A LOW TEMPERATURE DIFFERENCE RINGBOM STIRLING DEMONSTRATION ENGINE

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ABSTRACT

This paper describes a Ringbom Stirling engine designed and built to demonstrate overdriven mode operation. The overall size of the engine is roughly comparable to two sets of last year's IECEC proceedings but far lighter in weight. It can operate on the thermal energy in a few cups of hot water for long periods. Clear plastic and glass were employed extensively in the construction of the engine which provides a clear view of the inner moving parts. The engine runs steadily at speeds low enough for direct visual observation of the cycle of operation while operating between temperature differences ranging from 90°C down to 7°C. The analytic design of the engine followed a first order mathematical model developed earlier by the author. A new concept, the *critical temperature ratio*, which turns out to be of special importance in the design of Ringboms operating at small temperature differentials, is discussed in this paper in full generality. Details of the performance of the engine are also presented here.

INTRODUCTION

A Ringbom engine is a Stirling engine with a free displacer and a crank operated piston. It offers several significant advantages over the conventional full kinematic Stirling, most notably mechanical simplicity and an improved thermodynamic cycle. It is therefore a potentially important form of the Stirling engine for practical applications.

The subtleties of the operational cycle of the overdriven Ringbom are not generally readily grasped and therefore an amply sized model which could demonstrate this operation in a particularly lucid way was thought valuable. Heretofore the only Ringbom engines suitable for any sort of demonstrative use followed more or less typical Stirling engine construction and practice. For example, the engines described in references (4) and (6) were designed to be heated by a small flame. Thus heater temperatures were in the 400°-600°C range. For these temperatures one typically fabricates most of the engine in metal and therefore very little can be seen of the working parts. Moreover, at these temperatures engine speed tends to be quite high and visible moving parts appear only as a blur. Furthermore, an open flame is not always easy or safe to use. These engines have been of incalculable value in formulating and confirming the author's overdriven theory as developed in (3), (5), and (6), and, through the use of high speed photography, Fauvel (1) has obtained dramatic experimental confirmation from a similar engine. But still desired was a more docile, more convenient, and more visible demonstrator.

Ivo Kolin (2) recently reported on a very successful full kinematic Stirling engine capable of running on very low temperature differentials - on the order of 16°C. A small reservoir of hot water and another of cold water conveniently and safely served as the heat source and sink, respectively. With a maximum engine temperature below 100°C, transparent plastics can be used which allows a view of the inner workings of the machine. Kolin's engine employed an over-center mechanism for driving the displacer; this moved the displacer rapidly from one end of its chamber to the other with dwell periods at its extreme positions. In general terms, this is the type of displacer motion obtained in an overdriven Ringbom (3,5). Kolin's engine also operated at low speeds - below 70 rpm - which is slow enough for observers to follow the operation.

These considerations prompted the author to design the low temperature difference Ringbom engine described here. The engine was built and tested while on sabbatical at Argonne National Laboratory in the fall of 1983.

DESCRIPTION OF ENGINE

Two views of the Ringbom engine are given in Figures 1 and 2; Figure 3 is a schematic of the engine illustrating the major features. The engine follows the typical two-cylinder Ringbom configuration with a small piston to drive the displacer in the desired manner. The details of the operational cycle of the Ringbom have been thoroughly dealt with in (3) and (5). The present engine is unusual in the rather large displacer-to-piston swept volume ratio which was necessary because of the small temperature differences between which the engine operates; this will be discussed in greater depth below.

The primary specifications of the engine are given in Table 1; the nomenclature used here follows that established in (5). For convenience a brief listing of the terminology for this paper is given below.

DESIGN CONSIDERATIONS

The design began with the selection of a stock piston/cylinder assembly manufactured by Airpot Corporation. These units are made for use as dashpots and actuators. The cylinder is precision bore Pyrex and the selectively fitted piston is graphitized carbon; sealing is excellent and friction is extremely low. The largest stock unit available was chosen giving a nominal swept volume of 150 cm^3 with a stroke of 9.68cm as indicated in Table 1.

The original goal was to design the engine for operation with a temperature difference of 100°C on down to at least a differential of 55° C; this, it was felt, would give a satisfactory length of running time on convenient amounts of hot and cold water - i.e. cups rather than buckets. This goal was at the piston swept volume of 150cm^3; for smaller temperature differentials the stroke could be decreased.

This goal dictated a displacer swept volume in the neighborhood of 800cm^3. This is largely an empirical determination and normally subject to considerable latitude. It basically amounts to balancing the thermodynamic gains of higher compression ratios against the resulting increases in mechanical friction losses in the linkage. In the present case, high specific power was definitely not a high priority but the ability to run well on small temperature differences was. Therefore a relatively large displacer swept volume was favored. The matter is this simple for kinematic Stirlings but it was discovered that for some Ringboms there is still another consideration due to the existence of what is called the *critical temperature ratio*. This turns out to impose particularly stringent restrictions for low temperature differential Ringboms. The next section will fully discuss this matter; its result in the case of this engine design was to force the displacer swept volume to be decreased to 620cm^3.

As was shown in (3), a short-stroke large-diameter displacer is to be preferred for Ringbom engines. The low temperatures and pressures employed in this engine made practical a rather large diameter displacer chamber with flat end plates used as the heat exchangers, as in Kolin's engine. With acrylic plastic as the side wall, the unit could be made quite short without incurring excessive conduction losses, which contributes to longer running times. A convenient diameter was chosen (∿ 25cm) so that standard pans could be used for the water reservoirs. This gave a displacer area of 370 cm^2 so that only a very short displacer stroke was required - in the neighborhood of 2cm. Expanded bead Styrofoam was chosen as the displacer material; its low density and low thermal conductivity are ideal for this application. The disc-shaped displacer is 19mm thick and is fitted to allow a radial gap of 2.5mm to the displacer chamber wall.

It remained then to select a suitable piston/cylinder to drive the displacer and to determine the exact displacer stroke. A tentative 2cm displacer stroke was assumed for the purpose of choosing the area of the displacer drive piston. For the standard Airpot units available, the overdriven speed limit was calculated using the analysis given in (5). The target speed here was a minimum of 5 Hz which is more than one can expect on air with the rudimentary heat exchangers used. The drive piston diameter chosen was a nominal 16mm, which gave a minimum overdriven limit of near 7 Hz over the temperature range to be used. At this point the influence of gravity on displacer motion was thoroughly studied and found to be negligible.

Finally, the exact displacer stroke was determined to satisfy the critical temperature ratio limitations discussed below. It turned out that a displacer stroke of 1.68cm would allow operation to 100°C on the hot side with an ample safety margin. Since this stroke was less than the 2cm assumed in the overdriven calculations, the speed capability would, in fact, be improved.

TEMPERATURE LIMITS

Any Ringbom engine must satisfy the inequality

$$\frac{\lambda\kappa}{1-\rho-\tau} > 1$$

where $\lambda\kappa$ is the swept volume ratio of the piston to the displacer, ρ is the ratio of displacer drive area to the displacer area, and τ is the temperature ratio of the cold to the hot space (5). Because $\lambda\kappa$ is of course positive, this inequality can be written as

$$1-\rho > \tau > 1-\rho-\lambda\kappa \qquad (1)$$

The first part of (1), $1-\rho > \tau$, ensures that the displacer will change engine pressure in the appropriate way, namely that displacer motion toward the hot end will decrease pressure, and motion toward the cold end will increase pressure. This of course assumes the typical Ringbom configuration in which the displacer rod or drive piston exits on the cold side of the displacer chamber. We shall refer to $1-\rho$ as the *common temperature ratio limit* for Ringbom engines.

The second half of (1) ensures that the piston will initiate displacer motion. In an overdriven Ringbom, engine pressure fluctuates more or less equally above and below the external or buffer space pressure and as the displacer contacts its stroke limits and comes to a stop, it is held there by the pressure difference across the rod or drive piston area. The piston must thus move to reverse the pressure direction and drive the displacer the other way. The inequality $\tau > 1-\rho-\lambda\kappa$ ensures that the piston swept volume is large enough to do that relative to the rod area and temperature ratio.

Considering only the engine geometry involved in (1), namely ρ and $\lambda\kappa$, Ringboms can be classified into two types. First, the engine may have a relatively large swept volume ratio and satisfy

$$\lambda\kappa \geq 1-\rho \qquad (2)$$

In this case, the second half of (1) is automatically satisfied because $\tau > 0$. We call engines satisfying (2) *universal*. The range of permissible temperatures for a universal Ringbom is governed only by the common temperature ratio limit $1-\rho$.

A Ringbom that is not universal we will all *special*. Specials are characterized by

$$\lambda\kappa < 1-\rho \qquad (3)$$

In this case (1) and (3) imply there is a positive minimum above which τ must be. We call his value the *critical temperature ratio* and enote it by

$$\tau_C = 1-\rho-\lambda\kappa.$$

For a given lower engine temperature T_C, here is, for all Ringboms, a minimum value for he upper temperature T_E necessary for engine peration. This is determined by the common emperature ratio limit; we must have

$$\frac{T_C}{1-\rho} < T_E$$

or universal Ringboms there is no upper bound n T_E; all above the minimum are admissible. owever, for special Ringboms there is an upper imit on T_E, namely

$$T_E < \frac{T_C}{\tau_C}$$

peration simply cannot occur for T_E values above the limit T_C/τ_C.

In a Ringbom intended to operate between idely separated temperatures, there is little ifficulty with this upper temperature limit. ndeed, the engine usually turns out to be universal because $\lambda\kappa$ is near unity. But a low temperature differential Ringbom invariably tends to be special. First, if the design point $\Delta T = T_E-T_C$ is small, then the temperature ratio τ will be near 1. This forces the displacer rod area ratio ρ to be small since we must have $1-\tau > \rho$ by (1). Furthermore, the small ΔT requires a small $\lambda\kappa$ to avoid high friction power losses in the piston linkage. This forces $1-\rho > \lambda\kappa$, so the engine is special.

Furthermore, the smaller the design ΔT, the more pronounced will be the above effects, making the engine all the more special, that is making the critical temperature ratio closer to the design temperature ratio. This produces an engine which, although capable of operating between T_E and T_C, will not operate at upper temperatures much beyond the design point T_E. Therefore if one wants operation over a considerable span of temperatures, one must choose the engine geometry carefully. One must ensure first that the engine is capable of operation over the desired temperature range relative to the limits discussed here; second, that the engine geometry and temperatures will give the desired speed capability based on the overdriven theory discussed in (5); and, finally, that the geometry produces a machine with a sufficiently high mechanical efficiency. This is quite a balancing act for low ΔT Ringboms.

PERFORMANCE

The engine turned out to be a virtuoso performer. With about two cups of near boiling water placed in the lower reservoir (Figure 2) and a like amount of ice water in the upper reservoir, the engine starts in a matter of seconds and runs for nearly an hour with no further intervention required. After the water temperatures degrade to the point where the engine stops, the piston stroke can be decreased and operation will continue. This can be repeated until the piston swept volume is a mere 30cm^3 and the engine will run on down to a temperature differential of just under 7^{o}C (T_E = 26^{o}C and T_C = 19.5^{o}C). Total running time on one thermal charge is about two hours.

The engine has logged many hours of running time, much of it in the laboratory where speed, shaft torque, and heater and cooler plate temperatures (T_E and T_C) were monitored. The engine has proven very amenable to laboratory experiments and much data has been collected under various operating conditions. Results of one of the more interesting experiments is presented in Figure 4. Here the engine was operated with helium as the working fluid and the resulting power measurements are compared to normal running results using air; in both runs the operating temperatures were the same, the mean cycle pressure was atmospheric, and the piston swept volume was 150 cm^3. Power was measured using a simple friction brake on the engine shaft.

This experiment is typical of the elementary but very enlightening experiments that can be carried out with this engine. The visibility, ample size, slow speed, and ease of temperature control all combine to clearly illustrate basic facts about the behavior of Ringbom engines, and of Stirling engines in general. Other experiments included verifying the critical temperature ratios discussed above, and determining minimal operating temperature pairs for various compression ratios which will be of great value for future designs. More experiments are planned that promise to further extend and clarify our understanding of Ringbom engines.

APPLICATIONS

The sole purpose of this engine construction project has been to produce an effective demonstration Ringbom engine. Experience has shown, however, that demonstrations seem to invariably evoke speculations on the practical use of Stirling engines for operation from low temperature heat sources such as geothermal, industrial waste heat, and unfocused solar energy. Kolin (2) indicates similar interests. Apart from the Fluidyne, very little has been done on Stirling engines operating on heater temperatures much lower than, say 600°C. It therefore seems worthwhile to investigate the practicality of Stirlings for lower temperature applications.

ACKNOWLEDGEMENTS

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NOMENCLATURE

Primary Engine Parameters

A	cross sectional area of displacer
A_P	cross sectional area of piston
A_R	cross sectional area of displacer drive piston
L	1/2 maximum displacer stroke
L_P	1/2 piston stroke
V_D	volume of dead space
M_D	mass of displacer
T_E	temperature of working fluid in the expansion space
T_C	temperature of working fluid in the compression space

Dimensionless Parameters

λ	L_P/L
κ	A_P/A
ρ	A_R/A
τ	T_C/T_E

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A	=	370 cm^2	L_P	=	4.84 cm
A_P	=	15.5 cm^2	M_D	=	16.5 g
A_R	=	2.00 cm^2	V_D	=	80 cm^3
L	=	0.84 cm			

Table 1. Final specifications of the low ΔT Ringbom engine.

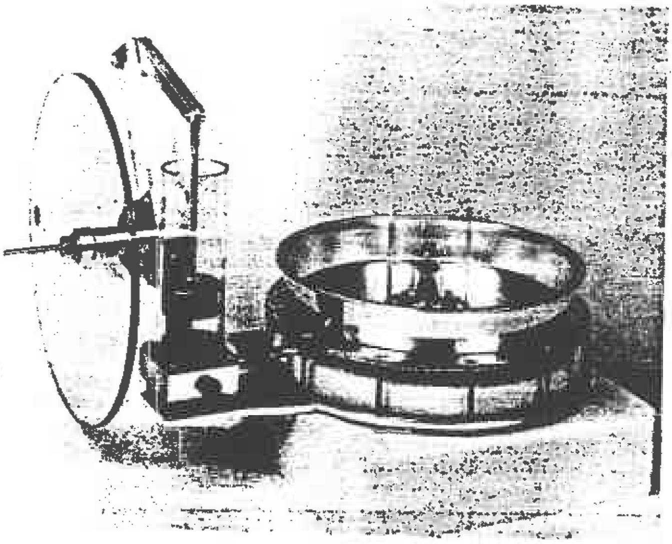

Figure 1. A photograph of the low temperature differential Ringbom engine built at Argonne National Laboratory.

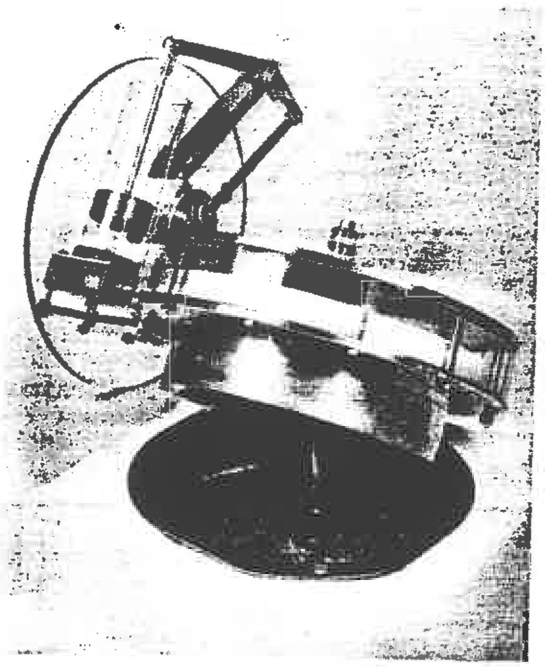

Figure 2. A view of the insulated hot water reservoir and conduction ring on the engine hot side.

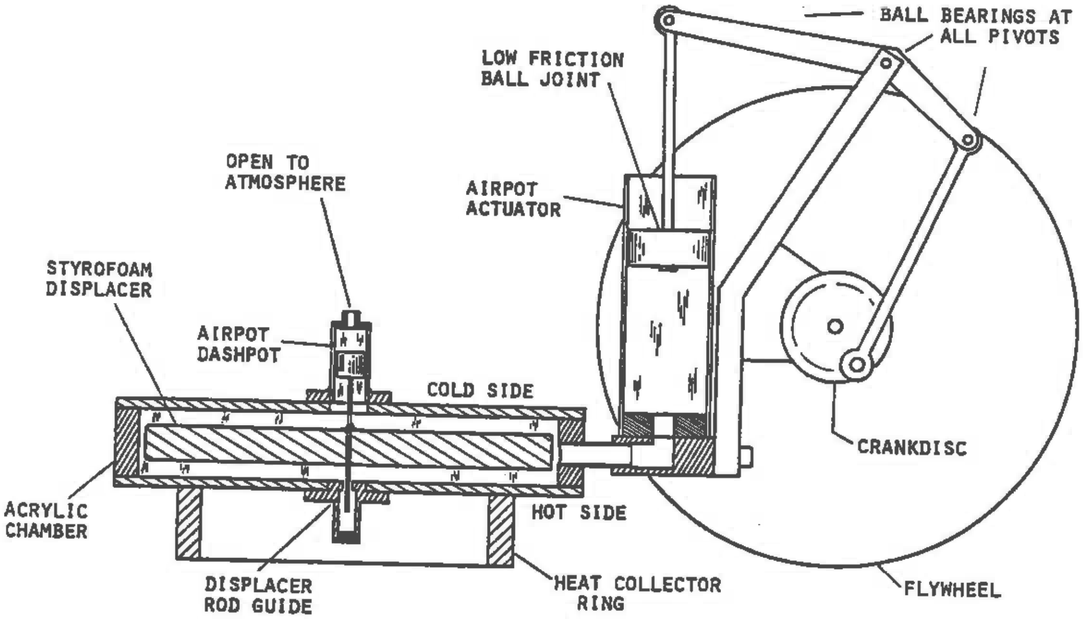

Figure 3. A schematic drawing of the engine.

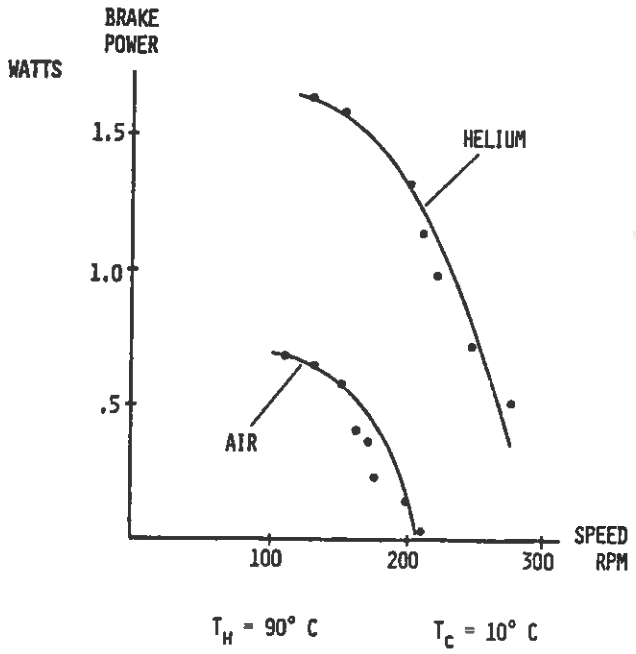

Figure 4. Comparison of engine power on helium and air.