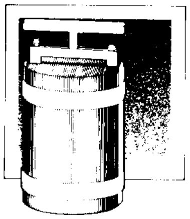

The Liquid Propylene Engine

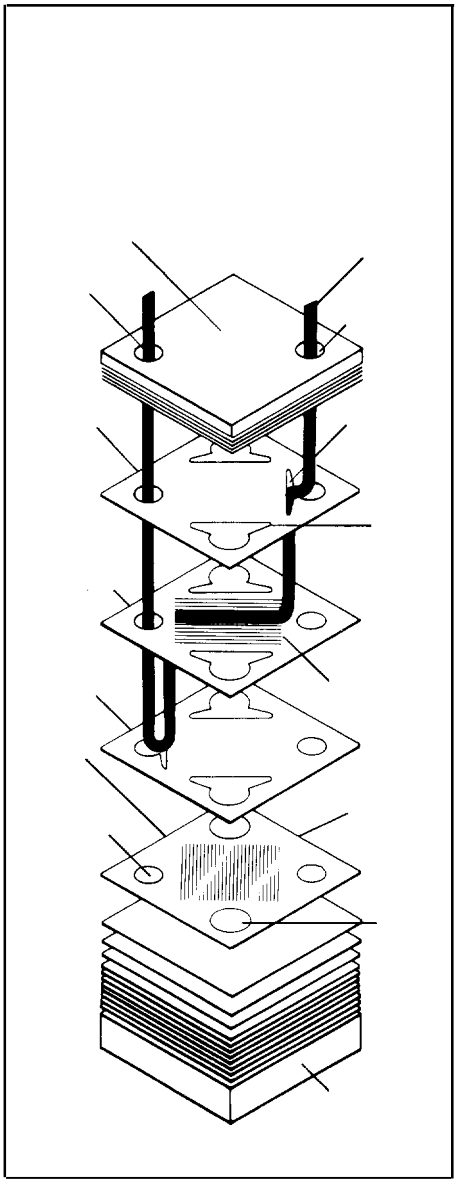

Fig. 1. In this propylene-to-water heat exchanger, made up of a stack of hundreds of stainless steel sheets copper-brazed together at Los Alamos, the propylene flows in at the top right of the stack and across through the propylene manifolds and channels, then moves up and out through the other propylene duct. The arrow in the figure traces the path through just one of the sets of channels and manifolds; similar flow occurs through the other, lower propylene channels and manifolds. At the same time, water flows in and up through one water duct and across the stack (but through alternate sets of plates and across the plates in a direction perpendicular to the corresponding propylene flow) until it returns, exiting through the other water duct. Because of the intimate thermal contact between fluid and stainless steel, heat can be transferred at a rate of 230 W/°C. ➤

An ideal use of geothermal energy is to warm buildings by extracting heat from ground water at temperatures of only about 10°C. This application involves the pumping of large amounts of heat across small temperature differences (of the order of 30°C). An efficient way to effect such heat transfer is from one liquid to another. As a result, a heat pump that appears well suited for this purpose is a conventional reciprocating heat engine using a *liquid* for a working substance.

We have been studying just such an engine—a Stirling engine that uses liquid propylene as its working fluid. Our discussion of this device will both contrast the simplicity of natural engines with the complexity of more traditional engines and, more important, will introduce the use of a liquid as a thermodynamic working substance. (The section in the main article called "The Liquid Sodium Acoustic Engine" discusses a *natural* heat engine that uses a liquid as its primary thermodynamic medium.)

It is a common misconception that liquids behave much like an idealized hydraulic fluid, with density independent of temperature and pressure, In fact, especially near the critical point (where the liquid and gaseous phases become indistinguishable), a typical real liquid is somewhat compressible, has a large thermal expansion coefficient (comparable to or larger than that of an ideal gas!), and has other attractive thermophysical properties. These facts were first appreciated by John Malone, who in the 1920s built several Stirling prime movers that used liquid water with pressures as high as 700 bars as the working substance. We chose liquid propylene (C_3H_6) for our work because its critical temperature is just above room temperature and its Prandtl number (which can be thought of as a measure of the material's viscous losses in relation to its thermal transport capacity) is lower than that of other fluids with similar critical temperatures,

A major advantage of a liquid working substance is that liquids have a very large heat capacity per unit volume compared to gases, making it possible to build efficient and compact heat exchangers and regenerators. This point is illustrated by the compact propylene-to-water heat exchanger we have developed for our engine (Fig. 1). The exchanger is made of hun-

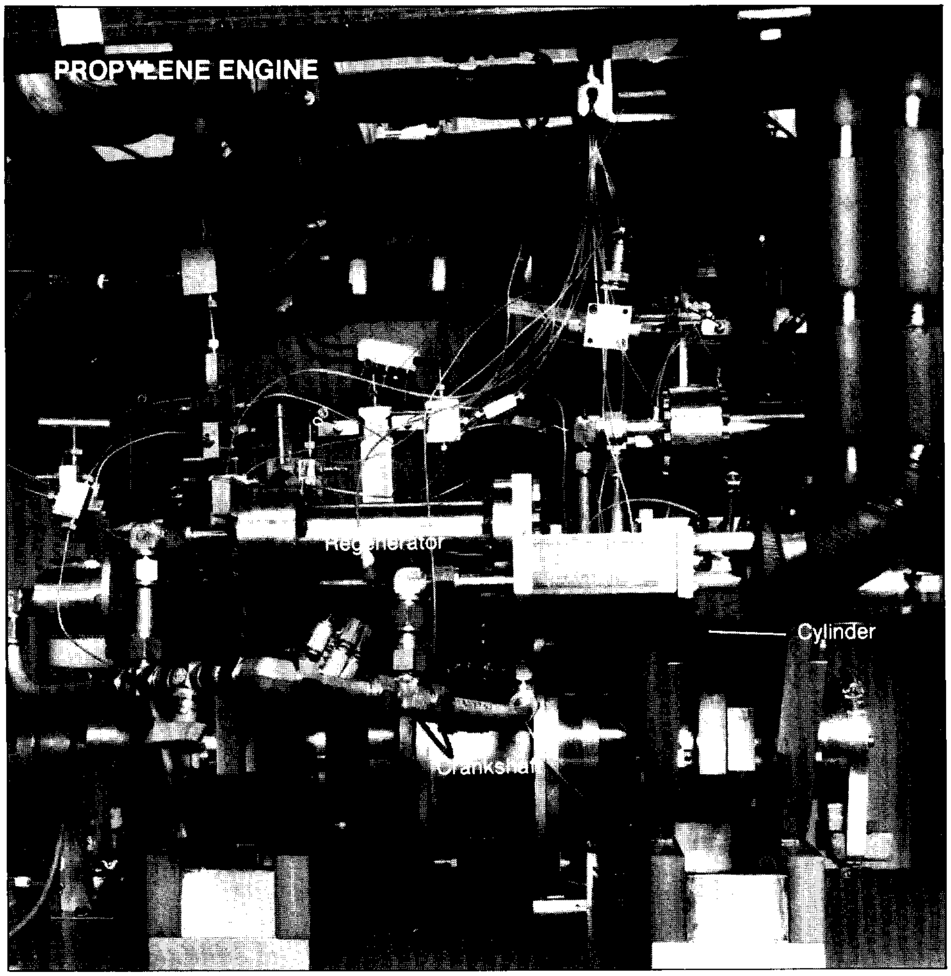

Fig. 2. The heat engine shown here consists of four Stirling engines of the Rider form operating from a common crankshaft but phased 90 degrees apart. The working medium is liquid propylene, and heat exchange between water and the propylene takes place in the stainless-steel exchangers depicted in Fig. 1.4

dreds of chemically milled stainless-steel sheets copper brazed together (several of the individual plates are shown on the cover). Although the exchanger (4 by 4 by 9 centimeters in size) entrains only a few cubic centimeters of propylene, it transfers heat between the two fluid streams at a rate of 230 watts per °C with only a few watts of power required to pump the fluids through the exchanger.

Another advantage of a liquid working substance is that liquids are typically much less compressible than gases. Thus the large pressure amplitudes needed to pump large amounts of heat can be achieved with only small displacements of a piston, even for a substantial volume of entrained liquid in the thermal elements. Because of this quality it is possible to build a high-power engine that uses a short stroke, making the mechanical elements very efficient without corn promising on the size and efficiency of the thermal elements.

Our Laboratory-scale liquid-propylene Stirling engine (Fig. 2) uses the same configuration of parts shown in Fig. 3 of the main article (the Rider form of the Stirling engine), except that we have *four* such assemblies, These assemblies operate from a common crankshaft and are mechanically phased 90 degrees apart so that the shaft torque oscillations are minimized, eliminating the need for a big flywheel. Although much of the wiring in Fig. 2 is for diagnostic purposes, the photograph, when contrasted with photographs of natural engines (see the main article) is nevertheless a dramatic representation of the complex of a more conventional reciprocating engine.

In its heat-pump mode, our engine uses work supplied by an electric motor to transfer heat from a source at or below room temperature to a heat sink consisting of flowing water at or above mom temperature. For convenient measurement, the low-temperature source is an electric heater. Mean pressure, oscillating pressure amplitude, volumetric displacement, shaft rotation frequency *f*, and hot and cold temperatures are all independently controllable. We can measure both the rate at which heat is pumped away from the heat source Q and the shaft torque τ, the latter giving us shaft power $W = 2\pi f\tau$.

In addition. our laboratory engine has valves that quickly change it from the ordinary heat-pump configuration to one in which there is no flow of propylene through the regenerators and heat exchangers, even though crankshaft and piston motion, pressure amplitudes, temperatures, and so forth remain the same. This feature allow's us to accurately measure just the torque *difference* $\Delta\tau$ required to pump the heat, with the background torques due to bearing and seal friction, piston blowby, and the like eliminated.

Large amounts of heat can be pumped by the engine (Fig. 3a)-around 1300 watts at a crankshaft rotation frequency of 4.5 Hz—and the data points match very well curves predicted from theory for the particular geometry of' the engine and for the use of propylene as the working fluid.

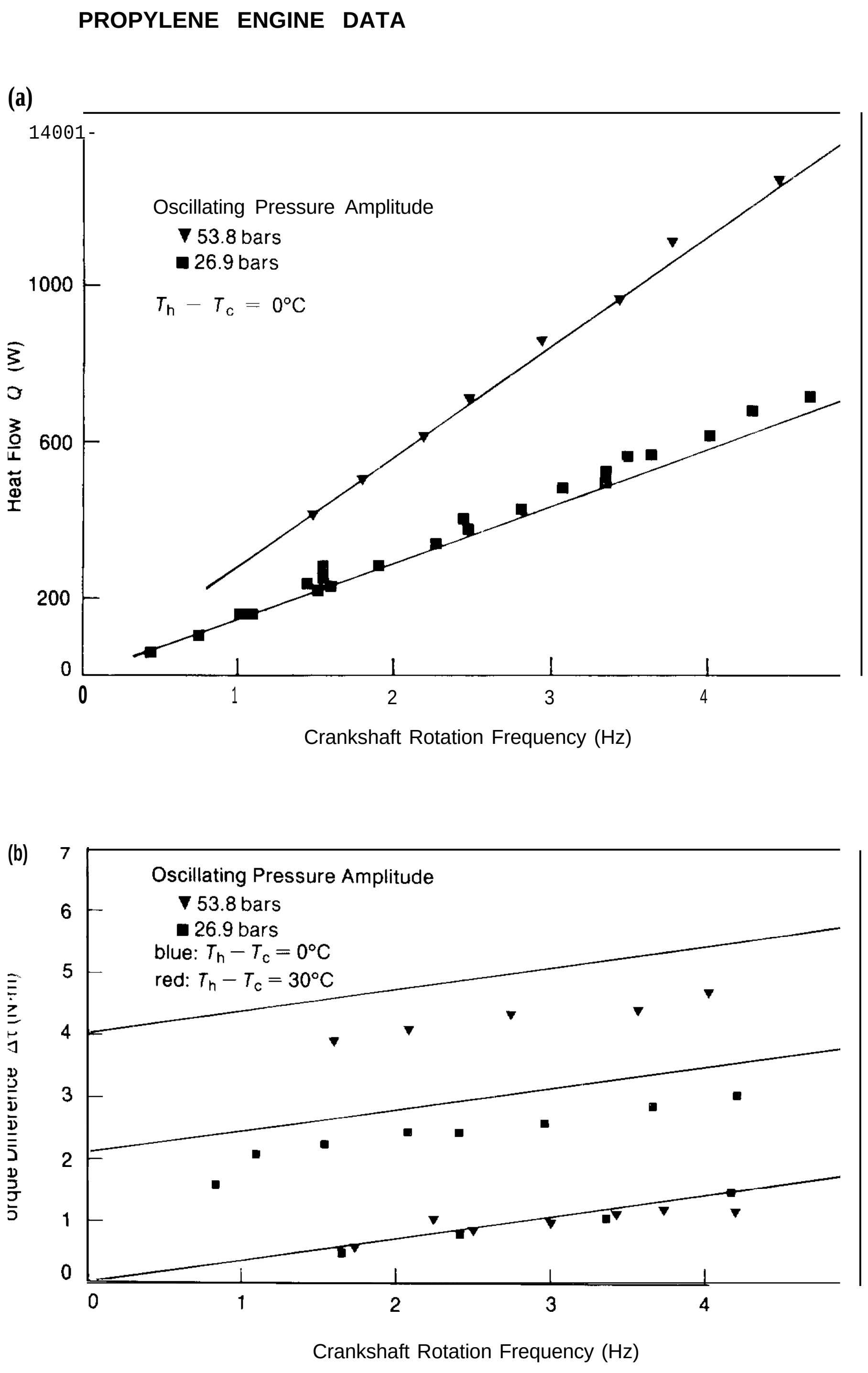

Fig. 3. (a) The rate at which the propylene engine pumps heat Q as a function of crankshaft rotation frequency f at two different oscillating pressure amplitudes agrees very well with theoretical curves predicted from the physical properties of propylene and the geometry of the engine. (b) The torque difference $\Delta\tau$, here also plotted as a function of f, is just that part of the torque needed to pump the heat. In both graphs the blue data points represent no temperature difference across the regenerators, whereas the red data points represent a 30°C difference. ◀

The lines drawn on Fig. 3b represent the torque required by an engine with the Carnot efficiency to pump the observed amount of heat added to the torque associated with just the viscous losses of pushing the fluid through the regenerators and heat exchangers. Our measured torque differences agree well with these theoretical curves.

Our laboratory engine is very far from a practical, economically useful device. Its scale and most of its design are appropriate for experimental measurements and for the understanding of principles. not for optimized efficiency or low manufacturing or operating costs in a specific application. But, as expected, we are learning that liquids are good heat engine working substances, Liquid engines may ultimately be of great technological importance.

We are also learning much about the practical details of the use of liquids in engines. For example, we suspect that the next logical step in the development of practical liquid engines is to abandon the reciprocating Stirling engine entirely. Instead, we would use the liquid in, say, a Brayton engine with rotary compressors and expanders. Such a configuration would reduce losses from such things as bearing and seal friction that, until now, we have regarded as quite uninteresting. ■