion.

represented by EXCEM, only mass and energy are subject to conservation laws. Cost increases or remains constant, while exergy decreases or remains constant. Balances can be written for each of the EXCEM quantities. The EXCEM code was developed by enhancing a process-simulation code for EXCEM analysis. Aspen Plus, a state-of-the-art process simulator, was used as the foundation of the EXCEM code. The code development is detailed in Refs. [18,20,26]. The code has been used to analyze several engineering processes. Processes traditionally assciated with mechanical engineering (coal-fired and nuclear power generation), and processes more often associated with chemical engineering (hydrogen and hydrogen-derived fuel production) have been considered. These applications are reported elsewhere, e.g., [18,20,26–33].

The simulations and analyses were performed using the EXCEM code as mentioned above. The computer files used in the analyses are given in Appendix B of Rosen [16]. The reference-environment model used has the following characteristics: $T_o = 15\,^\circ\mathrm{C}$; $P_o = 101$ kPa; and a composition of atmospheric air saturated with H_2O at $T_o = 15\,^\circ\mathrm{C}$ and $P_o = 1$ atm and the following condensed phases: water, limestone and gypsum. This is similar to the model used by Gaggioli and Petit [9]. An environment temperature of 15 °C was used because that is the approximate mean temperature of the lake cooling water.

Results of base case analysis

Simulation results (e.g., flows, temperatures, pressures, etc.) are summarized in Table 3 for the main process streams identified in Fig. 4. Detailed results are given in Appendix B of Ref. [21]. Energy and exergy values for the streams identified in Fig. 4 are given in Table 3 and presented graphically in Fig. 5. The results were examined and compared and found to be in broad agreement with the literature for analyses of similar processes [34–37]. Many of the numerical values in subsequent discussions are not rounded off so that comparisons of different values can be made.

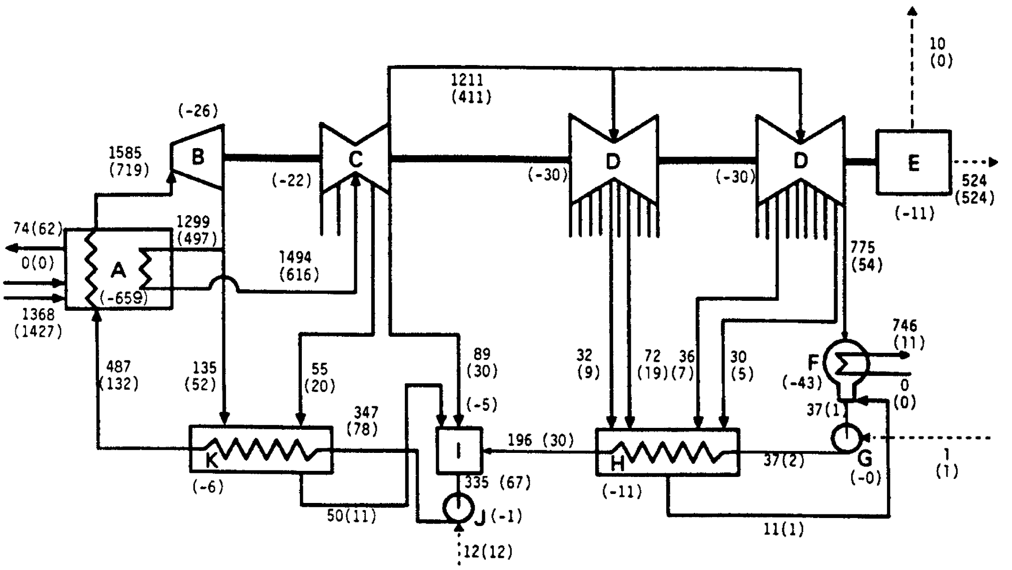

Fig. 5. Detailed flowsheets for a single unit of NGS indicating flow rates of energy (values not in parentheses) and exergy (positive values in parentheses) for streams, and exergy consumption rates (negative values in parentheses) for devices. All values in MW.

For the overall plant, energy efficiency (η) and exergy efficiency (ψ) values were evaluated as follows:

$$\eta = \frac{\text{net rate of energy output with electricity}}{\text{net rate of energy input}}(100\%)$$
$$= \frac{523.68 - 12.76}{1367.58}(100\%) = 37.359\% \tag{19}$$

$$\psi = \frac{\text{net rate of exergy output with electricity}}{\text{net rate of exergy input}}(100\%)$$
$$= \frac{523.68 - 12.76}{1426.73}(100\%) = 35.811\% \tag{20}$$

The net rate of electricity output is the difference between gross output and total pump input. Coal is the only input source of energy or exergy. Although the overall energy and exergy efficiencies were found to be similar, there are many devices in the station for which these efficiencies differ markedly.

In the steam generators, the energy and exergy efficiencies were evaluated, considering the increase in energy or exergy of the water as the product, as follows:

$$\eta = \frac{(1585.28 - 486.75) + (1494.16 - 1298.59)}{1367.58}(100\%)$$
$$= 94.627\%$$

$$\psi = \frac{(718.74 - 131.93) + (616.42 - 496.81)}{1426.73}(100\%)$$
$$= 49.513\%$$

The steam generators appear significantly more efficient on an energy basis than on an exergy basis. Physically, this discrepancy implies that although 95% of the input energy is transferred to the preheated water, the energy is degraded as it is transferred. The exergy consumptions in the steam generators are significant. Exergy consumptions in the steam generators are responsible for:

$$\frac{\dot{I}_{\text{steam generators}}}{\dot{\varepsilon}_{\text{coal}} - (\dot{W}_{\text{gross output}} - \sum \dot{W}_{\text{pumps}})}(100\%)$$
$$= \frac{659}{1426.73 - (523.68 - 12.76)}(100\%) = 72\%$$

of the total exergy losses. Of the 659 MW of exergy consumed in the steam generators, 444 MW was shown to be due to combustion, and 215 MW to heat transfer.

In the condensers, a large quantity of energy enters (about 775 MW for each unit), of which close to 100% is rejected; and a small quantity of exergy enters (about 54 MW for each unit), of which about 25% is rejected and 75% internally consumed. The characteristics of condensers can be seen more clearly by evaluating the net station condenser heat (energy) rejection rate,

$$R_{\text{energy}} = \frac{\text{heat rejected by condenser}}{\text{net electrical energy produced by station}}$$
$$= \frac{745.95}{523.68 - 12.76} = 1.46 \tag{21}$$

$$R_{\text{exergy}} = \frac{\text{exergy rejected by condenser}}{\text{net exergy produced by station}}$$
$$= \frac{10.54}{523.68 - 12.76} = 0.0206 \tag{22}$$

The R values indicate that the exergy rejected by the condensers is about 2% of the net exergy produced, while the energy rejected is approximately 150% of the net energy produced. Thus energy analyses lead to the conclusion that almost all plant losses are associated with the heat rejected by the condensers. But exergy analyses demonstrate that the condensers are not responsible for large losses. This

Table 4(a)
Exergy values (W) of streams in NGS for several values of T_o

Stream	Base case	Unaltered simulation		Altered simulation	
	$T_o = 288.15$ K	$T_o = 278.15$ K	$T_o = 298.15$ K	$T_o = 278.15$ K	$T_o = 298.15$ K
S1	0.142673×10^{10}	0.142672×10^{10}	0.142674×10^{10}	0.143453×10^{10}	0.141897×10^{10}
S2	0.000000×10^{0}	0.119030×10^{6}	0.116335×10^{6}	0.000000×10^{0}	0.000000×10^{0}
S3	0.982848×10^{9}	0.998136×10^{9}	0.967804×10^{9}	0.997529×10^{9}	0.968502×10^{9}
S4	0.622694×10^{8}	0.645947×10^{8}	0.601886×10^{8}	0.649489×10^{8}	0.598614×10^{8}
S5A	0.718735×10^{9}	0.749192×10^{9}	0.689037×10^{9}	0.749192×10^{9}	0.689037×10^{9}
S8	0.518142×10^{8}	0.547525×10^{8}	0.489476×10^{8}	0.547525×10^{8}	0.489476×10^{8}
S10	0.120188×10^{7}	0.273955×10^{7}	0.280530×10^{6}	0.273955×10^{7}	0.280530×10^{6}
S11	0.169604×10^{7}	0.323632×10^{7}	0.772081×10^{6}	0.323632×10^{7}	0.772081×10^{6}
S12	0.111060×10^{8}	0.125154×10^{8}	0.979522×10^{7}	0.125154×10^{8}	0.979522×10^{7}
S13	0.000000×10^{0}	0.158034×10^{8}	0.154199×10^{8}	0.000000×10^{0}	0.000000×10^{0}
S14	0.105387×10^{8}	0.518638×10^{8}	0.436886×10^{6}	0.234973×10^{8}	0.117218×10^{6}
S15	0.496806×10^{9}	0.524980×10^{9}	0.469321×10^{9}	0.524980×10^{9}	0.469321×10^{9}
S20	0.411156×10^{9}	0.439227×10^{9}	0.383700×10^{9}	0.439227×10^{9}	0.383700×10^{9}
S21	0.616415×10^{9}	0.647225×10^{9}	0.586294×10^{9}	0.647225×10^{9}	0.586294×10^{9}
S22	0.200234×10^{8}	0.212350×10^{8}	0.188385×10^{8}	0.212350×10^{8}	0.188385×10^{8}
S25	0.300932×10^{8}	0.321478×10^{8}	0.280837×10^{8}	0.321478×10^{8}	0.280837×10^{8}
S33	0.540663×10^{8}	0.793372×10^{8}	0.293133×10^{8}	0.793372×10^{8}	0.293133×10^{8}
S34	0.924260×10^{7}	0.100520×10^{8}	0.845072×10^{7}	0.100520×10^{8}	0.845072×10^{7}
S35	0.188192×10^{8}	0.206758×10^{8}	0.170026×10^{8}	0.206758×10^{8}	0.170026×10^{8}
S36	0.711577×10^{7}	0.812111×10^{7}	0.613174×10^{7}	0.812111×10^{7}	0.613174×10^{7}
S37	0.502829×10^{7}	0.591821×10^{7}	0.415706×10^{7}	0.591821×10^{7}	0.415706×10^{7}
S38	0.725296×10^{6}	0.114398×10^{7}	0.404174×10^{6}	0.114398×10^{7}	0.404174×10^{6}
S39	0.304140×10^{8}	0.364703×10^{8}	0.249739×10^{8}	0.364703×10^{8}	0.249739×10^{8}
S40	0.665154×10^{8}	0.762126×10^{8}	0.575781×10^{8}	0.762126×10^{8}	0.575781×10^{8}
S41	0.775709×10^{8}	0.873075×10^{8}	0.685942×10^{8}	0.873075×10^{8}	0.685942×10^{8}
S42	0.131931×10^{9}	0.144630×10^{9}	0.119993×10^{9}	0.144630×10^{9}	0.119993×10^{9}
Q5	0.000000×10^{0}	0.000000×10^{0}	0.000000×10^{0}	0.000000×10^{0}	0.000000×10^{0}
Q6	0.000000×10^{0}	0.000000×10^{0}	0.000000×10^{0}	0.000000×10^{0}	0.000000×10^{0}
P1	0.568770×10^{6}	0.568770×10^{6}	0.568770×10^{6}	0.568770×10^{6}	0.568770×10^{6}
P8	0.523680×10^{9}	0.523680×10^{9}	0.523680×10^{9}	0.523680×10^{9}	0.523680×10^{9}
P15	0.121910×10^{8}	0.121910×10^{8}	0.121910×10^{8}	0.121910×10^{8}	0.121910×10^{8}

discrepancy arises because heat is rejected by the condensers at a temperature very near that of the environment.

In other plant devices energy losses were found to be very small (about 10 MW total) and exergy losses were found to be moderately small (about 150 MW total). The exergy losses are almost completely associated with internal consumptions.

Results of the sensitivity analysis

The base case analysis of NGS in the previous section used $T_o = 288.15$ K. To determine the effects of varying dead-state temperature on energy- and exergy-analysis results, NGS was re-analyzed, again with the EXCEM code, for $T_o = 278.15$ K and $T_o = 298.15$ K.

For each new value of T_o two sets of energy and exergy values were obtained. The first set of values was obtained using the new value of T_o with the process simulated exactly as in base case. The second set was obtained using the new values of T_o, but with the base case simulation modified by setting the temperatures of streams entering from the environment (S1, S2, S13, S16, S18) to the appropriate value of T_o.

For the altered simulations, material and energy balances were achieved using the process simulation code. However, only rough modifications to plant components were considered. The optimal design for the plant under the new value of T_o was not determined.

Energy and exergy values respectively for streams in NGS (see Fig. 4) are listed in Table 4(a) and (b). The computer-generated values in Table 4(a) and (b) were not rounded off to fewer digits so that comparisons between the different values could be made. The variations for most energy and exergy values are less than 10%.

In general, since most of the material flows are 100% H_2O, the exergy analysis results are relatively insensitive to the composition of the reference environment. Since the flows of coal and stack gas are the only flows for which the composition are not 100% H_2O, it is only for these flows that one would expect exergy values to depend strongly on the choice of the chemical composition of the environment.

The numerical results in Table 4 were used to develop diagrams, of the type illustrated in Fig. 5, for each of the two modified T_o values considered, and for both the altered and unaltered simulations. Although the diagrams allow component irreversibilities and efficiencies to be visualized

Table 4(b)
Energy values (W) of stream in NGS for several values of T_o

Stream	Base case	Unaltered simulation		Altered simulation	
	$T_o = 288.15$ K	$T_o = 278.15$ K	$T_o = 298.15$ K	$T_o = 278.15$ K	$T_o = 298.15$ K
S1	0.136758×10^{10}	0.136730×10^{10}	0.136787×10^{10}	0.137504×10^{10}	0.136017×10^{10}
S2	0.000000×10^{0}	0.677958×10^{7}	-0.678194×10^{7}	0.000000×10^{0}	0.000000×10^{0}
S3	0.136850×10^{10}	0.137553×10^{10}	0.136145×10^{10}	0.137598×10^{10}	0.136108×10^{10}
S4	0.743925×10^{8}	0.814280×10^{8}	0.673419×10^{8}	0.818746×10^{8}	0.669759×10^{8}
S5A	0.158528×10^{10}	0.160720×10^{10}	0.156341×10^{10}	0.160720×10^{10}	0.156341×10^{10}
S8	0.135436×10^{9}	0.137506×10^{9}	0.133370×10^{9}	0.137506×10^{9}	0.133370×10^{9}
S10	0.365212×10^{8}	0.542968×10^{8}	0.187836×10^{8}	0.542968×10^{8}	0.187836×10^{8}
S11	0.370905×10^{8}	0.548662×10^{8}	0.193529×10^{8}	0.548662×10^{8}	0.193529×10^{8}
S12	0.502791×10^{8}	0.531213×10^{8}	0.474429×10^{8}	0.531213×10^{8}	0.474429×10^{8}
S13	0.000000×10^{0}	0.900528×10^{9}	-0.898601×10^{9}	0.000000×10^{0}	0.000000×10^{0}
S14	0.745946×10^{9}	0.164647×10^{10}	-0.152655×10^{9}	0.745946×10^{10}	-0.409578×10^{9}
S15	0.129859×10^{10}	0.131844×10^{10}	0.127878×10^{10}	0.131844×10^{10}	0.127878×10^{10}
S20	0.121105×10^{10}	0.122882×10^{10}	0.119331×10^{10}	0.122882×10^{10}	0.119331×10^{10}
S21	0.149416×10^{10}	0.151401×10^{10}	0.147435×10^{10}	0.151401×10^{10}	0.147435×10^{10}
S22	0.545449×10^{8}	0.553170×10^{8}	0.537744×10^{8}	0.553170×10^{8}	0.537744×10^{8}
S25	0.886386×10^{8}	0.899397×10^{8}	0.873404×10^{8}	0.899397×10^{8}	0.873404×10^{8}
S33	0.774703×10^{9}	0.789664×10^{9}	0.759773×10^{9}	0.789664×10^{9}	0.759773×10^{9}
S34	0.323101×10^{8}	0.328160×10^{8}	0.318053×10^{8}	0.328160×10^{8}	0.318053×10^{8}
S35	0.717336×10^{8}	0.728875×10^{8}	0.705821×10^{8}	0.728875×10^{8}	0.705821×10^{8}
S36	0.357739×10^{8}	0.363885×10^{8}	0.351605×10^{8}	0.363885×10^{8}	0.351605×10^{8}
S37	0.303987×10^{8}	0.309382×10^{8}	0.298604×10^{8}	0.309382×10^{8}	0.298604×10^{8}
S38	0.113669×10^{8}	0.141808×10^{8}	0.855892×10^{7}	0.141808×10^{8}	0.855892×10^{7}
S39	0.195940×10^{9}	0.213715×10^{9}	0.178202×10^{9}	0.213715×10^{9}	0.178202×10^{9}
S40	0.334857×10^{9}	0.356776×10^{9}	0.312985×10^{9}	0.356776×10^{9}	0.312985×10^{9}
S41	0.347048×10^{9}	0.368967×10^{9}	0.325176×10^{9}	0.368967×10^{9}	0.325176×10^{9}
S42	0.486750×10^{9}	0.508669×10^{9}	0.464878×10^{9}	0.508669×10^{9}	0.464878×10^{9}
Q5	0.534310×10^{7}	0.534310×10^{7}	0.534310×10^{7}	0.534310×10^{7}	0.534310×10^{7}
Q6	0.528970×10^{7}	0.528970×10^{7}	0.528970×10^{7}	0.528970×10^{7}	0.528970×10^{7}
P1	0.568770×10^{6}	0.568770×10^{6}	0.568770×10^{6}	0.568770×10^{6}	0.568770×10^{6}
P8	0.523680×10^{9}	0.523680×10^{9}	0.523680×10^{9}	0.523680×10^{9}	0.523680×10^{9}
P15	0.121910×10^{8}	0.121910×10^{8}	0.121910×10^{8}	0.121910×10^{8}	0.121910×10^{8}

Table 5
Comparison of some energy and exergy efficiencies for NGS for several values of T_o

	Base case	Unaltered simulation		Altered simulation	
	$T_o = 288.15$ K	$T_o = 278.15$ K	$T_o = 298.15$ K	$T_o = 278.15$ K	$T_o = 298.15$ K
Overall plant					
η	37.359	37.367	37.352	37.157	37.563
ψ	35.8106	35.8108	35.8103	35.616	36.006
Steam generators					
η	94.627	94.646	94.607	94.114	95.143
ψ	49.513	50.943	48.083	50.665	48.346

conveniently for each of the four non-base cases, they are not included here due to space limitations. However, some of the main results observed from examinations of these diagrams are discussed.

For the unaltered simulations, the variations in T_o caused the absolute values of the component irreversibilities to change, but left the relative component irreversibilities (as a fraction of the total plant irreversibility) unchanged. For the altered simulations, the irreversibilities are redistributed among the various components, as both the absolute and relative component irreversibilities are changed.

The efficiencies for the overall plant and for the steam generators are summarized in Table 5 for all cases considered in the sensitivity analyses. The efficiencies are evaluated following the definitions in Eqs. (19) and (20) and the descriptions provided earlier, but with the values for the altered simulations used in place of those for the unaltered simulations.

It is evident from the sensitivity analyses that the main results derived from the base case analysis are not significantly affected by the variations in T_o considered. The findings, conclusions and recommendations, which were demonstrated for the base case and which have been well understood for years, remain valid for the variations in the values of T_0 considered. That is, most of the energy losses were shown to be associated with emissions (mainly heat rejected by condensers) and most of the exergy losses with consumptions (mainly in the boilers), and the exergy losses associated with cooling water and stack gases were shown to be small.

It should be noted that although the variations in T_0 considered do not significantly affect the overall results, these variations are important in determining the optimal operation point for a given plant design.

4. Conclusions

It has been demonstrated that, although energy and exergy values are dependent on the intensive properties of the dead state, the main results of energy and exergy analyses are usually not significantly sensitive to reasonable variations in these properties. In some extreme cases, such as a rocket taking off from the ground level and flying to space, the evaluation of accurate energy and exergy values requires care because the variations in dead-state properties are large. For realistic dead-state properties, efficiencies which are a rational measure of an approach to an ideal and the major causes of process inefficiencies are only determined consistently with exergy analysis.

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Appendix A. Efficiency calculations

The evaluations of the efficiencies summarized in Table 5 are explained to avoid potential confusion.

For the unaltered simulations, the overall plant efficiencies are calculated to be

$$\eta = \frac{523.68 - 12.76}{1367.30}(100\%) = 37.367\%$$

and

$$\psi = \frac{523.68 - 12.76}{1426.72}(100\%) = 35.8108\% \quad \text{for } T_0 = 278.15\ \text{K}, \quad \text{and}$$

$$\eta = \frac{523.68 - 12.76}{1367.87}(100\%) = 37.352\%$$

and

$$\psi = \frac{523.68 - 12.76}{1426.74}(100\%) = 35.8103\% \quad \text{for } T_0 = 298.15\ \text{K}$$

Also, the steam-generator efficiencies are calculated to be

$$\eta = \frac{(1607.20 - 508.67) + (1514.01 - 1318.44)}{1367.30}(100\%) = 94.646\%$$

and

$$\psi = \frac{(749.19 - 144.63) + (647.23 - 524.98)}{1426.72}(100\%) = 50.943\% \quad \text{for } T_0 = 278.15\ \text{K}, \quad \text{and}$$

$$\eta = \frac{(1563.41 - 464.88) + (1474.35 - 1278.78)}{1367.87}(100\%) = 94.607\%$$

and

$$\psi = \frac{(689.04 - 119.99) + (586.23 - 469.32)}{1426.74}(100\%) = 48.083\% \quad \text{for } T_0 = 298.15\ \text{K}$$

For the altered simulations, the overall plant efficiencies were found to be

$$\eta = \frac{523.68 - 12.76}{1375.04}(100\%) = 37.157\%$$

and

$$\psi = \frac{523.68 - 12.76}{1434.53}(100\%) = 35.616\% \quad \text{for } T_0 = 278.15\ \text{K}, \quad \text{and}$$

$$\eta = \frac{523.68 - 12.76}{1360.17}(100\%) = 37.563\%$$

and

$$\psi = \frac{523.68 - 12.76}{1418.97}(100\%) = 36.006\% \quad \text{for } T_0 = 298.15\ \text{K}$$

Also, the steam-generator efficiencies are calculated to be

$$\eta = \frac{(1607.20 - 508.67) + (1514.01 - 1318.44)}{1375.04}(100\%) = 94.114\%$$

and

$$\psi = \frac{(749.19 - 144.63) + (647.23 - 524.98)}{1434.53}(100\%) = 50.665\% \quad \text{for } T_0 = 278.15\ \text{K}, \quad \text{and}$$

$$\eta = \frac{(1563.41 - 464.88) + (1474.35 - 1278.78)}{1360.17}(100\%) = 95.143\%$$

and

$$\psi = \frac{(689.04 - 119.99) + (586.23 - 469.32)}{1418.97}(100\%) = 48.346\% \quad \text{for } T_0 = 298.15\ \text{K}$$

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