Alternative Fuels

ALTERNATIVE FUELS

Chemical Energy Resources

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Preface

The whole concept of energy, its resources and consumption, was brought sharply into relief late in 1973 when the Western world was faced with massive increases in price and, on occasions, actual shortfalls in supplies. The end of the era of 'cheap energy' has been proclaimed frequently ever since, and predictions of future energy patterns and policies have featured in all forms of discussion, debate and dissemination. The vital nature of an assured supply of energy, at realistic costs, has now been recognised for the continuation, let alone development, of our lifestyles, and concern is felt by many over the impending gap which appears to be inevitable at the turn of this century between the eventual demise of some conventional fossil fuels, and the emergence of long-term replacements. Throughout the world, many active research programmes are directed towards the long-term harnessing of alternative sources of energy including wind, waves, tides, geothermal, direct solar radiation and nuclear fusion. From the viewpoint of fuel, as distinct from overall energy, this gap may well be postponed by the more logical conversion and use of the more enduring and available fossil-based fuels, and eventually filled to a large extent by means of fuels derived from alternative, replenishable sources. Both actions will help to provide a 'breathing period' for further development of alternative sources of energy.

This present work attempts to explore briefly the candidate alternative chemical fuels, in terms of their nature, availability, production, properties, combustion performance, emission characteristics, handling problems and, tentatively, possible future costs. It concerns fuels intended for oxidation only, either via combustion or by direct conversion in a fuel cell, and so excludes nuclear fuels and also the wider remit of alternative energy sources. In general, the fuels considered are by no means newcomers to the energy scene, but the incentive in the past has been to seek improved performance, whereas the present criterion is for continuing availability, with reasonable performance as an important but secondary issue.

For each geographical region at any given time, certain practices will be well established and classed as conventional, whereas others are either new or projected, and thus alternative. As these new practices themselves achieve

wide acceptance, they also become conventional, and the projected, if successful, become new. The dividing lines between these classes are not always clearly definable, and some fuels considered here may well have become commonplace in some parts of the world by the time the printing ink is dry! However, since a background picture of conventional fuels is essential as a comparative base from which to assess the potential of the alternative fuels, a brief review of conventional fuels is given in the early part of the book, and the dividing line between these two main types of fuel can be imagined steadily working its way through the book with the passage of time as the alternatives graduate to the conventional.

Energy, economics and the environment are inseparably linked within a modern society, and must be considered together in future planning. Limitation in demand by energy thrift, and protection of the environment from combustion-generated pollutants, are equally necessary. However, it was decided at the outset of this project to concentrate on the technical potential of alternative fuels as a stop-gap prior to the emergence of some new and copious energy source, and to refer only occasionally to the other related topics, which are dealt with in detail elsewhere.

As shown by the chapter headings, the layout of the book consists essentially of an initial background survey of conventional fuels, followed by a suggested classification of the alternative fuels of interest. After reviewing the theoretical and likely practical combustion processes of these alternatives, a summary is made of their reported laboratory and field performance in various types of combustor. Complementary data on the handling characteristics of these fuels are then examined, and the work concludes with a summary of the techniques proposed for the future production of the most promising of the alternative fuels, together with some forecasts of possible fuel utilisation patterns in the major energy-consuming sectors, and fuel costs. For ease of reference, all the major chemical reactions are numbered consecutively. A more detailed treatment of the book layout is made the subject of the introductory chapter.

By illustrating the range and availability of the various types of alternative fuel, the book identifies a substantial ray of hope for the future in an energy-hungry world, provided the options are managed with wisdom and justice, in the absence of some colossal accident or act of folly. The author feels confident that the energy problem can be met, and even cautiously optimistic that it will be. But the fact remains that the lead time for most of the technological developments discussed bears a striking resemblance to the period when fossil fuel production will already be well in decline. It would seem imperative, therefore, for a balance to be struck without delay between the conflicting needs to maintain a flexible approach and yet make firm decisions. To quote John R. Kiely of the World Energy Conference, 'Long term programmes, resolutely pursued, are required: and they are required now.'

A prologue to such a policy is a detailed study of all the likely fuel options available; consequently this book is offered as one convenient format for the collation and analysis of much relevant data scattered about the literature. It is a contribution to the creation of, in the words of Jean Monet, 'a common language between those who know and those who decide'. It is intended to serve the fuel specialist and decision-maker alike. In the event, of course, the successful exploitation of nuclear fusion, outgassing methane from the Earth's surface, or some as yet undiscovered energy bonanza may render most of these materials superfluous. However, until the dawning of that happy day, the creation of an insurance policy in the form of alternative fuels would seem more than prudent.

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Cranfield, 1979

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Units

In any system of units, a number of quantities are defined as basic to the system, and all the remaining quantities derived from them. If the system is coherent, the products and quotients of any two or more unit quantities themselves become the units of the derived quantities, in the absence of any conversion factors or proportionality constants. The rationalised system of metric units known as SI (Système International d'Unités) is coherent in this way, and applies to all branches of science and engineering.

The quantities and units of interest in this study consist of the following.

	<i>Quantity</i>	<i>Unit</i>	<i>Symbol</i>
<i>(Basic)</i>	length	metre	m
	mass	kilogram	kg
	time	second	s
	electric current	ampere	A
	thermodynamic temperature	kelvin	K
	amount of substance	mole	mol
<i>(Derived)</i>	force	newton	N (= kg m/s ²)
	pressure	pascal	Pa (= N/m ²)
	energy	joule	J (= N m)
	power	watt	W (= J/s)

No change is made to any symbol to indicate the plural, and quantities are expressed in units which result in numerical values between 0.1 and 1000, with preferred single multiples and sub-multiples that differ in stages of 10 raised to a power which is a multiple of ± 3 , ranging normally from 10^{18} , exa, to 10^{-18} , atto. Those used most commonly in this study are as follows.

<i>Factor</i>	<i>Prefix</i>	<i>Symbol</i>
10^{18}	exa	E
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ

SI has been adopted by various industries (for example, *Recommended SI units*, Institute of Petroleum, London, 1970), some of which also use earlier metric units (litre, bar, centipoise, centistokes) together with non-metric units (atmosphere) which are considered acceptable. Since the adoption of SI is not yet worldwide, the following conversion factors and other metric relationships are given.

Length	1 in. = 25.4 mm 1 ft = 0.304 8 m 1 mile = 1.609 km
Volume	1 ft ³ = 0.028 32 m ³ 1 UK gal = 1.201 US gal = 4.546 l 1 US gal = 0.832 7 UK gal = 3.785 l 1 US barrel = 34.97 UK gal = 42 US gal = 158.9 l
Mass	1 lb = 0.453 6 kg 1 (long) ton = 2240 lb = 1016 kg 1 short ton = 2000 lb = 907.6 kg 1 tonne = 0.984 2 (long) ton = 1000 kg = 1 Mg
Density	1 lb/ft ³ = 16.02 kg/m ³
Force	1 lbf = 4.448 N
Pressure	1 lbf/in. ² = 6.895 kPa 1 mm Hg = 133.3 Pa 1 atm = 1.013 25 bar = 101.325 kPa 1 bar = 100 kPa = 10⁵ Pa
Energy	1 Btu = 1.055 kJ 1 Chu = 1.899 kJ 1 kcal (international table) = 4.186 8 kJ 1 kcal (thermochemical) = 4.184 kJ 1 kW h = 3.6 MJ 1 hp h = 2.685 MJ 1 therm = 10⁵ Btu = 105.5 MJ
Specific energy	1 Btu/lb = 2.326 kJ/kg 1 Chu/lb = 4.186 8 kJ/kg
Specific energy capacity	1 Btu/lb °R = 1 Chu/lb K = 4.186 8 kJ/kg K 1 Btu/ft ³ = 0.037 26 kJ/l (or MJ/m ³) 1 Chu/ft ³ = 0.067 07 kJ/l (or MJ/m ³) 1 Btu/UK gal = 0.232 1 kJ/l (or MJ/m ³)
Power	1 hp = 745.7 W

(Figures in bold type are exact)

Approximate Fuel Energy Equivalents

	b.o.e.	t.o.e.	t.c.e.	c.m.n.g.e.
1 barrel oil equivalent (b.o.e.)	1	0.136	0.211	163
1 tonne oil equivalent (t.o.e.)	7.35	1	1.55	1200
1 tonne coal equivalent (t.c.e.)	4.74	0.645	1	775
1 cubic metre natural gas equivalent (c.m.n.g.e.)	0.006	83×10^{-3}	1.29×10^{-3}	1

Note: 100 ppm = 0.01%

Notation

(Customary units are given)

<i>a</i>	annually
<i>A/F</i>	air/fuel molar ratio
<i>a/f</i>	air/fuel mass ratio
API	American Petroleum Institute
BFG	blast furnace gas
bp	boiling point (°C)
BWG	blue water gas
CFR	Co-operative Fuel Research
CHP	combined heat and power
COG	coke oven gas
CPG	coke producer gas
CTF	coal tar fuel
CWG	carburetted water gas
daf	dry ash-free
dmmf	dry mineral-matter-free
<i>E</i>	electrical potential
<i>E_{ign}</i>	ignition energy (mJ)
EAD	equilibrium air distillation
fbp	final boiling point (°C)
FL	flash point (°C)
<i>G</i>	Gibbs free-energy molar function (kJ/mol)
(g)	gaseous phase
(gr)	graphite
<i>H</i>	molar enthalpy (kJ/mol)
H/C	hydrogen/carbon atomic (or molar) ratio
HTP	high test peroxide (concentrated H ₂ O ₂)
<i>I</i>	specific impulse (N s/kg, or N s/l)
ibp	initial boiling point (°C)

imep	indicated mean effective pressure (kPa)
IP	Institute of Petroleum
K	equilibrium constant
k	rate constant
L	liquid volume
(l)	liquid phase
LNG	liquefied natural gas
LPG	liquefied petroleum gases
m	moles of oxygen per mole of fuel
MM	molar mass (g/mol)
mp	melting point ($^{\circ}\text{C}$)
n	moles of given product per mole of fuel
NASA	National Aeronautics and Space Administration
NCB	National Coal Board
n-f	non-flow
NG	natural gas
NO_x	mixed oxide products of nitrogen
p	pressure (kPa)
PI	performance index
P/R	products/reactants molar ratio
Q	calorific value (MJ/kg, MJ/l, or MJ/m ³)
Q	heat transfer
r	ratio
R, R', etc.	radicals
R_0	universal gas constant (kJ/mol K)
rel d	relative density
RFNA	red fuming nitric acid
RFO	residual fuel oil
RON	research octane number
S	entropy
(s)	solid phase
s-f	steady-flow
sfc	specific fuel consumption
SIT	spontaneous ignition temperature ($^{\circ}\text{C}$)
SMW	solid municipal waste
SNG	supplemental natural gas
T	absolute thermodynamic temperature (K)
tdc	top dead centre
TEB	triethyl borane
TEL	tetraethyllead
TML	tetramethyllead
TVO	tractor vaporising oil
U	internal energy
UBF	unburnt fuel

UDMH	unsymmetrical dimethylhydrazine
UFL	upper flash point ($^{\circ}\text{C}$)
UHC	unburnt hydrocarbons
V	volume
V	vapour volume
VP	vapour pressure
W	work transfer
Wo	Wobbe number (MJ/m^3)
x	carbon number
α	cut-off ratio in diesel cycle
γ	ratio of c_p/c_v for ideal gas
Δ	finite change in a quantity
η	efficiency
ϕ	equivalence ratio

Superscripts

0	standard state of 25°C (298.15 K) and 1 atm
$'$	concentration basis
$*$	algebraic sum of sensible and standard formation values

Subscripts

a	atomisation
ad	adiabatic
F	forward
f	formation
gr	gross value
I	initial
i	any arbitrary reactant component
j	any arbitrary product component
max	maximum
min	minimum
net	net value
P	product
p	pressure or constant pressure
R	reactant
R	reverse
r	reaction
s	stoichiometric
sp	specific
T	total
v	volume or constant volume