SAWYER'S GAS TURBINE ENGINEERING HANDBOOK

Third Edition
Three Volumes

VOLUME I
THEORY & DESIGN

TURBOMACHINERY INTERNATIONAL PUBLICATIONS

SAWYER'S GAS TURBINE ENGINEERING HANDBOOK

Third Edition

Volume I of Three Volumes

I Theory & Design

II Selection & Application

III Accessories & Support

Editor

John W. Sawyer
Turbomachinery International
Publications

Associate Editor

David Japikse
President
Concepts ETI, Inc.

Turbomachinery International Publications
Division of Business Journals, Inc.
22 South Smith Street
Norwalk, Connecticut, USA 06855

1985

Library of Congress Cataloging in Publication Data
Gas turbine engineering handbook.
Sawyer's Gas turbine engineering handbook.

Contents: v. 1. Theory & design -- v.2. Selection & application -- v.3. Support & accessories.
Includes bibliographies and indexes.
1. Gas-turbines--Handbooks, manuals, etc. I. Sawyer, John W. (John William), 1911- . II. Japikse, David. III. Title.
TJ778.G243 1985 621.43'3 83-18100
ISBN 0-937506-13-3 (set)

ISBN Vol. I 0-937506-14-1
ISBN Vol. II 0-937506-15-X
ISBN Vol. III 0-937506-16-8

22 South Smith Street
Norwalk, Connecticut 06855
United States of America

Contents of the Three Volume Sawyer's Gas Turbine Engineering Handbook

CONTRIBUTORS

ARIGA, Ichiro, Professor, Keio University, Tokyo
AULD, Andrew J., Jr., Consultant
BROADLEY, Ian C., Director of Product and Engineering Development, John Brown Engineering Limited
CARMICHAEL, A. Douglas, Professor of Power Engineering, Massachusetts Institute of Technology
CHETTY, Roy C., Manager of Business Planning, Westinghouse Electric Corporation
DAVIS, F. N., Specialist - Materials and Coatings, Rolls-Royce Limited
DONACHIE, Matthew J., Jr., Staff Project Engineer, Pratt & Whitney, Division of United Technologies and Adjunct Professor of Metallurgy, The Hartford Graduate Center
DUNDAS, Robert E., Mechanical Engineering Specialist, Factory Mutual Research Corporation
EDERVEEN, Jan, Sales Manager, Engine and Turbines Controls Division, Woodward Governor Company
EMMERSON, Calvin W., Manager, Centaur Gas Turbine Engineering, Solar Turbines Incorporated
FISTERE, John C., Staff Engineer, Solar Turbines Incorporated
FOLLETT, Roger N., Training and Development Manager, John Brown Engineering Limited
FOSTER-PEGG, Richard W., Consultant, Westinghouse Electric Corporation
HAFER, Alva A., Manager, Requisition Engineering, Gas Turbine Engineering and Manufacturing Department, General Electric Company
HANDKINS, David M., Advanced Reliability Engineer, Westinghouse Electric Corporation
HANNA, William T., Manager of Engineering, Construction Services, Solar Turbines Incorporated
HAUSCHILDT, Maurice R., Marine Engineering Consultant
HAZARD, Herbert R., Senior Consultant, Fuel and Combustion Research, Battelle Memorial Institute
HOWARD, Charles P., Director of Field Services, Regions VIII and IX, The American Society of Mechanical Engineers
HOWARD, George S., Manager, Flow Path Design and Performance, Westinghouse Electric Corporation
ISTRE, Felix J., Jr., President, Istre-Mac Service Corporation
JAPIKSE, David, President, Concepts ETI, Inc.
KEIR, Blair T. B., Training Officer, Sullom Voe Terminal, Shetland, BP Petroleum Development (N.W. Europe)
LANG, Richard P., Application Engineer, General Electric Company
LARREW, Gary D., Project Engineer, Engine and Turbine Controls Division, Woodward Governor Company
LEE, Daniel T., Senior Engineer, Combined Cycle Applications, Gas Turbine Division, General Electric Company
LORISIKA, Gerhard, Technical Adviser, Service Engineering, BBC Brown Boveri & Company, Limited
McDONALD, Colin F., Project Manager, GA Technologies, Inc.

MALANOSKI, Stanley B., Manager, Analysis and Design Engineering, Mechanical Technology Incorporated

MARSCHER, William D., Director of Mechanics, Worthington Division, McGraw-Edison Company

MAY, Walter R., President, SFA Technologies, Inc.

MELCONIAN, Jerry O., President, SOL-3 Resources, Inc.

MIZUMACHI, Nagao, Professor Emeritus, The University of Tokyo and Professor, Chiba Institute of Technology

MODAK, Ashok T., Vice President of Research, SOL-3 Resources, Inc.

MOON, David M., Research Director, Energy Technology Research Laboratories, Westinghouse Electric Corporation

NEBINGER, Edward M., Director of Research, Forecast Associates, Inc.

NEVILLE, E. D., Quality Director, John Brown Engineering Limited

NOUSE, Hiroyuki, Head of Heat Transfer Laboratory, National Aerospace Laboratory, Tokyo

OSTRAND, Gary G., Manager, Sales and Engineering, Gas Turbine Systems, Donaldson Company, Inc.

PIETSCH, Anthony, Senior Project Engineer, The Garrett Corporation

PINKUS, Oscar, Consulting Engineer, Mechanical Technology Incorporated

RADKEVICH, Thomas J., Manager, Plant Development Engineering, Westinghouse Electric Corporation

RUSSELL, Michael R., Project Engineer, Vosper Thornycroft (UK) Controls

SCHEIRER, Scott T., Manager, Metallurgical Engineering, Westinghouse Electric Corporation

SCHORR, Marvin M., Senior Environmental Engineer, General Electric Company

SHAH, Ramesh K., Technical Director of Research, Harrison Radiator Division, General Motors Corporation

SULLIVAN, C. P., Senior Materials Project Engineer, Pratt & Whitney, Division of United Technologies

SUROWIEC, Michael W., Manager, Engineering, Sound Control Systems Group, Environmental Elements Corporation

TEMPESCO, Donald E., Director, Internal Combustion Engines and Gas Turbine Division, Naval Sea Systems Command

THOMAN, Ronald J., Manager, Energy Program Development, Westinghouse Electric Corporation

THOMPSON, Robert G., Consulting Engineer, R. G. Thompson & Associates

TOMLINSON, Leroy O., Manager, Combined Cycle Engineering, Gas Turbine Division, General Electric Company

VAN HOUSEN, Robert L., Cogeneration Systems Engineer, General Electric Company

WATANABE, Ichiro, Professor Emeritus, Keio University, Tokyo

WINN, Leo W., Manager, Applied Tribology Center, Mechanical Technology Incorporated

WRIGHT, Robert M., Marketing Manager, TRI-SEN Systems, Inc.

ZIRKELBACK, Charles E., Senior Staff Engineer, Maintenance Department, Union Carbide Corporation

PREFACE

This new edition has been written for those in the gas turbine field who are concerned with research, design, manufacture, selection, application, evaluation, teaching, training, marketing, and related activities. It is a comprehensive work that consists of 41 chapters, with contributions from 57 authors. These individuals are recognized authorities from a number of countries. They represent universities, research organizations, manufacturers, users, government, training establishments, and consultants.

The book is to serve as a reference, text, and specific guide for people in the many areas of gas turbine endeavor. The designer, engineer, manufacturer, user, selector of equipment, instructor, student, researcher, and others will find it of considerable help.

The gas turbine field is broad and highly technical, thus it is not feasible for a single author to put together a reference work with the vast scope and technical depth presented here. For this reason it has been necessary to bring together a number of authorities from the many areas of gas turbine technology to write this book.

Volume I concerns thermodynamics and fundamentals; cycle variations and calculations; aerodynamic design of compressors and turbines; combustor design; bearing design; structural design and analysis; computers in design and testing, and preliminary and detailed design of the complete gas turbine engine.

Volume II deals with selection and application of gas turbines in the major fields of use. These include: electric power generation; pipeline industry; marine, ships; offshore; cogeneration; cryogenics refrigeration and power recovery; combined cycles; legislation and regulations; economic evaluation; calculation and performance adjustment for on site conditions; maintainability, and the market.

Volume III covers materials, fuels, and treatment; controls; instruments, accessories, and internal systems; heat exchangers; inlet air filtration; noise control, ISO Standard testing and measuring tolerances; U.S. Standards; monitoring and control; fundamentals of energy exchange in the turbine; training, and quality assurance.

A comprehensive subject index for the entire book is incorporated into each volume. This provides a detailed source of the subject matter contained in the book. It is cross-referenced where appropriate.

It is appreciated that a single book cannot give comprehensive coverage to every topic in this highly technical field. In order to provide additional reference sources, extensive bibliographies have been included with a number of the more involved chapters. In addition to the bibliographies, references are listed in many chapters to offer greater detail on specific subjects under discussion.

Since the second edition was published in 1972, thirteen years ago, the developments of gas turbines have been extremely significant. The improvements include materials, component efficiencies, higher operating temperatures, design methods involving use of computers, new manufacturing techniques, instrumentation, and new industrial uses for the gas turbine.

The number of gas turbines in use and also the number and types of applications have increased greatly during the past decade. This has resulted in impressive growth in the number of people involved in manufacturing, design, marketing, selection, operation, inspection, maintenance, development, education, and training.

In summary the rapid development in the past thirteen years has been such that it was considered essential to prepare this third edition to provide an all inclusive update on this prime mover. The gas turbine community will find this book to be a valuable reference.

ACKNOWLEDGMENTS

This, the third edition, is a tribute to the authors and their organizations for their contribution of many thousands of manhours in researching and preparing this updated and outstanding treatise on gas turbine engineering. It is a timely and valuable technical addition to this engineering field. The authors' efforts are recognized and deeply appreciated.

Sincere thanks are extended to my many colleagues who so kindly debated both the subject matter and its manner of presentation in the book.

It has been my pleasure to have worked with Mr. G. Renfrew Brighton, Chairman of the Board, Business Journals, Inc., for 25 years on gas turbine publications, including magazines, catalogs, and handbooks. Since 1966 he has given me encouragement and support in the preparation and publication of ten volumes of engineering handbooks, including this three volume, third edition, of Sawyer's Gas Turbine Engineering Handbook.

Dr. David Japikse, Associate Editor of this handbook, provided technical expertise in many cases. He was also instrumental in developing content and modifications in the book. In addition, Dr. Japikse authored a number of important chapters for this edition. Members of his staff including Helen D. Tucker, Marguerite B. Bradshaw and Sharon E. Wight did outstanding work in typesetting, layout, and proofreading the material in these volumes.

The assistance of Kurt Hallberg, Director/Publisher, Turbomachinery International, and Frances Salamon, Director of Manufacturing and Production, Business Journals, Inc., was invaluable.

I want to recognize the following outstanding and dedicated educators: Professor William Hand Browne, Jr. (deceased), former Head of the Department of Electrical Engineering, North Carolina State College; Professor F. W. Marquis (deceased), former Head of the Department of Mechanical Engineering, Ohio State University; and Miss Dama Hill, my former teacher and long time friend.

To my wife, Dorothy Uhl Sawyer, I am sincerely grateful for her valuable help, understanding, and encouragement throughout the four years this book was in preparation.

John W. Sawyer
January 1985

TABLE OF CONTENTS

VOLUME I THEORY AND DESIGN

CHAPTER 1

THERMODYNAMICS AND FUNDAMENTALS OF THE GAS TURBINE CYCLE

by Charles P. Howard

CONTENTS

1.0 INTRODUCTION

This chapter will review the thermodynamic fundamentals which are necessary for an understanding of the basics for a gas turbine cycle analysis. A more detailed consideration of thermodynamic analyses as applied to variations in cycles, and the use of working substances other than air, will be presented in Chapter 2, Cycle Variations and Calculations.

2.0 NOMENCLATURE

English Symbols	Definitions SI Units, [English Units]
a	Acceleration, m/s², [ft/sec²]
c_p	Specific heat at constant pressure, J/kg-K, [Btu/lbm-R]
c_v	Specific heat at constant volume, J/kg-K, [Btu/lbm-R]
E_c	Internal chemical energy, J, [Btu]
e_c	Specific internal chemical energy, J/kg, [Btu/lbm]
F	Force, N, [lbf]
g	Local gravity acceleration, m/s², [ft/sec²]
g_c	Gravitational constant = $1/k_c$, 1 kg-m/N-s², [32.1739 lbm-ft/lbf-sec²]
H	Enthalpy, J, [Btu]
h	Specific enthalpy, J/kg, [Btu/lbm]
k	Ratio of specific heats, c_p/c_v, dimensionless
k_c	Proportionality constant in Newton's Second Law, 1 N-s²/kg-m, [1/32.1739 lbf-sec²/lbm-ft]
M	Mass, kg, [lbm]

$\dot{m}$	Mass flow rate, kg/s, [lbm/sec]
$\underline{m}$	Molal mass, kg/kg_{mol}, $[lbm/lb_{mole}]$
p	Pressure, absolute or gage, Pa, $[lbf/ft^2]$
Pr	Relative pressure, dimensionless
Q	Heat energy, J, [Btu]
$\dot{Q}$	Heat rate, dQ/dt, W, [Btu/sec]
q	"Specific" heat energy, J/kg, [Btu/lbm]
$\underline{R}$	Gas constant, 8.3143 J/mol-K, $[1545.32\ ft\text{-}lbf/lb_{mole}\text{-}R]$
S	Entropy, J/K, [Btu/R]
$\dot{S}$	Entropy rate, dS/dt, J/s-K, [Btu/sec-R]
s	Specific entropy, J/kg-K, [Btu/lbm-R]
t	Time, s, [sec]
T	Absolute temperature K, [R]
U	Internal thermal energy, J, [Btu]
u	Specific internal thermal energy, J/kg, [Btu/lbm]
V	Velocity, m/s, [ft/sec]
v	Specific volume, m^3/kg, $[ft^3/lbm]$
W	Work energy, J/kg, [Btu/lbm]
$\dot{W}$	Work rate, dW/dt, W, [Btu/sec]
Z	Height, m, [ft]
ρ	Density, kg/m^3, $[lbm/ft^3]$
Σ	Summation symbol
η	Efficiency, dimensionless

Subscripts

o	Stagnation condition, base condition
1,2,3..	State points
a	Air, actual, added
c	Compressor, cold
i	Ideal
t	Turbine

3.0 MASS, FORCE, AND ENERGY

3.1 Mass

Mass is a quantity of matter. The quantity which has been arbitrarily selected as the fundamental unit of mass on the macroscopic scale for the International System (SI) of units is the kilogram (kg). However, in the English engineering system of units, it has become commonplace to use the pound mass (lbm) as the basic quantity of matter. In this text the SI units will be shown as primary with English units following in brackets. The pound mass is defined as 1/2.205 part of the kilogram mass.

3.2 Force

Force is a derived unit and can be related to mass by Newton's Second Law of Motion, which in equation form is:

$$F = k_c Ma \tag{1}$$

where F = force, M = mass, a = acceleration, and k_c = the proportionality constant which relates force to mass. If the force is taken to be one pound (lbf) and the mass taken to be one pound (lbm), with the acceleration to be that of an apple falling from Newton's tree in England and measured as 32.1739 ft/sec^2, then the value of the proportionality constant will be:

$$k_c = 1/32.1739\ lbf\text{-}sec^2/lbm\text{-}ft \tag{2}$$

The acceleration of the apple is due to the gravitational pull of the earth, so that the proportionality constant is usually called the "gravitational constant" and written as:

$$g_c = 1/k_c = 32.1739\ lbm\text{-}ft/lbf\text{-}sec^2 \tag{3}$$

If, on the other hand, the force is taken to be one Newton (N) and the mass taken to be one kilogram (kg), with an acceleration of 1 m/sec^2, then the value of thc proportionality constant will be:

$$k_c = 1\ N\text{-}s^2/kg\text{-}m \tag{4}$$

with a gravitational constant of:

$$g_c = 1/k_c = 1\ kg\text{-}m/N\text{-}s^2 \tag{5}$$

This has nothing at all to do with the apple but does define a Newton of force which, when equated to the English system, gives:

$$1 \text{ lbf} = 4.4482 \text{ N} \quad (6)$$

The use of the same name, pound, for a quantity of mass and a unit of force has, on occasion, created problems in calculations when using the English system of units. This can be easily avoided if the units of the quantities involved are clearly written out, and then the appropriate constants or conversion factors applied to make the equation "dimensionally homogenous." As is apparent in the SI unit system, the intermingling of force and mass presents little problem since they each have different names.

3.3 Energy

Energy is a property of matter. The exchange and transformation of energy, particularly in the forms of work and heat, make up the science of thermodynamics. The most common units of energy in the English engineering unit system are the foot-pound force (ft-lbf) and the British Thermal Unit (Btu), which are related as:

$$1 \text{ Btu} = 778.16 \text{ ft-lbf} \quad (7)$$

The Btu is historically related to the caloric theory of heat as that amount of energy, transferred as heat, necessary to raise 1 lbm of water 1°F at "room conditions."

There is only one accepted unit of energy in the SI unit system and that is the joule (J). However, the newton-meter (N-m) and the watt-second (W-s) are sometimes used, and are related as:

$$1 \text{ J} = 1 \text{ N-m} = 1 \text{ W-s} \quad (8)$$

and can likewise be related to the English system as:

$$1 \text{ Btu} = 1.055 \text{ kJ} \quad (9)$$

4.0 PROPERTIES, CONCEPTS, AND DEFINITIONS

4.1 Properties

Properties are those quantities which when determined will allow the state of a substance to be completely defined. The immediate properties of interest are those which relate to the thermodynamic state of the substance. Odor, color, flavor and toxicity are some of the non-thermodynamic properties but are ones which might influence the selection of a substance for eventual use. There are two general types of properties: those which are independent of the quantity of mass are called "intensive" and those which are proportional to the quantity of mass are called "extensive." Pressure, temperature, and density are typical thermodynamics intensive properties. Volume, energy, and mass itself are typical extensive properties. However, it frequently becomes convenient to intensify an extensive property by dividing the quantity by the mass involved, thus obtaining the "specific volume," the "specific energy," or any other "specific" or intensive property.

4.2 Concepts

While it has been stated that "mass" is a quantity of matter and that "energy" is a property of matter, mass and energy are also two of the most important concepts of thermodynamics. Concepts should be related to our physical senses in order to derive physical meaning. The concepts of length and time are readily perceived when one travels from one place to another. The concept of temperature is also readily understood by the "hotness" or "coldness" to the touch. The concept of mass, however, must come indirectly from the "push" or "pull" of a force due to the acceleration or deceleration on the body. The concept of mass is, therefore, more than a mere quantity of matter. Likewise, the concept of energy is indirect and must be experienced by the pushing or pulling over a distance (work) or the feeling of becoming warm or cold (heat). The fact that neither heat nor work can be stored further complicates the concept of energy as a property. Energy then, is that property of matter which manifests itself either in the form of work or heat.

Work is a mechanism for the transfer of energy and is computed by the displacement of a quantity of matter times the force in the direction required to produce the displacement. Heat is another mechanism for the transfer of energy to or from a quantity of matter and is determined as that energy transferred which cannot be recognized as work. The driving potential for this energy is usually the difference in temperature between the matter and its surroundings.

4.3 Definitions

There are several forms of energy which can be divided into classes, and only those thermodynamic forms related to the gas turbine will be given here.

Mechanical Forms

- Work: W, transient, non-storable and a path function, J, [ft-lbf] - w, J/kg, [ft-lbf/lbm]

- Kinetic energy: $V^2/2$, storable and a state function, J/kg, [ft-lbf/lbm]

- Potential energy of position: gZ, storable and a state function, J/kg, [ft-lbf/lbm]
- Flow work: p/ρ, transient, storable and a state function, J/kg, [ft-lbf/lbm]

Note that for a closed system (i.e., a system in which no mass crosses the boundaries of the defined system) there will be no flow work even though it will be possible to compute a value for p/ρ.

Thermal Forms

- Heat: Q, transient, non-storable and a path function, J, [Btu] - q, J/kg, [Btu/lbm]
- Internal thermal: U, storable and a state function, J, [Btu] - q, J/kg, [Btu/lbm]

Chemical Forms

- Internal chemical: E_c, storable and a state function, J, [Btu] - e_c, J/kg, [Btu/lbm]

Besides the various energy forms, other quantities which need definition are:

- Enthalpy: $h = u + p/\rho$, J/kg, [Btu/lbm]
- Entropy: $ds = dq/T$ for a reversible process, J/kg-K, [Btu/lbm-R]
- Specific heat, constant pressure: $c_p = (\partial h/\partial T)_p$, J/kg-K, [Btu/lbm-R]
- Specific heat, constant volume: $c_v = (\partial u/\partial T)_v$, J/kg-K, [Btu/lbm-R]
- Ratio of specific heats: $k = c_p/c_v$, dimensionless
- The temperature scale: the absolute temperature scale in the SI system is the Kelvin scale, K, and it begins at zero. The relative temperature scale, Celsius (°C), is so chosen that 1°C = 1 K and absolute zero temperature equals -273.15°C. In the English system the absolute temperature scale is the Rankine scale, R, and it also begins at zero. The relative temperature scale, Fahrenheit, (°F), is so chosen that 1°F = 1 R and absolute zero equals - 459.67°F. The SI and English scales are related as 1 K = 9/5 R.
- The pressure scale: the absolute pressure scale in the SI system is the Pascal scale, Pa, and it begins at zero. In the English system, the absolute scale is the pounds-per-square-inch-absolute, psia, and it begins at zero. These units are related to the standard atmosphere as:
- 1 atm = 14.696 psi = 101.325 kPa
  = 29.92 in-Hg
  = 406.79 in-H_20 = 1.01325 bar
  = 760 torr

  Pressures relative to the ambient are referred to as "gage pressure."

5.0 EQUATION OF STATE

The relationship between properties of matter at some state is the "Equation of State." Whether the relationship is presented in tabular, graphical, or mathematical form usually depends upon the substance and, in many cases, all three forms are used. While it is not necessary, most equations of state give the relationship of intensive properties. When an extensive property has been "intensified," the quantity of mass is the kilogram in the SI system and the pound-mass in the English system.

Properties, to be useful, should either be measurable or be readily related to other measurable properties. Pressure and temperature are usually readily measurable since they are inherently intensive properties. All energy propertics, intensive or extensive, must be deduced from other measurable properties. Most working fluids used in gas turbines, which operate at modest pressures and temperatures well above the critical, closely obey the "perfect gas law" equation of:

$$p/\rho = (\underline{R}/\underline{m})/T \qquad (10)$$

where $\underline{R}$ is the universal gas constant and $\underline{m}$ the molal mass for the gas of interest. When utilizing the first and second law of thermodynamics, along with the perfect gas equation, it can be shown that the specific heats, c_p, c_v, specific enthalpy, h, specific internal energy, u, and pressure ratios relative to a base temperature, P_r, are functions solely of the absolute temperature. Normally a single substance in a single state of either solid, liquid, or gas requires two independent properties to determine its state.

Since the majority of gas turbines operate as open cycle using air as the working fluid, excerpted tables in English and SI units for a limited range of selected properties are included in Table 1, (*Gas Tables*, Keenan, J.H. and Kaye, J., John Wiley & Sons, Inc.), and Table 2, (*Thermodynamic Properties in SI*, Reynolds, W.C., Courtesy of Department of Mechanical Engineering, Stanford University). The thermodynamic properties for other gas turbine working fluids are readily available in the literature. Computer codes are likewise available for most of the common working fluids found in gas turbine usage, which is most convenient in performing this type of cycle analysis.

6.0 CONTINUITY EQUATION

In simple systems, where processes occur without nuclear reactions, the continuity equation is a statement of the observation that all of the mass under consideration is accounted for, i.e., the conservation of mass is preserved.

Systems, as such, are defined by an arbitrarily selected boundary to encompass the device, or volume, to be analyzed--thus, the "open" or "closed" system or simply the "control volume." Open or closed refer to whether or not any mass crosses the boundary during the time of observation. The control volume can be viewed during an instant of time, as a photograph, or over a specified time interval, as a growth process. In either case, the continuity equation states:

$$\sum \text{mass in} = \sum \text{mass out} + \sum \text{mass stored} \qquad (11)$$

It is important when indicating the direction in which any mass flows that this direction be appropriately accounted for in the equation; for if, in the calculations, an inflow or outflow determination turns out to have a negative sign, it means only the perceived direction is otherwise.

For the case of an instant of time, the operational form of Eq. (11) is:

$$\sum \dot{m}_1 = \sum \dot{m}_2 + \sum (dm/dt)_{stored} \qquad (12)$$

where 1 is "in," 2 is "out," and the dot quantities, $\dot{m}$, imply the instantaneous "rate." If the process being observed is "steady state," the term, dm/dt, would be zero.

For the case of an interval of time, the operational form of Eq. (10) is:

$$\sum dM_1 = \sum dM_2 + \sum dM_{stored} \qquad (13)$$

Again, if the process is steady state, dM_{stored} would be zero.

While these statements seem rather simple, in many of the gas turbine designs there are many places the working fluid can be diverted for such things as cooling air for turbine blades and nozzles, combustion control, auxiliaries' use, pressure level control and others. Sometimes careful bookkeeping is needed to account for all the various "masses."

7.0 FIRST LAW OF THERMODYNAMICS

The principle which states that energy is conserved for any system, either open or closed, is the first law of thermodynamics. For the usual energy analysis of a system, the continuity equation for mass is applied along with the conservation of energy. The more general formulation which relates the interchange of energy and mass, as put forth by Einstein, is excluded in this treatment, i.e., no nuclear reactions are occurring.

The general formulation of the first law of thermodynamics for a control volume at either an instant of time or an interval of time is:

$$\sum \text{energy in} = \sum \text{energy out} + \sum \text{energy stored} \qquad (14)$$

with the requirements that system boundaries be defined, all energy forms be recognized, and those energy forms crossing the system boundaries and undergoing change within the boundaries be specified.

The operational form of Eq. (14) should include all of those previously listed energy forms associated with the gas turbine. However, in many cases some of these forms are either negligible due to small changes as they pass through the control volume or are completely absent. For instance, when only the compressor component of a gas turbine is considered, the change in the potential energy of position for the gas as it enters and leaves the system is certainly very small relative to all the other energy changes involved. Also there is no internal chemical energy involved at all. Further, if the process is operating at "steady state," there is no change in the internal thermal energy stored. There is flow work since mass is crossing the boundaries even though, through the continuity equation, the $mass_{in}$ equals the $mass_{out}$. Finally, if the compressor (control volume) is well insulated so there is effectively no heat transfer to, or from, the system, heat energy will not be an item; this means the system is "adiabatic." So Eq. (14) for an instant of time would become:

$$\dot{W}_c + \dot{m}\,[u + p/\rho + V^2/2]_1 = \dot{m}\,[u + p/\rho + V^2/2]_2 \qquad (15)$$

Table 1. Thermodynamic Properties of Low Density Air in English Units

T R	h Btu/lbm	Pr	T R	h Btu/lbm	Pr	T R	h Btu/lbm	Pr
400	95.53	0.4858	900	216.26	8.411	1400	342.90	42.88
410	97.93	0.5295	910	218.72	8.752	1410	345.52	44.06
420	100.32	0.5760	920	221.18	9.102	1420	348.14	45.26
430	102.71	0.6253	930	223.64	9.463	1430	350.75	46.49
440	105.11	0.6776	940	226.11	9.834	1440	353.37	47.75
450	107.50	0.7329	950	228.58	10.216	1450	356.00	49.03
460	109.90	0.7913	960	231.06	10.610	1460	358.63	50.34
470	112.30	0.8531	970	233.53	11.014	1470	361.27	51.68
480	114.69	0.9182	980	236.02	11.430	1480	363.89	53.04
490	117.08	0.9868	990	238.50	11.858	1490	366.53	54.43
500	119.48	1.0590	1000	240.98	12.298	1500	369.17	55.86
510	121.87	1.1349	1010	243.48	12.751	1510	371.82	57.30
520	124.27	1.2147	1020	245.97	13.215	1520	374.47	58.78
530	126.66	1.2983	1030	248.45	13.692	1530	377.11	60.29
540	129.06	1.3860	1040	250.95	14.182	1540	379.77	61.83
550	131.46	1.4779	1050	253.45	14.686	1550	382.42	63.40
560	133.86	1.5742	1060	255.96	15.203	1560	385.08	65.00
570	136.26	1.6748	1070	258.47	15.734	1570	387.74	66.63
580	138.66	1.7800	1080	260.97	16.278	1580	390.40	68.30
590	141.06	1.8899	1090	263.48	16.838	1590	393.07	70.00
600	143.47	2.005	1100	265.99	17.413	1600	395.74	71.73
610	145.88	2.124	1110	268.52	18.000	1610	398.42	73.49
620	148.28	2.249	1120	271.03	18.604	1620	401.09	75.29
630	150.68	2.379	1130	273.56	19.223	1630	403.77	77.12
640	153.09	2.514	1140	276.08	19.858	1640	406.45	78.99
650	155.50	2.655	1150	278.61	20.51	1650	409.13	80.89
660	157.92	2.801	1160	281.14	21.18	1660	411.82	82.83
670	160.33	2.953	1170	283.68	21.86	1670	414.51	84.80
680	162.73	3.111	1180	286.21	22.56	1680	417.20	86.82
690	165.15	3.276	1190	288.76	23.28	1690	419.89	88.87
700	167.56	3.446	1200	291.30	24.01	1700	422.59	90.95
710	169.98	3.623	1210	293.86	24.76	1710	425.29	93.08
720	172.39	3.806	1220	296.41	25.53	1720	428.00	95.24
730	174.82	3.996	1230	298.96	26.32	1730	430.69	97.45
740	177.23	4.193	1240	301.52	27.13	1740	433.41	99.69
750	179.66	4.396	1250	304.08	27.96	1750	436.12	101.98
760	182.08	4.607	1260	306.65	28.80	1760	438.83	104.30
770	184.51	4.826	1270	309.22	29.67	1770	441.55	106.67
780	186.94	5.051	1280	311.79	30.55	1780	444.26	109.08
790	189.38	5.285	1290	314.36	31.46	1790	446.99	111.54
800	191.81	5.526	1300	316.94	32.39	1800	449.71	114.03
810	194.25	5.775	1310	319.53	33.34	1810	452.44	116.57
820	196.69	6.033	1320	322.11	34.31	1820	455.17	119.16
830	199.12	6.299	1330	324.69	35.30	1830	457.90	121.79
840	201.56	6.573	1340	327.29	36.31	1840	460.63	124.47
850	204.01	6.856	1350	329.88	37.35	1850	463.37	127.18
860	206.46	7.149	1360	332.48	38.41	1860	466.12	129.95
870	208.90	7.450	1370	335.09	39.49	1870	468.86	132.77
880	211.35	7.761	1380	337.68	40.59	1880	471.60	135.64
890	213.80	8.081	1390	340.29	41.73	1890	474.35	138.55

Table 1. Thermodynamic Properties of Low Density Air in English Units (Continued)

T R	h Btu/lbm	Pr	T R	h Btu/lbm	Pr	T R	h Btu/lbm	Pr
1900	477.09	141.51	2200	560.59	256.6	2500	645.78	435.7
1910	479.85	144.53	2210	563.41	261.4	2510	648.65	443.0
1920	482.60	147.59	2220	566.23	266.3	2520	651.51	450.5
1930	485.36	150.70	2230	569.04	271.3	2530	654.38	458.0
1940	488.12	153.87	2240	571.86	276.3	2540	657.25	465.6
1950	490.88	157.10	2250	574.69	281.4	2550	660.12	473.3
1960	493.64	160.37	2260	577.51	286.6	2560	662.99	481.1
1970	496.40	163.69	2270	580.34	291.9	2570	665.86	489.1
1980	499.17	167.07	2280	583.16	297.2	2580	668.74	497.1
1990	501.94	170.50	2290	585.99	302.7	2590	671.61	505.3
2000	504.71	174.00	2300	588.82	308.1	2600	674.49	513.5
2010	507.49	177.55	2310	591.66	313.7	2610	677.37	521.8
2020	510.26	181.16	2320	594.49	319.4	2620	680.25	530.3
2030	513.04	184.81	2330	597.32	325.1	2630	683.13	538.9
2040	515.82	188.54	2340	600.16	330.9	2640	686.01	547.5
2050	518.61	192.31	2350	603.00	336.8	2650	688.90	556.3
2060	521.39	196.16	2360	605.84	342.8	2660	691.79	565.2
2070	524.18	200.06	2370	608.68	348.9	2670	694.68	574.2
2080	526.97	204.02	2380	611.53	355.0	2680	697.56	583.3
2090	529.75	208.06	2390	614.37	361.3	2690	700.45	592.5
2100	532.55	212.1	2400	617.22	367.6	2700	703.35	601.9
2110	535.35	216.3	2410	620.07	374.0			
2120	538.15	220.5	2420	622.92	380.5			
2130	540.94	224.8	2430	625.77	387.0			
2140	543.74	229.1	2440	628.62	393.7			
2150	546.54	233.5	2450	631.48	400.5			
2160	549.35	238.0	2460	634.34	407.3			
2170	552.16	242.6	2470	637.20	414.3			
2180	554.97	247.2	2480	640.05	421.3			
2190	557.78	251.9	2490	642.91	428.5			

(Excerpted from Gas Tables, Joseph H. Keenan and Joseph Kaye, Copyright 1948. Reprinted from Gas Tables, 12th printing April 1966, by permission John Wiley & Sons, Inc., Publishers)

where 1 is "in" and 2 is "out" for the control volume. The work of compression would then be found as:

$$\dot{W}_c = \dot{m}\,[(u + p/\rho)_2 - (u + p/\rho)_1]$$

$$+ \dot{m}\,[V_2^2 - V_1^2]/2$$

$$= \dot{m}\,[h_2 - h_1] + \dot{m}\,[V_2^2 - V_1^2]/2$$

$$= \dot{m}\,[(h + V^2/2)_2 - (h + V^2/2)_1]$$

$$= \dot{m}\,[h_{02} - h_{01}] \quad W, \text{[Btu/sec]} \qquad (16)$$

where the definitions of enthalpy, h, and "stagnation condition" have been introduced. The latter means that state to which the velocity has been reduced to zero. For a time interval:

$$dW_c = dM\,[(u + p/\rho)_2 - (u + p/\rho)_1]$$

$$+ dM\,[V_2^2 - V_1^2]/2$$

$$= dM\,[h_2 - h_1] + dM\,[V_2^2 - V_1^2]/2$$

Table 2. Thermodynamic Properties of Low Density Air in SI Units
(Courtesy Department of Mechanical Engineering, Stanford University)

T K	h kJ/kg	P_r	T K	h kJ/kg	P_r	T K	h kJ/kg	P_r	T K	h kJ/kg	P_r
200	359.8	17.81	500	662.8	445.0	800	981.4	2520.	1100	1319.9	8797.
205	364.8	19.41	505	668.0	461.1	805	986.9	2581.	1105	1325.7	8959.
210	369.8	21.11	510	673.1	477.7	810	992.4	2643.	1110	1331.5	9124.
215	374.8	22.92	515	678.3	494.8	815	997.9	2706.	1115	1337.3	9291.
220	379.8	24.84	520	683.4	512.3	820	1003.4	2770.	1120	1343.1	9460.
225	384.9	26.86	525	688.6	530.2	825	1008.9	2836.	1125	1348.9	9632.
230	389.9	29.01	530	693.8	548.6	830	1014.4	2902.	1130	1354.7	9807.
235	394.9	31.27	535	699.0	567.5	835	1019.9	2970.	1135	1360.5	9983.
240	399.9	33.65	540	704.1	586.9	840	1025.5	3039.	1140	1366.3	10163.
245	404.9	36.17	545	709.3	606.7	845	1031.0	3110.	1145	1372.1	10345.
250	409.9	38.81	550	714.5	627.1	850	1036.5	3181.	1150	1378.0	10529.
255	414.9	41.59	555	719.7	648.0	855	1042.1	3254.	1155	1383.8	10716.
260	419.9	44.51	560	724.9	669.4	860	1047.6	3328.	1160	1389.6	10906.
265	425.0	47.57	565	730.1	691.3	865	1053.2	3404.	1165	1395.4	11098.
270	430.0	50.78	570	735.3	713.8	870	1058.7	3481.	1170	1401.3	11293.
275	435.0	54.14	575	740.5	736.8	875	1064.3	3559.	1175	1407.1	11490.
280	440.0	57.66	580	745.8	760.4	880	1069.9	3638.	1180	1413.0	11691.
285	445.0	61.34	585	751.0	784.6	885	1075.4	3719.	1185	1418.8	11894.
290	450.0	65.19	590	756.2	809.3	890	1081.0	3802.	1190	1424.7	12100.
295	455.1	69.20	595	761.5	834.6	895	1086.6	3886.	1195	1430.5	12309.
300	460.1	73.39	600	766.7	860.6	900	1092.2	3971.	1200	1436.4	12520.
305	465.1	77.76	605	772.0	887.1	905	1097.8	4058.	1205	1442.2	12735.
310	470.1	82.32	610	777.2	914.2	910	1103.4	4146.	1210	1448.1	12952.
315	475.1	87.06	615	782.5	942.0	915	1109.0	4235.	1215	1454.0	13172.
320	480.2	91.99	620	787.8	970.4	920	1114.6	4327.	1220	1459.8	13395.
325	485.2	97.13	625	793.0	999.5	925	1120.2	4419.	1225	1465.7	13622.
330	490.2	102.5	630	798.3	1029.	930	1125.9	4514.	1230	1471.6	13851.
335	495.3	108.0	635	803.6	1060.	935	1131.5	4610.	1235	1477.5	14083.
340	500.3	113.8	640	808.9	1091.	940	1137.1	4707.	1240	1483.4	14318.
345	505.3	119.7	645	814.2	1123.	945	1142.8	4806.	1245	1489.3	14557.
350	510.4	125.9	650	819.5	1155.	950	1148.4	4907.	1250	1495.2	14798.
355	515.4	132.4	655	824.8	1188.	955	1154.1	5010.	1255	1501.0	15043.
360	520.4	139.0	660	830.1	1222.	960	1159.7	5114.	1260	1507.0	15291.
365	525.5	145.9	665	835.4	1257.	965	1165.4	5219.	1265	1512.9	15542.
370	530.5	153.1	670	840.8	1292.	970	1171.0	5327.	1270	1518.8	15797.
375	535.6	160.5	675	846.1	1329.	975	1176.7	5436.	1275	1524.7	16054.
380	540.6	168.1	680	851.4	1366.	980	1182.4	5547.	1280	1530.6	16315.
385	545.7	176.1	685	856.8	1403.	985	1188.1	5660.	1285	1536.5	16580.
390	550.7	184.2	690	862.1	1442.	990	1193.7	5775.	1290	1542.4	16847.
395	555.8	192.7	695	867.5	1481.	995	1199.4	5891.	1300	1554.3	17393.
400	560.8	201.4	700	872.9	1521.	1000	1205.1	6009.	1310	1566.1	17953.
405	565.9	210.5	705	878.2	1563.	1005	1210.8	6130.	1320	1578.0	18526.
410	571.0	219.8	710	883.6	1604.	1010	1216.5	6252.	1330	1589.9	19114.
415	576.0	229.4	715	889.0	1647.	1015	1222.2	6376.	1340	1601.8	19717.
420	581.1	239.3	720	894.4	1691.	1020	1227.9	6501.	1350	1613.7	20335.
425	586.2	249.6	725	899.8	1735.	1025	1233.7	6629.	1360	1625.6	20968.
430	591.3	260.1	730	905.2	1781.	1030	1239.4	6759.	1370	1637.6	21617.
435	596.4	271.0	735	910.6	1827.	1035	1245.1	6891.	1380	1649.5	22281.
440	601.5	282.2	740	916.0	1875.	1040	1250.8	7025.	1390	1661.5	22961.
445	606.5	293.7	745	921.4	1923.	1045	1256.6	7161.	1400	1673.5	23658.
450	611.6	305.6	750	926.8	1972.	1050	1262.3	7299.	1410	1685.4	24372.
455	616.7	317.8	755	932.3	2022.	1055	1268.0	7439.	1420	1697.4	25102.
460	621.8	330.4	760	937.7	2073.	1060	1273.8	7581.	1430	1709.4	25849.
465	627.0	343.4	765	943.1	2126.	1065	1279.5	7725.	1440	1721.4	26614.
470	632.1	356.7	770	948.6	2179.	1070	1285.3	7872.	1450	1733.5	27397.
475	637.2	370.4	775	954.0	2233.	1075	1291.1	8020.	1460	1745.5	28193.
480	642.3	384.6	780	959.5	2288.	1080	1296.8	8171.	1470	1757.6	29017.
485	647.4	399.0	785	965.0	2345.	1085	1302.6	8324.	1480	1769.6	29856.
490	652.6	414.0	790	970.4	2402.	1090	1308.4	8479.	1490	1781.7	30713.
495	657.7	429.3	795	975.9	2461.	1095	1314.1	8637.	1500	1793.7	31589.

(Courtesy Department of Mechanical Engineering, Stanford University)