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APPLICABILITY OF THERMOACOUSTIC PHENOMENA TO MHD CONVERSION SYSTEMS

R. L. Carter
Professor, Electrical Engineering
University of Missouri

K. T. Feldman, Jr.
NDEA Fellow, Mechanical Engineering
University of Missouri

C. N. McKinnon, Jr.
Instructor, Mechanical Engineering
University of Missouri

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APPLICABILITY OF THERMOACOUSTIC

PHENOMENA TO MHD CONVERSION SYSTEMS

R. L. Carter, K. T. Feldman, Jr. and C. N. McKinnon, Jr. presented at the Fifth Symposium on Engineering Aspects of Magnetohydrodynamics, April 1 and 2, 1964.

There are numerous problems in present-day MHD converters. Two important ones are thermal motivation of a suitably conducting gas in a closed-cycle system, and conversion of low-impedance D. C. electrical power to A. C. power.

Both of these problems are automatically solved if a non-equilibrium ionized gas is forced to oscillate in a duct passing transversely through an externally generated magnetic field. The electrical output of this generator is a current alternating at the same frequency as the oscillating gas. In order for such a generator to be practical, the power density must be of the order of at least 1 watt per cubic centimeter. To attain this power density, assuming that a magnetic field of 100 kilo gauss and a gas conductivity of 100 mhos per meter could be provided, one would have to achieve mean velocities of at least 20 meters per second.

One possible means for obtaining such an oscillating gas is provided by the phenomenon of Thermoacoustical Resonance which utilizes thermal energy directly to produce an oscillating gas. The limiting gas velocity that can be attained by this acoustical phenomenon is the speed of sound in the gas, which is several hundred meters per second at the temperatures necessary for ionization. Velocities observed in our experimental thermoacoustical oscillators are less than one meter per second for heat inputs of several hundred watts. However, it does not seem unreasonable at this time to expect that the thermoacoustical oscillator could ultimately deliver velocities approaching the 20 meters per second mentioned earlier.

The first account in the literature of thermoacoustical resonances seems to be that of Sondhauss, published in 1850. Sondhauss investigated a sound produced by heat that was often observed by glass blowers when blowing a bulb on the end of a narrow tube. This type of a tube is illustrated in figure 1. Also shown in figure 1 is another example of thermoacoustical resonance that was described by Rijke in 1859. Rijke observed oscillations in an open-ended tube when heat was added to a wire screen located in the lower half of the tube. A considerable amount of work has been done on the Rijke Phenomenon and it is relatively well understood today. In 1878, Lord Rayleigh verified and explained the work of both Sondhauss and Rijke. Rayleigh's explanation for the maintenance of thermoacoustical resonance is as follows: "If heat be given to the air at the moment of greatest condensation or be taken from it at the moment of greatest rarefaction, the vibration is encouraged." This criterion has been the basis of most all of the investigations of thermoacoustical resonance since Rayleigh's time.

The particular type of thermoacoustical oscillator presently being studied is shown in figure 2. The closed end of this oscillator acts as an acoustic compliance or in terms of the mechanical analogy, as a spring. A bundle of pyrex glass tubes, across which a temperature gradient is maintained, acts as an acoustic impedance, and the column of gas in the open end acts as a distributed acoustic inertance or in the mechanical analogy, as a distributed mass. Thus, all the elements necessary for an acoustic oscillator exist.

When heat is added to the closed end of the tube so that a temperature gradient of several hundred degrees is maintained across the tube bundle, the system becomes unstable and acoustical oscillations are set up in the gas column. Heat has been supplied to the closed end of the experimental tube by an external gas flame and also by an internal electric heater.

In figure 3 a four inch diameter tube, five feet long, is shown. When 500 watts of thermal power are added at a temperature of 900 degrees Fahrenheit, oscillations occur at 60 cycles per second frequency and one-and-one half inches peak-to-peak displacement amplitude on the centerline. The oscillations are of one fundamental frequency with no substantial overtones, thus they are nearly perfect sinusoid waves. Maximum amplitude oscillations occur when the heat source and the tube bundle are placed close together in the tube at a position about one-fourth to one-half of the length of the tube from the closed end. Increasing the heat input increases the amplitude of the oscillations while the frequency remains constant. The frequency of the oscillations is primarily dependent on the length of the tube, that is, lengthening the tube decreases the frequency. Provision of auxiliary cooling of the tube at the end of the tube bundle opposite the heater has been found to increase the amplitude of the oscillations.

A double-ended closed thermoacoustical oscillator as shown in figure 4, offers the best configuration for a closed alternating current MHD generator. Here, energy is added at the ends as heat, converted to oscillating kinetic energy and then removed as alternating current electrical energy by MHD coupling.

It has recently been observed that the addition of water into the tube greatly increases the amplitude of oscillations. Rayleigh mentions that alcohol vapor and ether vapor also encourage oscillations. Water added to the hot closed end of the tube vaporizes, passes through the tube bundle and condenses on the relatively cool wall in the open end of the tube. In figure 5 a slightly different configuration is depicted where a condensible fluid, such as water, is used to encourage the oscillations. The condensed fluid would be collected below the tube bundle and then recycled back to the hot end by gravity flow.

The specific mechanism which causes thermoacoustical oscillations has not yet been satisfactorily explained. Lord Rayleigh's criterion that energy is added to the gas during the moment of greatest compression and removed at the moment of greatest expansion is certainly correct, but it remains to determine in detail how this is accomplished.

In attempting to understand better this energy exchange mechanism, it became apparent that the operation of the thermoacoustic oscillator was for all practical purposes the same as that of a Stirling Engine. In figure 6 the thermoacoustical oscillator is shown side by side with the Stirling Engine to illustrate their similarities. The basic difference between the two is that the Stirling Engine uses an essentially static working gas and a movable regenerator, while the thermoacoustic oscillator uses a moving working gas and a static regenerator. The purpose of the regenerator is to provide energy storage so that constant temperature expansion and compression occur in the ideal cycle. The pressure-volume and temperature-entropy diagrams illustrate the ideal thermodynamic cycle. The ideal efficiency of the reversible Stirling Engine is the same as that of the Carnot Cycle.

In an approximate analysis the thermoacoustic oscillator can be considered as a simple damped harmonic oscillator being driven as a resonant Stirling Engine. One may consider the closed end as a spring, the tube bundle as a friction element, and the open end as a distributed mass. This treatment is similar to the usual acoustic analysis of a Helmholtz Resonator. Such an analysis very closely predicts the resonant frequency of the system.

From this type of analysis the characteristics of the thermoacoustical converter for selected gas mixtures will become better understood and it will be possible to determine the geometry for maximum effectiveness. Further work should indicate what magnitude of oscillating velocity can reasonably be obtained. The outstanding feature of this MHD generator concept is that 60 CPS alternating current could be produced directly from the application of heat energy and magnetic field refrigeration energy for a high-field magnet. Thus, the thermoacoustic oscillator offers a novel approach to two corollary problems of present-day MHD converters, namely: thermal motivation of a gas in a closed-cycle system, and conversion of low-impedance direct current to alternating current power.

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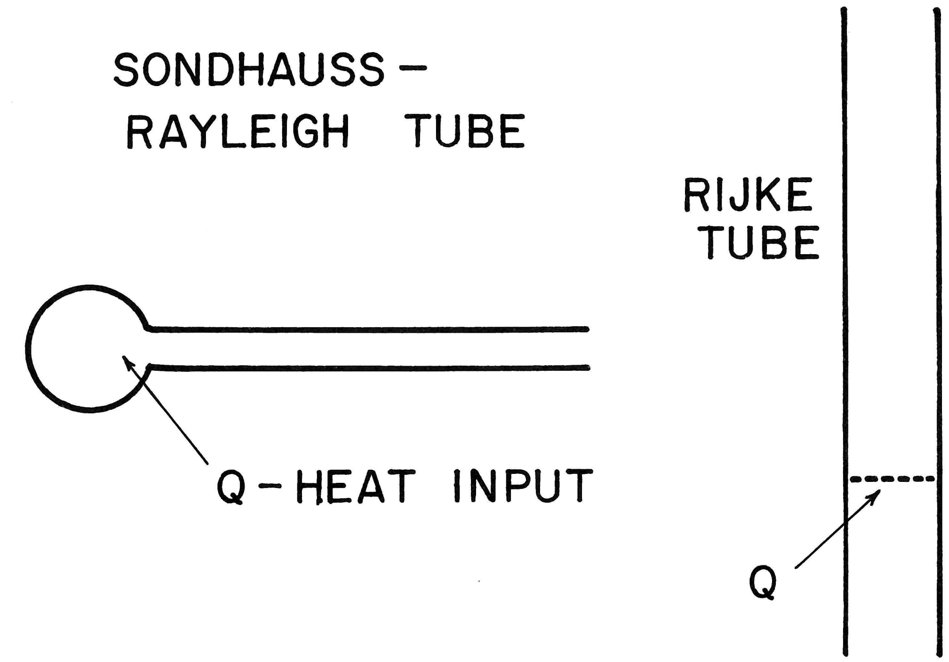
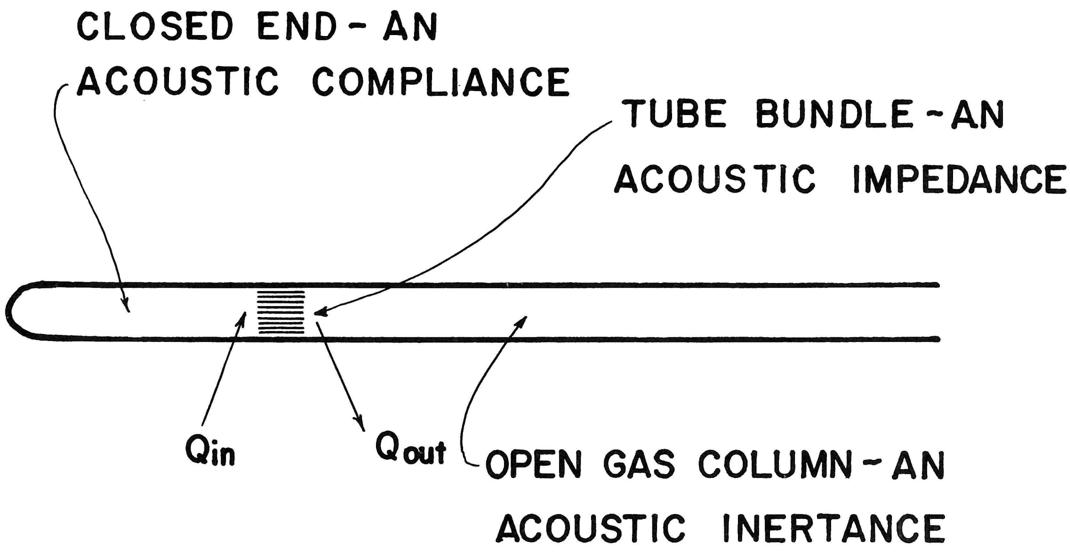


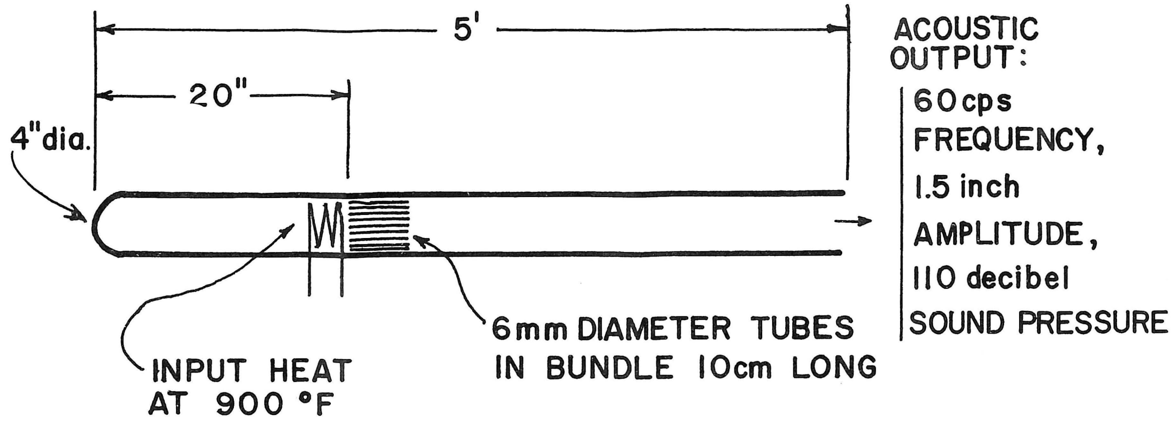
EARLY THERMOACOUSTIC OSCILLATORS

FIGURE 1



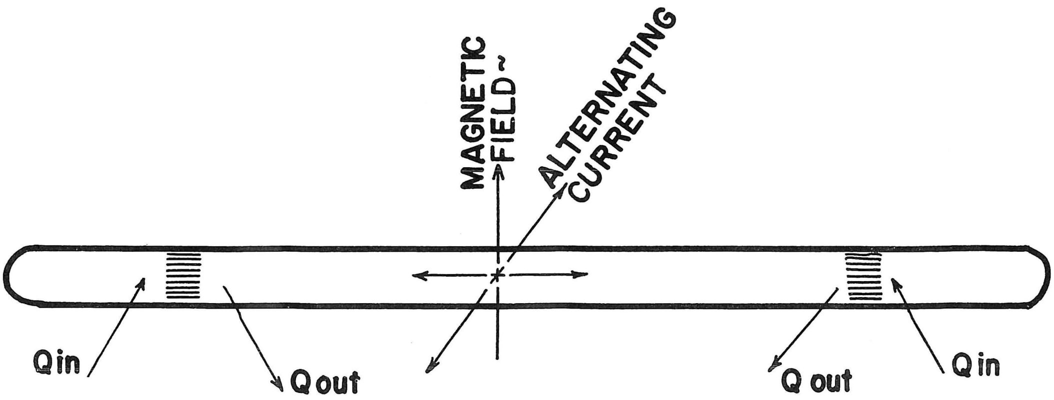
THERMOACOUSTIC OSCILLATOR

FIGURE 2



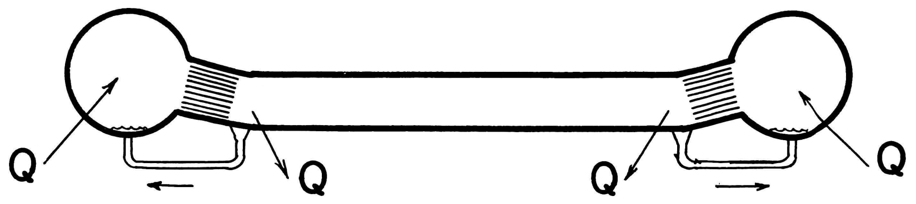
TYPICAL DIMENSIONS & OPERATING PARAMETERS FOR A THERMOACOUSTIC OSCILLATOR

FIGURE 3



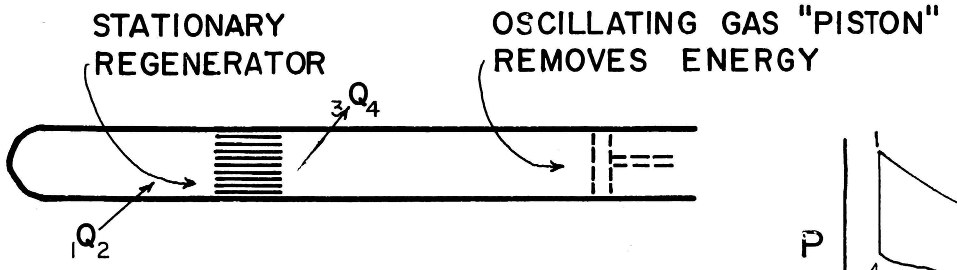
CLOSED THERMOACOUSTIC MHD GENERATOR

FIGURE 4

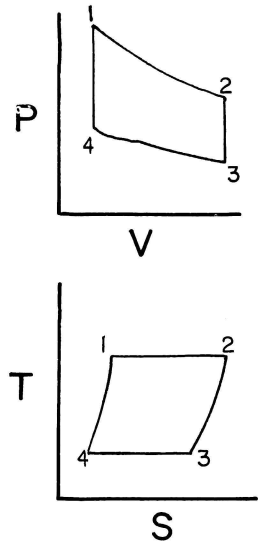


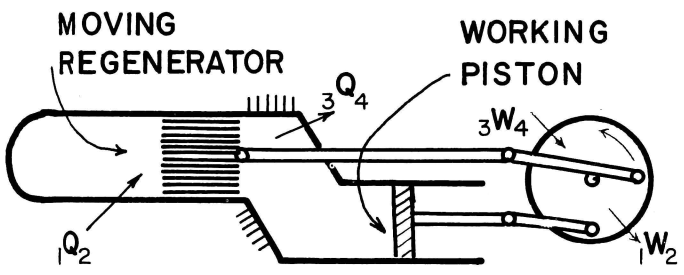
CLOSED THERMOACOUSTIC OSCILLATOR
USING A CONDENSIBLE FLUID TO
ENCOURAGE OSCILLATIONS

FIGURE 5



SINGLE CYCLE THERMOACOUSTIC
OSCILLATOR





CONVENTIONAL SINGLE CYCLE STIRLING
ENGINE

FIGURE 6

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