V. S. Stepanov

Analysis of Energy Efficiency of Industrial Processes

Springer-Verlag

Vladimir S. Stepanov

Analysis of Energy Efficiency of Industrial Processes

With 38 Figures and 31 Tables

Springer-Verlag
Berlin Heidelberg New York
London Paris Tokyo
Hong Kong Barcelona
Budapest

Professor Dr. Vladimir S. Stepanov
Sibiran Energy Institute, Lermontov Street 130,
664033 Irkutsk, Russia

ISBN 3-540-54908-0 Springer-Verlag Berlin Heidelberg New York
ISBN 0-387-54908-0 Springer-Verlag New York Berlin Heidelberg

Library of Congress Cataloging-in-Publication Data.
Stepanov, V. S. (Vladimir Sergeevich) [Analiz energeticheskogo sovershenstva technologicheskikh protsessov. English] Analysis of energy efficiency of industrial processes / Vladimir S. Stepanov. p. cm. Translation of: Analiz energeticheskogo sovershenstva tekhnologicheskikh protsessov. Includes bibliographical references and index. ISBN 3-540-54908-0. -- ISBN 0-387-54908-0 1. Industry–Energy conservation. 2. Metallurgical plants–Energy conservation. I. Title. TJ163.3.S7413 1992 670.42–dc20 92-33780

Printed in the United States of America

Typesetting: Camera ready by the authors
57/3140 - 5 4 3 2 1 0 - Printed on acid-free paper

Analysis of Energy Efficiency of Industrial Processes

Preface

It is universally recognized that the end of the current and the beginning of the next century will be characterized by a radical change in the existing trends in the economic development of all countries and a transition to new principles of economic management on the basis of a resource and energy conservation policy. Thus there is an urgent necessity to study methods, technical aids and economic consequences of this change, and particularly, to determine the possible amounts of energy resources which could be conserved (energy "reserves") in different spheres of the national economy.

An increased interest towards energy conservation in industry, one of the largest energy consumers, is quite natural and is manifested by the large number of publications on this topic. But the majority of publications are devoted to the solution of narrowly defined problems, determination of energy reserves in specific processes and plants, efficiency estimation of individual energy conservation measures, etc. However, it is necessary to develop a general methodological approach to the solution of such problems and create a scientific and methodical base for realizing an energy conservation policy.

Such an effort is made in this book, which is concerned with methods for studying energy use efficiency in technological processes and estimation of the theoretical and actual energy reserves in a given process, technology, or industrial sector on the basis of their complete energy balances.

The book generalizes the results of studies in this field conducted over many years at plants of ferrous and non-ferrous metallurgy with the use of exergy analysis, which were performed by the author himself and with co-authors. These works were started in the 1960s at the Kazakh Energy Institute under the directory of I. Kh. Ozoling and are continued now in the Siberian Energy Institute, Siberian Branch of the Russian Academy of Sciences.

This book is of interest to diverse audience of specialists in the areas of thermodynamics, industrial energetics, and energy economy.

Data for the calculation of energy balances of processes and plants in Chaps. 5, 6 are obtained in a study conducted by the author at plants operating in the USSR. The calculations described in Chap. 8 are based on official statistics, on the data of reports and forecasts from the USSR Ministry of Metallurgy.

Chapters 7 and 8 are written jointly with T. B. Stepanova whose help at all the stages of work on the monograph is gratefully acknowledged. I wish to express my gratitude to V. P. Ermakova, V. G. Borovikova and V. I. Viryukina for translating this book into English.

Irkutsk, March 1992 *Vladimir S. Stepanov*

Nomenclature

A	work, J
ΔA	work losses, J
A	ash content in fuel
a	fuel cost, currency /kg c.e. (coal equivalent)
B, b	anergy (total and specific), J
C	specific heat capacity, J/kg · K
C, c	annual costs, currency/year; currency/year · unit of process product
D	damage, monetary
d	number of considered technological schemes
E, e	exergy (total and specific), J, kW h; J/kg, J/mol, kW h/ton
EF	economic effect, currency/year
F	Helmholtz free energy, J
F	Faraday constant, k Coulomb/mol
G	Gibbs free energy, J
ΔG_z^0	standard Gibbs energy of formation of substance z, J
ΔG_{ion}^0	standard Gibbs energy of ion formation in aqueous solution, J
ΔG_{a}^0	standard Gibbs energy of anion formation, J
ΔG_{c}^0	standard Gibbs energy of cation formation, J
$(\Delta G_{\text{s}})_z$	change of Gibbs energy in formation of an infinitely dilute solution of substance z in water, J
$(\Delta G_z^0)_{\text{aq}}$	standard Gibbs energy of forming substance z in aqueous solution, J
g	tons of consumption of raw material, per ton of process end product
H	enthalpy (total or specific), J; J/kg, J/mol
ΔH_z^0	standard heat of formation of substance z, J
ΔH_{ion}^0	standard enthalpy of ion formation in aqueous solution, J
ΔH_{a}^0	standard enthalpy of anion formation, J
ΔH_{c}^0	standard enthalpy of cation formation, J
$(\Delta H_{\text{s}})_z$	enthalpy change in formation of infinitely dilute solution of substance z in water, J
$(\Delta H_z^0)_{\text{aq}}$	standard heat of formation of substance z in aqueous solution, J
ΔH_{com}^0	heat of combustion, kJ/kg
I, i	energy (total and specific), J, kW h; J/kg, J/mol, kW h/ton
K, k	monetary capital investment
L	heat output, kW

M	input and output material flows, ton
m	mass of elements, anions, cations
m	number of considered energy carriers
N	electric capacity, kW
N	number of process links in a technological scheme
n	amount of process product
n	number of conisdered technologies in one link of technological chain
n_e	number of electrons in a reaction
O	oxygen content in fuel
P	energy conserved potential, J, kW h
p	pressure, Pa
Q	heat, J, kW h
ΔQ	heat losses, J/kg, J/mol, kW h/t
Q_h	high calorific value, kJ/kg
Q_l	low calorific value, kJ/kg
q	heat amount per unit of substance, J/kg, J/mol, kW h/ton
q	specific heat consumption in electricity production, g c.e./kW h
R	energy conserved, J, kW h
r	number of processes in a production scheme
S, s	entropy (total and specific), J/K; J/kg · K, J/mol · K
ΔS	entropy change, J/K
T	temperature in Kelvin, K
T_0	temperature of environment, K
t	temperature on a Celsius scale, °C
t	time, h, y
U	internal energy, J
V, v	volume (total and specific), m^3; m^3/kg, m^3/mol
V, v	industrial pollutants (total and specific), m^3; m^3/ton of process product, or ton pollutants per ton of process product
W	fuel moisture
W_w	electricity production, kW h
w	number of seasons in year
Z, z	costs (total and specific), currency/year; currency/year per unit of process product
α	conversion factor of different energy carriers into common units of energy, g c.e./kW h, kg c.e./GJ
β	fraction of technology in product output specific fuel consumption, g c.e./kW h, kg c.e./GJ
γ	coefficient of useful product extraction in a process
δ	content of useful component in raw and auxiliary materials
ε	coefficient of cost elements
ε_s	interest of capital
ν	fraction of chemical compound (element) per unit of considered substance
φ^{ϕ}_{ion}	standard electrode potential, V

Subscripts

a	anion
aq	aqueous
ave	average
c	cation
cc	production of cogeneration plant by condensing mode
ch	chemical
c	cooling system
ck	coke
cl	coal
compl	complex
con	concentrate, concentration
cons	consumed
cp	cogeneration plant
ct	production of cogeneration plant by thermal mode
e	electron
ec	existing condensation power plants
el	electric energy
en	energy
endo	endothermic
enw	electric network
es	electrical smelting
ex	exergy
exo	exothermic
f	fuel
f	furnace facility
h	high
hnw	heat network
i	additional reference species
i	original substance of the process
ib	industrial boiler
id	ideal
if	intersystem power flow
ion	ion
ir	iron
j	element
j	process
k	final substance of the process
k	resulting reference species
l	low
l	product from the process
los	loss
m	mechanical

mat	material
ml	melting
n	nominal
nc	new condensation power plants
oc	oxygen converter
oh	open-hearth
or	ore
p	heat capacity at constant pressure
p	product
p	technology
pb	peak boilers
pr	previous
q	thermal
r	raw material
res	resulting
r	heat recovery installation
s	infinitely dilute solution
sm	smelting, smelted
st	structural change
stb	stand-by
str	steel as rolled stock
t	technological
tot	total
us	useful
w	waste
z	substance

Superscripts

abs	absolute
add	additional
b	base
ce	coal extraction
ck	coke
con	concentration
cs	cast
d	discharge (industrial discharge)
ext	extraction
fut	future
g	gases (waste gases)
id	ideal
met	metallurgical
opt	optimal

or	ore
pel	pellets
pr	production
qn	quenching
real	real
rel	relative
rol	rolling
rs	rolled stock
sc	scrap
st	steel
str	steel as rolled stock

Abbreviations

CCM	continuous casting machine
ESS	energy supply system
SER	secondary energy resources

Contents

Introduction

Chapter 1 briefly describes the concepts and laws of thermodynamics that form the basis for the exergy method. It also considers in detail the technique for drawing and analyzing the complete energy balance of a process, methods for computing the chemical energy and exergy of substances which have been developed with the participation of the author and differ from those proposed by other researchers (Chaps. 2 and 3).

Chapter 4 presents the method of complex analysis of processes and plants which includes both the thermodynamic and techno-economic analysis on the example of utilizing thermal secondary energy resources. Such an analysis allows the determination of both the amounts of secondary energy resources which are theoretically and technically applicable for the utilization and the degree of their economically optimal use.

Despite the fact that the fundamentals of the exergy method of analysis have largely been elaborated, this method has not yet found broad practical application. Therefore, the author has tried to show the practical value of this method, its simplicity and the results that can be obtained.

Chapters 5 and 6 give examples of drawing up the complete energy balance of individual technological processes and complexes of ferrous and non-ferrous metallurgy, determining their efficiency, analyzing their losses with identification of irrevocable losses and those that are theoretically recoverable.

In Chaps. 7 and 8 we estimate the energy reserves of industries (comprised of technological processes) using the usual methodological principles based on the concept that energy conservation in an industry results from more efficient energy use in its individual technological processes, as demanded by the final products.

Thus, the contents of the book can be divided into three sections. The first includes Chaps. 1–4 and can be titled "The theoretical bases for the analysis of energy use in technological processes". The second section (Chaps. 5, 6) is devoted to the application of the developed methods for the analysis of metallurgical processes and technological schemes. The third part (Chaps. 7, 8) illustrates the application of these methods for solving larger problems, such as estimation of energy reserves in industries, forecasting the structure, i.e., the types of fuels used and amounts of future energy consumption.

1. The Technological Process as a Subject of Thermodynamic Analysis

All processes proceeding in nature and technical facilities transform some given form of energy into another. Therefore, material changes that underlie any technological process should be considered as the consequences of the energy transformations.

In assessing the thermodynamics of a process, the capability of different processes to selectively utilize energy inputs is evaluated. Only energy of the required kind is consumed while other energy forms are rejected. Because this selectivity is a function of the physical and chemical parameters of a system, to optimize a technological production process the interrelation between material and energy changes, the laws of energy transformation must be understood.

Thus, in the analysis of technological processes it is required to study material transformations and first of all, the processes causing them and the laws of energy transformations. The goal of thermodynamics to devise methods for such studies [13, 28, 38, 67, 69, 87, 89–92, 199, 202].

1.1 Thermodynamic Systems and Processes

A thermodynamic system is a set of material bodies and fields interacting with each other and with the environment. The choice of the system is purely arbitrary and depends only on the objectives of the experiment. Thermodynamic phenomena can be considered to be macrophysical, independent of the underlying microphysical processes if the dimensions of the studied bodies are large in comparison to the size of elementary particles and the distances between them.

Thermodynamic systems are characterized by the so-called state parameters that are divided into *intensive* and *extensive* (additive). Intensive parameters (such as pressure and temperature) do not depend on the amount of a substance in the system, whereas extensive or additive ones (e.g. volume, heat capacity) are proportional to the system mass.

Interactions between a system and the environment are taken into account only in so far as they are connected with the energy and substance exchange of interest. If there is no energy and substance exchange, the system is called *isolated.* If they interact only due to energy exchange, the system is called *closed.* If interaction between them is represented by both energy and substance exchanges,