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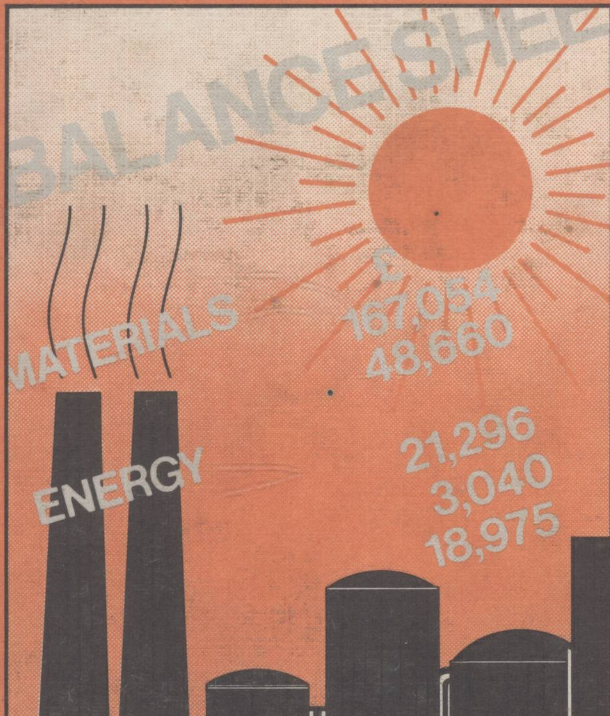

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PLENARY PAPERS
Introducing the Six Themes of the Symposium

PLENARY LECTURES

Contents

THERMODYNAMICS AND ECONOMICS - IS THERE A CONFLICT ?

W.R. Hawthorne*

The paper discusses the role of thermodynamics in engineering using some prime movers to illustrate its application. It suggests that the conflict between economics and thermodynamics has been sharpened by the energy crisis, and gives examples illustrating how past failures to give sufficient weight to thermodynamic efficiency have over-stocked us with plants and buildings whose fuel costs are now an unnecessarily heavy burden. It is suggested that incorrect economic signals may lead to the same result in future.

INTRODUCTION

Thermodynamics, the science of the relationship between heat, work and the properties of systems, is not much more than twice as old as this Institution. Unlike most other sciences, its origins stem more from the study of machines and man-made processes than the study of natural phenomena. It has been said that thermodynamics owed more to the steam engine than the steam engine to thermodynamics. It is certainly true that Newcomen's steam engines for pumping water were in use for nearly a century before Rumford attacked the caloric theory and measured the mechanical equivalent of heat. And it was not until 1824 that Carnot, in attempting to answer the question, "What is the maximum theoretical efficiency of an engine working between two prescribed temperature limits ?", laid the foundations of the Second Law of Thermodynamics. Contributions from Joule, Clausius, Helmholtz, Kelvin, Maxwell and others were necessary before the laws of classical thermodynamics were formulated in the mid-nineteenth century. Of great importance to chemical engineers was the work of Willard Gibbs, who in 1878 set out the criteria of thermodynamic equilibrium and laid the basis of chemical thermodynamics. The laws of thermodynamics and their corollaries not only enable us to define the actual and potential efficiencies of an engine, but also to do the same for any individual process, either in an engine or a chemical plant. We also use them in the derivation of the properties of the substances which we are using in our plants. Provided this can be done accurately, we can obtain an analytical model of thermodynamic processes which may either be used for the optimization of the

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design of an engine or a plant, or as a means for assessing the direction and success of research work aimed at improving its performance.

Improvements in the efficiency of plants and processes have occurred mainly because improved technology has enabled more output per unit of fuel input to be achieved at the same or lower capital cost. Quite often the cost of fuels relative to other costs in a process has led to the installation of more efficient but more expensive equipment. On the other hand, in the past most energy prices have decreased in real terms, and the saving of labour and other costs has been as large or larger an element in the economic balance as the saving of fuel costs. From time to time, governments have encouraged and even enforced fuel and power conservation for strategic or other reasons.

Thermodynamics of Engines

The pressure to improve efficiency may take different forms, as for instance in aircraft propulsion, where the sum of engine and fuel weights has a critical effect on the payload. Table I illustrates the effect of technological improvements on the performance of jet engines between 1946 and 1977. Substantial improvements, not only in overall efficiency, but also in component efficiencies and weights, have clearly been achieved, as shown by the reduction

TABLE I - RB.211 and Derwent V comparison.

	RB.211-22B	RB.211-524B	Derwent V
Data for: Take-off - Static - Sea Level - ISA			
In-service date	1972	1977	1946
Thrust, lb	42 000	50 000	3500
Specific fuel cons, lb/hr/lb	0.35	0.36	1.01
Airflow, lb/sec	1380	1520	60
Pressure ratio	25	27	4
Bypass ratio	5.0	4.5	0
Turbine entry gas temp, ^oK (^oF)	1430 (2120)	1470 (2190)	1110 (1540)
Jet velocity, ft/sec	1300 and 890	1400 and 970	1880
Thrust/Weight	4.7	5.1	2.8
Thrust/Airflow	30.5	33.0	58.5
Data for: Max cruise at 35 000 ft and 0.85 Mach			
Thrust, lb (inc bypass duct losses)	9000	10 650	1100
Specific fuel cons, lb/hr/lb	0.64	0.66	1.3
Airflow, lb/sec	614	640	25
Pressure ratio	28.2	29.2	4.1
Bypass ratio	4.8	4.4	0
Turbine entry gas temp, ^oK (^oF)	1330 (1940)	1370 (2010)	1060 (1450)
Jet velocity, ft/sec	1750 and 1200	1840 and 1280	2200
Thrust/Weight	1.01	1.08	0.88
Thrust/Airflow	14.6	16.6	44.0

of specific fuel consumption at cruising from 1.3 to 0.64 kg/hr/kg of thrust. The increase of compressor pressure ratio from 4 to 27, when accompanied by reductions in both overall specific fuel consumption and specific weight (or an increase in thrust/weight ratio), indicates that a significant improvement in stage efficiency in compressors and turbines has been achieved even while their loading has been substantially increased and the number of stages, and hence the weight required to obtain a certain pressure ratio, have been reduced.

The aero-engine provides a good example to illustrate the way in which thermodynamics may be used for analysis and design. Fuel carried in the aircraft reacts with air from the atmosphere to produce enough thrust to propel the aircraft. Now thermodynamics tells us that the maximum work we can get out of a kilogram of fuel is given to us by the change in free energy between the reacting fuel and air, and the products when they finally reach equilibrium in the atmosphere. By imagining that this work is used in the most efficient way possible to propel the aircraft, we can calculate the theoretical minimum specific fuel consumption for the thermodynamically perfect engine. Some examples of these calculations are given in Table II, which shows the minimum specific fuel consumptions for thermodynamically reversible engines using different fuels under the cruising conditions of Table I.

TABLE II - Lower calorific value, Gibbs Free Energy and specific fuel consumption for simple fuels at 11 000 m altitude. Pressure 22 632 N/m^2. Temperature 216.65K.

Fuel	Net or Lower ΔH	ΔG	$\Delta H/\Delta G$	ΔG*	Specific$^+$ fuel consumption kg/hr/kg
H_2	241.2	230.9	0.957	248.0	0.072
C (solid)	393.7	394.4	1.002	406.2	0.261
CO	282.5	263.0	0.931	276.2	0.897
CH_4	803.6	801.8	0.998	845.0	0.168
C_2H_4	1324.9	1317.8	0.995	1372.8	0.181
C_2H_6	1430.5	1440.6	1.007	1511.3	0.176
C_3H_8	2047.7	2070.3	1.011	2168.3	0.180
C_8H_{18} (liquid)	5079.0	5191.7	1.022	5427.2	0.186
H_2O	0	0		17.17	9.0

*Reactants and products at pressure corresponding to their partial pressure in the atmosphere, CO_2 300 ppm. H_2O (100% relative humidity).

$^+$Flight at M = 0.85. Kinetic energy of fuel included.

For the fuel closest to aviation fuel (C_8H_{18}), it will be seen that a figure of about 0.19 kg/hr/kg of thrust is obtained. When we compare this figure with that obtained in practice, namely just over 0.6 kg/hr/kg, it appears at first sight that there is still substantial room for improvement in the fuel economy of aero-engines. But it is at once a strength and a weakness of this thermodynamic calculation that we do not need to prescribe anything other than the properties of the reactants and products, and some of the properties of the atmosphere in which we are flying. The difficulties begin when we have to describe the engine and propulsive equipment. Here some stretch of the imagination is required and we have, for instance, to visualise a reversible fuel cell which drives through an electrical and mechanical transmission of zero loss a propeller of practically infinite diameter. Clearly there are grave practical difficulties with any such propulsion system, even though some loss of efficiency were tolerated, and the fuel cell were placed on some suitable mountain peak with an electric cable stretching up to the aircraft! At this point, there is no need to reject thermodynamics. We proceed by projecting practical engines and propulsive systems whose performance we can analyse, using thermodynamic principles and properties. Such analysis is comparatively simple for aero-engines based on gas turbines. A whole range of calculations can be made for differing compressor pressure ratios, fan bypass ratios, and turbine inlet temperatures. The main difficulty in these so-called cycle calculations is the estimation of the efficiencies or irreversibilities which are involved in the various processes of compression, expansion, and combustion at high speed, etc. The improvement of such efficiencies has been the subject of much research and development, and thermodynamics may be said to hold a watching brief over such research, particularly when it is concerned with the cooling of turbine blades, mixing of streams and combustion at high speeds.

In the Otto and Diesel cycle engines, thermodynamic analysis is more difficult. The flow is essentially unsteady and not adiabatic, and the processes of compression, combustion and expansion all occur in the same volume the size of which varies periodically. Nevertheless, the modelling and analysis of the processes in the cylinder have been reasonably successful, and considerably more progress can be expected in all aspects, including that of the estimation of the emissions. In spite of the difficulties of accurate modelling, and as a result of intensive development and research on piston engines, one of them - the diesel engine - has achieved thermal efficiencies of only just under 50%, making it the most efficient of the commercial prime movers which use fossil fuels. Improvement in its efficiency appears possible by further optimisation of cylinder pressures and temperatures, the use of new materials and a detailed study of the various irreversibilities in and outside the cylinder. Substantial efforts have been made to adapt the gas turbine for road vehicle use and to make its cost and fuel consumption competitive with the diesel engine. At the moment, a thermodynamic efficiency of about 35% has been achieved on a truck gas turbine, but to reach present-day diesel engine fuel consumptions will require substantially higher maximum temperatures in the gas turbine and the use of ceramic combustion chambers, turbines and heat exchangers. These developments may take some time and be paralleled by further developments of the diesel engine. The social advantages of the gas turbine automotive engine, namely minimum vibration and noise and low emissions, may also be reduced as the diesel engine is improved in these respects.

Economics and the Conflict

The examples given here and in the paper by Dr. N.L. Franklin will, I hope, illustrate the role and power of thermodynamics in its application to engines and exchange and separation processes. Let us now consider the role of economics. Economics, like thermodynamics, is a word which comes to us from Greek. Its original meaning of household management was extended to include the science of managing not only households, but the resources of a people and of its government - the production and distribution of wealth in a community. Like thermodynamics, economics relies heavily on the use of models from which mathematical and numerical deductions can be made. The laws of economics are, however, much more debatable and subject to change than those of thermodynamics.

To ask whether there is a conflict between these two disciplines, one a natural science and the other a social science, is, if interpreted narrowly, relatively meaningless. The manipulation of the resources of a country or a company are determined by many factors, including its aims, its financial and labour resources, and its managerial and technical capabilities. Such topics fall definitely within the realm of economics. Most managers and governments seem to regard thermodynamics as part of the panoply of technical expertise on which they need to call from time to time when reaching decisions. It is certainly true that economists appear to be consulted more by governments and the media than thermodynamicists. On the other hand, few chemical engineering companies have been developed and launched, or can be managed, without a heavy dependence on thermodynamics. In fact, in the starting up of a new enterprise, thermodynamics and economics may play an equal role.

To give meaning to the question, "Is there a conflict between thermodynamics and economics ?", we need to interpret it in a different way. We might assume, for instance, that we are being asked whether, in the planning and design of buildings, plant and equipment, insufficient weight has been put on thermodynamic efficiency and fuel economy in comparison with the emphasis attached to economic factors such as profitability, capital cost and cash flow. To this we may add several subsidiary questions such as, "Are we retaining thermodynamically obsolete plant too long ?", "Do we introduce technical inprovements fast enough ?", and so on. Such questions offer plenty of scope for conflicting views. Those who argue in favour of thermodynamic efficiency or modernisation are not likely to be too impressed by the precision of economic forecasts or present value calculations based on predicted fuel and other costs. Arguments over the weight to be placed on thermodynamic efficiency have, of course, been known to chemical engineers for years, but the so-called energy crisis caused by the consecutive rises in the real price of oil over the last decade has sharpened them greatly, as well as making governments and the public aware of a significant change in the energy scene.

The glut of oil which we are at present experiencing, together with the effects of the economic recession, may well have obscured the message conveyed by the fact that, after nearly three hundred years of a declining real price of energy, there has been a sharp upturn, which could only be reversed if economic growth were greatly curtailed. However, even if we are at the moment on one of those low scenarios of energy supply and demand, the thermodynamicists should not give up their struggle with the economists. A few moments of hindsight may serve to justify this exhortation, at least in part.

Energy - a Renewed Challenge

Thirty years ago, coal was the principal fuel used in this country, and 70% or more of the fuel supplied to our chemical industry. It was in short supply and was rationed to households and allocated to industrial companies. A government committee published a report with some 50 recommendations, many of them concerned with thermodynamic efficiency, energy conservation and building insulation. Very few of these recommendations were accepted, because they became submerged in those great lakes of oil found in the Middle East and elsewhere, which now supply half the world's energy demand. This abundant high-quality fuel ushered in a new era of cheap and convenient energy and led to a great loss of interest in energy conservation by governments, architects and the public. As a result, about one third of our publicly-built local council houses are uninsulated, and at least one third inadequately insulated. Most industrial buildings in this country were built without any insulation whatsoever, and the majority of our building stock is well below the insulation standard of a thatched cottage. In twenty years, all sorts of other themodynamic follies were committed: combined heat and power, or co-generation, was rejected as uneconomic; work on alternative energy sources was dropped; in automobiles, acceleration was regarded as more important than fuel economy; environmental regulations were introduced, regardless of their energy expense; every gas stove had a pilot light; boilers and electric motors were oversized, and the energy required for new building heating systems went up by a factor of four or five. In the domestic sector, the extravagance in energy consumption was masked by the switch from very inefficient coal fires to oil and gas heating. Otherwise the motto was 'comfort, convenience and waste'. I expect that through this period the majority of chemical engineers played the role of the thermodynamicist, but of course lost the battle with the economists, most of whom saw no end to this era of cheap oil. The legacy of this period is still with us in the form of buildings, plant and machinery. Energy conservation measures, and government support for them, have been actively pursued in most countries in the last eight years, and much progress has been made in good housekeeping and in short pay-back projects involving modification and replacement of plant. Governments have also pledged themselves to support a switch to coal, but we should note that the consumption of coal by the U.K. chemical industry, which was more than 70% in 1952, is now somewhat less than 5%. However, we can give good marks to the U.K. cement industry which, after flirting with oil, has gone back to coal.

It seems to me that history is about to repeat itself and that the economic recession, high interest rates, and the momentary excess production capacities for oil and electricity form a still snapshot which will be used by economists and accountants to bamboozle and cozen the chemical engineer. This is no time for the chemical engineer to relax his rigour in applying thermodynamic principles to chemical processes. He needs to improve the optimisation of the design of energy-using equipment and processes by an awareness of future trends in energy supply. He should, perhaps, stand back and look again at the optimum way of using our most plentiful fossil fuel, coal, as an energy source and a feed-stock. He should look with some suspicion on the waste of energy in the conversion of coal into S.N.G. or syn-fuels, when the advantages of convenience and cleanliness can also, perhaps, be obtained by using coal directly in well-engineered equipment at a much higher overall thermodynamic efficiency. This is a challenging time for all engineers, for apart from their conventional professional expertise, they need a good working familiarity with computers and microprocessors, control techniques, materials and materials handling. In addition, they must know enough about energy economics and the characteristics of the future supply of energy if they are to give the leadership their important industry requires.

Conclusion

At the beginning of this paper, I pointed out the gap between the actual achievements in fuel economy and the theoretical thermo-dynamic limit. I also pointed out very serious practical, including fiancial, difficulties of bridging the entire gap. We know that in some processes major gains can be made without much difficulty, but we also know that in other processes improvement in efficiency is a task with rapidly diminishing returns. We shall have to try to explain these subtleties of thermodynamics to some of those lobbies which are demanding 100% thermodynamic efficiency. On the other hand, we must not relent in our efforts to achieve improvements in thermodynamic efficiency, for who, least of all the economist on his past record, can tell us what the real price of energy is going to be ten years from now ? In fact, whose judge-ment is better than that of the practising chemical engineer with his background of thermodynamics and experience in plant management ?

To sum up, I believe that there is a conflict between the thermodynamicist and the economist when the question is interpreted in the way that I have suggested. I believe that the chemical engineer must play his role in this battle, and in particular make the case for thermodynamic efficiency in view of the uncertainty of our future energy supplies. To the mastery of his technology, he will need to add a breadth of perspective if he is to resolve those many conflicts which lie before us.