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Cycles for coal-fired engines for marine applications

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SYNOPSIS

This paper discusses the main characteristics of coal-fired engines in the megawatt range of power output. Stirling, Rankine and Field cycles are discussed, together with their applications to coastal and inland waterways.

INTRODUCTION

There are several areas of the world where coal is readily available and costs much less than imported oil. There are a number of interesting possible applications for an engine of the order of 1 MW power output, including power for ships on inland waterways, small electricity generating stations and rail locomotives. Currently these requirements are met almost entirely by the diesel engine.

This paper discusses the problems associated with the introduction of high-efficiency coal-burning prime movers, and the thermodynamic approaches which might lead to improvement in efficiencies. It is desirable that such engines should maximize the availability of the heat source and the conclusions reached suggest that there is a good possibility that such prime movers can be developed for marine and other applications.

One attractive feature of prime movers for use in ships is the availability of unlimited cooling water, and the coastal and river applications considered here do not involve the length of voyage, which makes fuel weight as important as it is in the large ocean-going vessel. All marine transport is subject to the consequences of Froude's law, which means that large ships are much cheaper to operate than small ones, but the cost of harbours and the depth of water channels effectively keeps the size of vessel down to that which requires power in the megawatt range[1].

Fig. 1, which shows the power required by ships, includes rail transport since, generally, this will be in direct competition with marine transport for these applications. Reliability of operation is of great importance but weight and volume of the engine and its accessories is less so.

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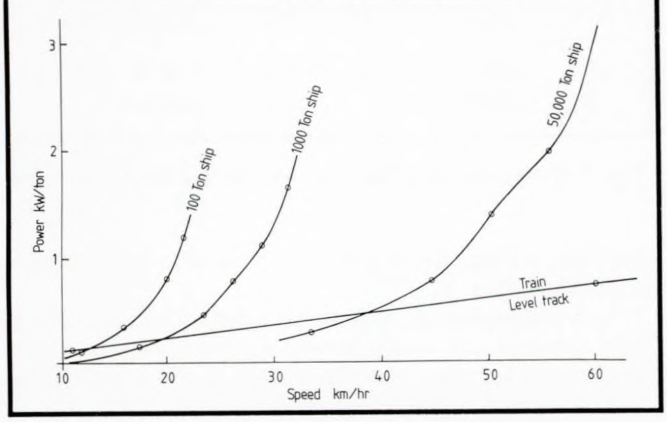

Fig. 1. Comparison of power required by ships and trains

TYPES OF ENGINE

Possible cycles include the Rankine, Stirling and combined cycles such as the dual gas turbine/steam turbine and the Field[2]. The gas turbine/steam turbine cycle[3] is more suited to higher power applications than those discussed in this paper and will not be considered further. On the other hand the Field cycle, which includes regeneration in a similar manner to the Stirling cycle, shows some promise.

Another way of using coal is by gasification, to provide a gaseous fuel for an internal combustion engine. This solution merits serious considerations, but preliminary enquiries into the state of the art suggest that there are several problems to be solved. Not least of these is the efficiency of conversion and its associated problems of the carry over of unburnt fuel. If the latter is not dealt with thoroughly by the use of scrubbing plants there is a problem of heavy engine wear. We are not convinced that the solution of these problems could yield an economic solution to the provision of megawatt size power, but nevertheless consider that the progress of this technology should be monitored, as any breakthrough could lead to it becoming a serious competitor.

This paper compares the Rankine, Stirling and Field cycles, all of which are heat engines and can be used with a coal-fired fluidized bed[4,5] as the heat source[6,7]. Heat can be extracted from the bed and transferred to the working fluid by conventional means in the low-temperature range but in the case of all cycles using higher temperatures, sodium heat pipes provide an elegant solution to the problem of heat transport[8]. When a hot gas is used as the source of heat, it is important to incorporate an air preheater or recuperator to recover some of the heat corresponding to the temperature at which the gas leaves the engine (see Fig. 2).

In a recuperator the incoming air to the combustor is preheated by the hot exhaust gas and with a well designed recuperator most of this exhaust heat will be recovered. The choice of engine exhaust temperature and the design of the recuperator is an important factor in the design of engines.

Unlike the internal combustion engine, closed-cycle heat engines all suffer from the problem of heat rejection at the low-temperature end of the cycle. In the steam cycle the heat transfer on the steam side of the condenser is high and the size is determined by the cooling requirement. In the Stirling engine, air is used on the engine side of the heat exchanger, but to some extent the poor heat-transfer properties of the air are offset by the high (70 bar) pressure on the engine side of the heat exchanger.

Work ratio is a useful criterion for comparing thermodynamic cycles and provides a measure of sensitivity to component efficiencies. The work ratio is defined as the net power divided by the gross power.

Since gas compression is not required in the Rankine cycle, the work ratio of the cycle is as high as 0.98. This is not the case in the Stirling cycle where the work ratio is nearer to 0.6 and the condensing Field cycle has a work ratio of around 0.55. For the gas turbine cycle it is as low as 0.3.

In earlier days, some of the gas turbines could hardly drive their own compressors and very careful attention to detailed design of compressor and expander is necessary.

STIRLING CYCLE

In the ideal Stirling cycle a gas is expanded at a constant temperature, doing work in the process. The gas is cooled at constant volume to a lower temperature and is then compressed, at the constant lower temperature, to its original volume. Finally, the gas is heated to the original temperature at constant volume, to complete the cycle (see Fig. 3). The heat abstracted during the cooling process is stored in a regenerator and used to reheat the gas during the heating process.

Hence, external heat is added only during the isothermal expansion and removed during the isothermal compression. Thus the theoretical Stirling cycle has the maximum possible heat engine efficiency; the Carnot efficiency. The regenerator is usually a mass of metal gauze which is arranged to have one end maintained at the higher temperature and the other end at the lower temperature.

Hot gas will be cooled on passing through the generator and a cold gas passed in the reverse direction will be correspondingly heated. Since the heat in the cooling/heating process is several times that which is taken in from the heat source, the efficiency of regeneration is of considerable importance in practical engines.

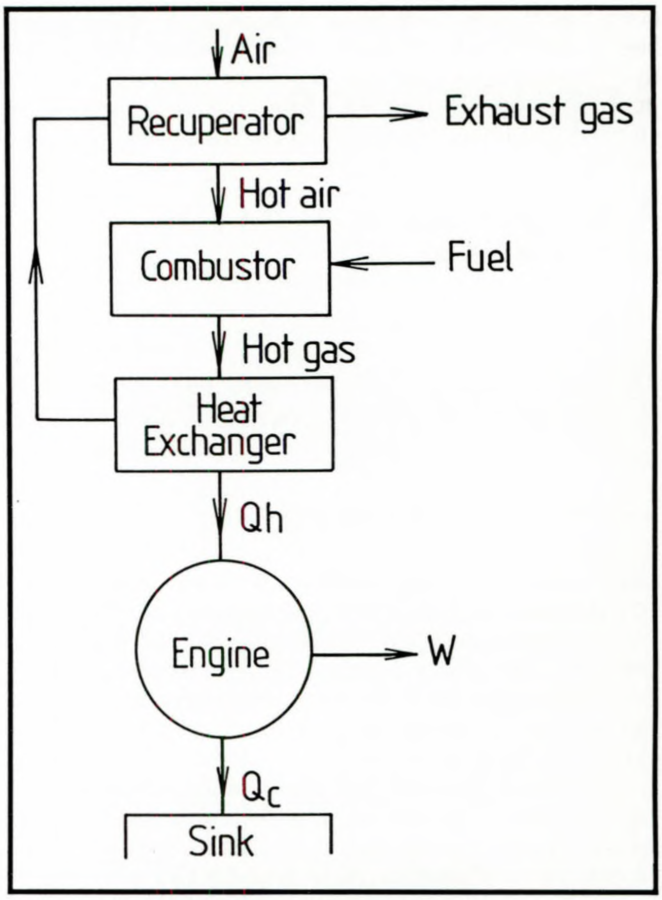

Fig. 2. Exhaust heat recuperation

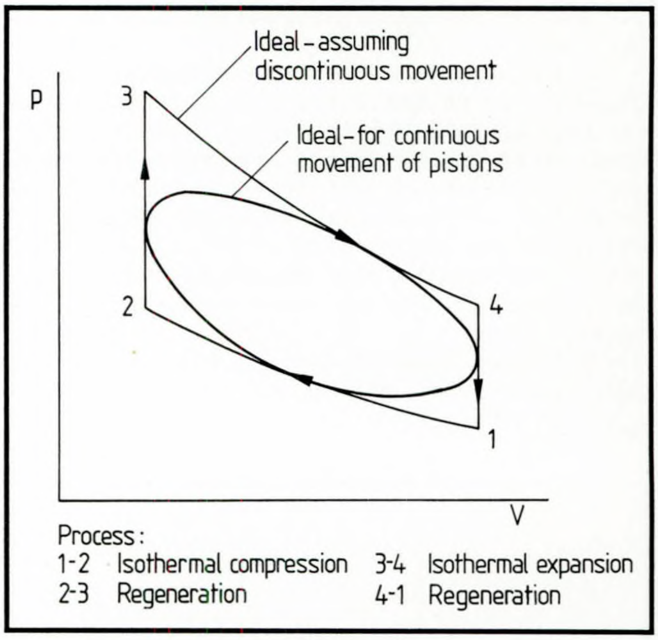

Fig. 3. Pressure–volume diagram for the Stirling engine

In actual engines the heater and cooler volumes are comparable to the expansion volume and the expansion and compression strokes are rapid and hence more nearly adiabatic than isothermal.

The energy/cycle or area of the indicator diagram (see Fig. 3) can be increased by raising the mean pressure. Modern engines have mean pressures as high as 100 atmospheres. The heat transfer can be improved if a gas of high thermal conductivity such as helium or hydrogen is used instead of air, but these gases have the practical disadvantage of requiring an effective seal to prevent gas loss. In the case of air the charge can readily be made up using a small air compressor driven by the engine.

CHARACTERISTICS OF STIRLING ENGINES

Stirling engines have been constructed over the power range from a few watts to 400 or 500 h.p. The high-performance high-pressure helium-charged high-temperature (700 °C) engines have a power to weight ratio, power to size ratio, and efficiency performance similar to that of a diesel engine of the same power and speed.

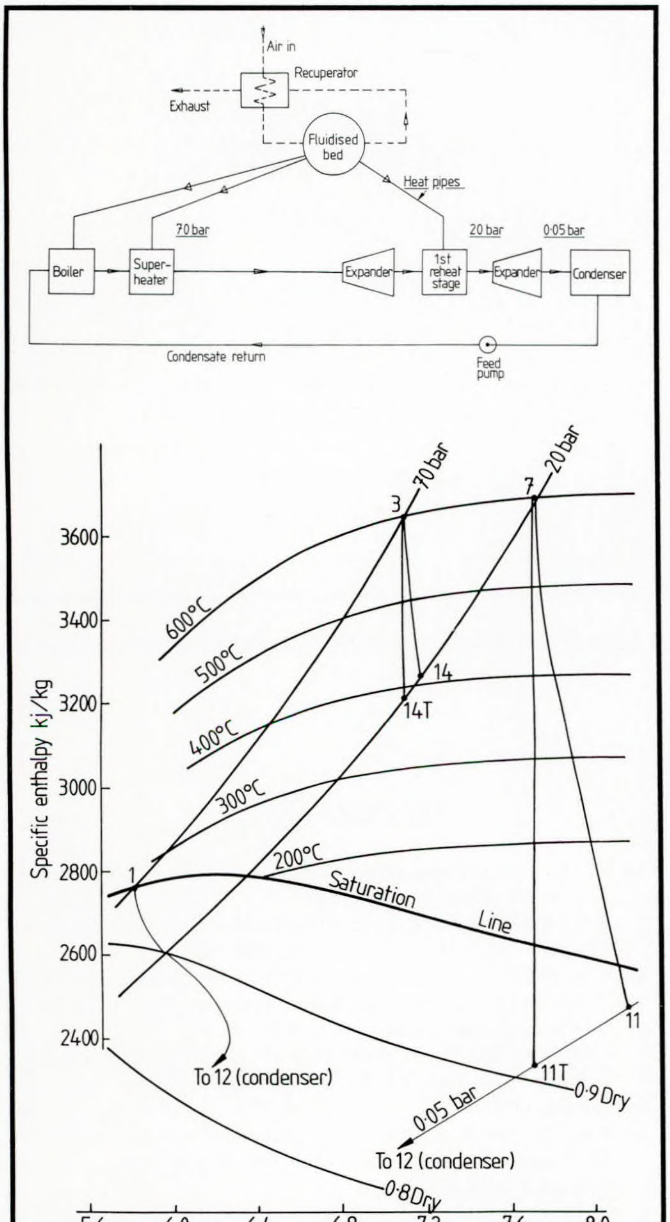

Fig. 4. Block diagram and Mollier diagram for condensing Rankine cycle

Cheaper engines use air as the working fluid, are operated at lower speeds and are heavier and more bulky. For marine applications these disadvantages are not severe and indeed they are more than offset by the simplicity of sealing and other constructional factors. General features of the Stirling engine include the following.

1. A sealed unit, which simplifies lubrication problems, reduces maintenance requirements and contributes to long life. Another helpful factor in achieving a long life is the absence of valves and valve gear.
2. The ability to operate on different fuels.
3. Low exhaust emission. Unlike the internal combustion engine the combustion process is continuous and thus more complete combustion is achieved.
4. The torque does not vary greatly with speed and maintains its value at low speeds.
5. Low noise and vibration. One contributory factor is the absence of an explosion in the cylinder which is present in the internal combustion engine, and also less exhaust noise is produced than with the internal combustion engine.

FIELD CYCLE

This cycle was proposed by F. F. Field in a paper 'The application of gas turbine technique to steam power', which he presented to a joint meeting of the Institution of Mechanical Engineers and the Institution of Electrical Engineers on 24 February 1950.

The cycle consisted of an externally fired Joule cycle using steam as the working fluid. After expansion, the flow of steam was divided, with a smaller fraction of the flow going through a further expansion stage to a condenser, thereby producing a supply of water which was mixed with the main flow of steam to the point required for the commencement of the compression stage of the Joule cycle.

A recuperative heat exchanger is an essential feature of the cycle. Naturally, many configurations are possible and Field gave a number of examples.

It will be realized that steam, in the superheated state, behaves very much like an ideal gas. Heat addition is not isothermal but if further stages of reheat are included an approximation to isothermal heat addition is obtained. The Rankine sub-cycle is, within the limitations of its temperature range, a very close approximation to an ideal cycle. The Rankine cycle only begins to deviate from the ideal as it is extended upwards in temperature. As all cooling is carried out in the condenser and is therefore isothermal, it is clear that the cycle can be a close approximation to the ideal.

Work was carried out on the Field cycle by the Central Electricity Generating Board in the U.K. up to approximately 1965, but in the application to large power stations there are other methods (e.g. regenerative feed heating) which can give good efficiency and, as stated above, cycles which involve the compression/expansion cycle suffer from stage inefficiency much more than the Rankine cycle.

Thus the anticipated savings were so much reduced that the project was terminated. The alternative technologies which are involved in the very large power stations are not appropriate to the smaller power levels discussed here and the Field cycle has attractive features in the megawatt power range.

Table 1. Cycle comparison

Cycle	Conditions	Ideal cycle efficiency	Relative cycle efficiency
Stirling	70 bar peak T_{max} 600 °C T_{min} 33 °C	46%	1.00
Rankine	70 bar peak Superheat 600 °C Reheat 600 °C	40%	0.87
	70 bar peak Superheat 600 °C No reheat	38%	0.83
Field	70 bar peak Superheat 600 °C Reheat 600 °C	45.5%	0.99
	70 bar peak Superheat 600 °C No reheat	37%	0.80

CYCLE COMPARISON

Stirling cycle

A good description of a large Stirling engine is given in ref. 6 by Walker *et al.* In our calculations the following assumptions were made:

Maximum gas temperature	600 °C
Maximum pressure	70 bar
Minimum gas temperature	33 °C
Air-charged regenerator efficiency	100 %

Rankine cycle

The maximum temperature and pressure (600 °C, 70 bar) adopted for the Stirling engine were also used in these calculations although it is recognized that these are higher than is normal practice in this power range.

Similarly a minimum condenser temperature of 33 °C was used. The adiabatic efficiency is 90%. Fig. 4 shows a block diagram of a cycle together with the appropriate Mollier diagram.

Field cycle

The same steam conditions as the Rankine cycle apply. The cycle is illustrated in Fig. 5. The results of these calculations are given in Table 1.

CONCLUSIONS

All the cycles in Table 1 will be used with recuperators and the overall cycle efficiency reduced by heat exchange inefficiencies. Calculations suggest that heat exchange performance will be similar in all the five cases considered so will not change the overall conclusions.

At the lower end of the power range under discussion, the relative simplicity of the Stirling engine suggests that this might well be the best choice. As power rises, Rankine and Field cycles become more attractive. The Field cycle offers a high efficiency but at the cost of additional complexity.

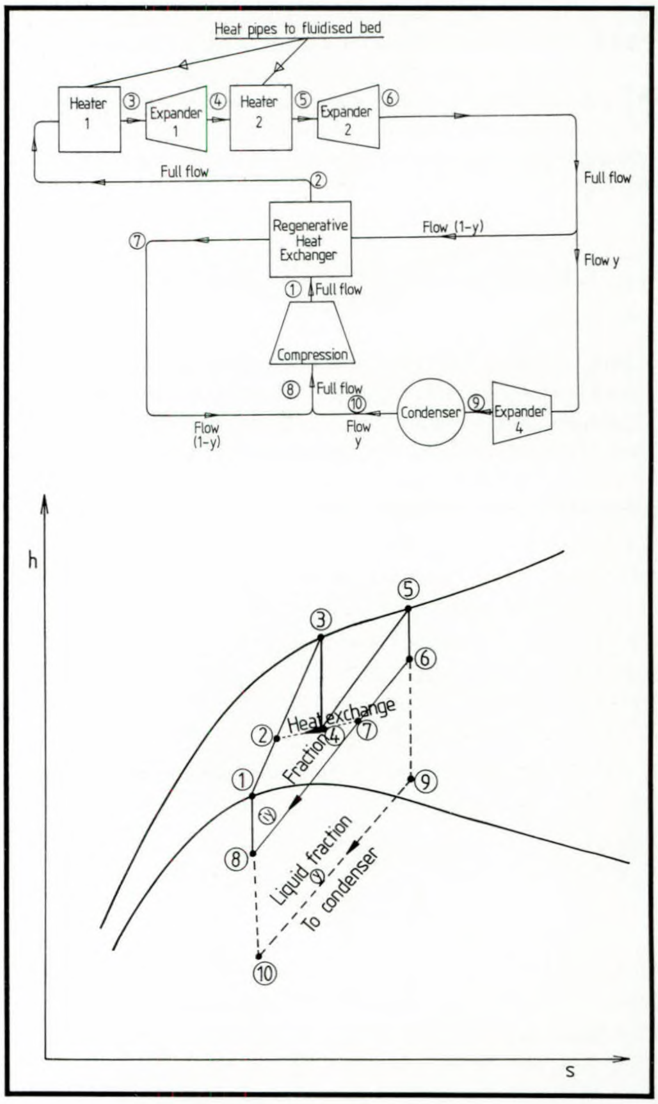

Fig. 5. Block diagram and Mollier diagram for Field cycle

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