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Measurements of the Efficiency and Refrigeration Power of Pulse-Tube Refrigerators

Steffen Herrmann
Ray Radebaugh

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Pulse-tube or thermoacoustic refrigerators have the potential for high reliability since they require only one moving part--an oscillating piston or diaphragm at room temperature.

If a tube is closed at one end and connected to a pressure wave generator at the open end, and if the phase angle between mass flow and pressure is shifted from 90°, then refrigeration occurs at the open end. The shift in phase angle can be realized by thermal relaxation between the gas and the tube walls or by an orifice at the closed end. A low temperature of 60 K using helium gas in a one stage orifice pulse tube has been achieved at NBS. This report describes the first measurements of the efficiency, refrigeration power, and refrigeration power per unit mass flow, for three pulse-tube refrigerators. Three tube sizes, differing in length and diameter, were studied over a frequency range of 3 to 11.5 Hz. Cooling efficiencies as high as 90% of the Carnot efficiency were obtained when compressor and regenerator losses are neglected. With the optimum orifice setting, gross refrigeration powers of 14 W were measured at a temperature of 100 K in a tube of 12.7 mm diameter and 240 mm length at a pulse frequency of 6 Hz. The influence of pulse frequency, orifice setting, diameter, and length of tube are discussed in relation to some theoretical understanding of pulse-tube behavior.

Key words: cryocooler; cryogenics; efficiency; pulse-tube refrigerator; refrigeration power; refrigerator; regenerative refrigerator.

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1. Introduction

The lack of reliability in small cryocoolers is a problem that has been studied for many years. One approach to increased reliability is the elimination of some of the moving parts in a mechanical refrigerator. Stirling refrigerators have only two moving parts--the compressor piston and the displacer. In 1963 Gifford and Longsworth [1] discovered a new refrigeration technique which eliminates the displacer from the Stirling refrigerator. They called it pulse-tube refrigeration, but we refer to it here as the "basic" pulse tube. Under Gifford's direction [2-5], basic pulse-tube refrigeration was advanced to the point where a temperature of 124 K was achieved with one stage, and of 79 K with two stages [4]. A single-stage unit with the warm end at 65 K achieved 30 K [4].

The principle of operation, as given by Gifford and coworkers [1-5] and by Lechner and Ackermann [6], is qualitatively simple. The basic pulse tube, shown in Figure 1, is closed at the top end, where a good heat-transfer surface must exist between the working gas (helium is best) and the surroundings, in order to dissipate heat. The bottom, open, end also has a good heat transfer surface to absorb heat from its surroundings. The open end is connected to a pressure-wave generator (in our case a compressor) via a regenerator. During the compression part of the cycle any element of gas in the pulse tube moves toward the closed end and at the same time experiences a temperature rise due to adiabatic compression. At that time the pressure is at its highest value. During the maximum in the pressure wave the gas is cooled somewhat by heat transfer to the tube walls. In the expansion part of the cycle the same element of gas moves toward the open end of the pulse tube and experiences cooling due to adiabatic expansion. During the pressure minimum the gas is warmed by heat transfer from the tube walls. The net result of cycling the pressure in this manner is a "shuttle" heat transfer process in which each element of gas transfers heat toward the closed end of the pulse tube. The heat pumping mechanism described here requires that the thermal contact between the gas and tube be imperfect, so that the compression and expansion processes are somewhere between isothermal and adiabatic. The best intermediate heat transfer generally occurs when the product of pulse frequency and thermal relaxation time between the gas and the tube walls is approximately unity.

The early work on this type of refrigerator was done using a valved compressor and a rotary valve to switch the pulse tube alternately between the high and low pressure sides of the compressor; the pressure wave was approximately a square wave. Such a technique lowers the overall efficiency since no work is recovered in the expansion process. However the actual refrigeration process is relatively efficient because of the short times for compression and expansion, and the long times for heat transfer at the pressure plateaus. The lowest temperature of 124 K was achieved in 1967 by Longsworth [4] with a pulse tube 19 mm in diameter by 318 mm long. The high and low pressures were 2.38 MPa and 0.56 MPa, respectively, for a pressure ratio of 4.25, at a pulse frequency of 0.67 Hz. At the low temperature limit of 124 K, a gross heat pumping rate of 5 W was obtained which was totally consumed by loss terms such as conduction and regenerator ineffectiveness.

Also in 1967, Gifford and Kyanka [5] used a valveless compressor to recover work in the expansion process and increase overall efficiency. The pressure wave in that case was sinusoidal. The pressure ratio used was 4.2 and a low temperature limit of 165 K was achieved in one stage. The pulse tube consisted of a bundle of four stainless steel tubes, each having a diameter of 6.35 mm and a length of 102 mm. The peak pressure was 2.17 MPa and the minimum pressure was 0.52 MPa at a frequency of 6.2 Hz. They estimated that the work input for the same cooling power was approximately 10% of a system with a valved compressor.

In 1984 Mikulin, et al. [7] installed an orifice at the top of the pulse tube to allow some gas to pass into a large reservoir volume. This type of configuration is called the "orifice pulse tube." Although the original work of Mikulin et al. [7] placed the orifice just below the isothermal section, our version of this modification placed the orifice above this section (Fig. 2). They applied the pressure wave by the use of valves and used air as the working gas even though the Joule-Thompson effect is not used as a cooling mechanism in the orifice. They were able to obtain a low temperature of 105 K using a pulse tube 10 mm in diameter by 450 mm long with maximum and minimum pressures of 0.4 MPa and 0.2 MPa at a frequency of 15 Hz. The net refrigeration capacity at approximately 120 K was 10 W. It is not clear from their report what fraction of gas passed through the orifice.

A low temperature of 60 K was achieved in our laboratory using helium gas with our version of the orifice pulse tube [8]. The tube was 12.7 mm in diameter by 237 mm long and operated at a frequency of 9 Hz with a valveless compressor.

Measurements of the efficiency of these pulse tube refrigerators have not previously been made. Also, no measurements exist on the refrigeration capacity per unit mass flow. Such a quantity is needed to design the compressor and regenerator for a particular pulse-tube refrigerator. The purpose of this work is to provide measured values of the efficiency and refrigeration per unit mass flow for both the "basic" and "orifice" pulse tubes.

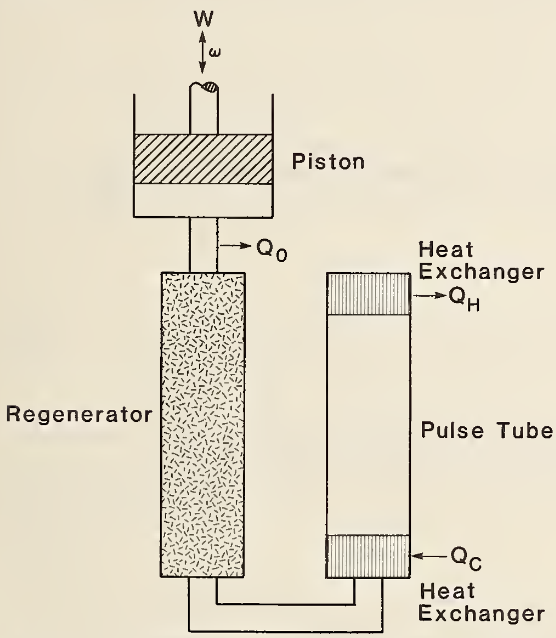


Fig. 1 Schematic diagram of the basic pulse-tube refrigerator

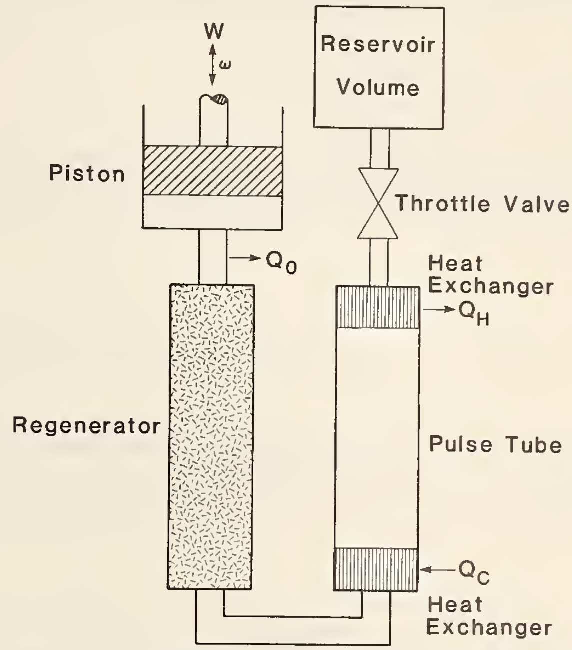


Fig. 2 Schematic diagram of the orifice pulse-tube refrigerator

2. Analysis

Unified explanations of the pulse tube as well as of the Stirling refrigerator, based on enthalpy flow, are given here which provide a basis for comparing different types of pulse tubes with each other and with other refrigerators. For steady-flow recuperative systems, such as the Joule-Thompson refrigerator, the enthalpy flow analysis is simple and has always been used. The enthalpy flow in regenerative systems, such as the Stirling and pulse-tube systems, is more complex because of the oscillation. The enthalpy flow $\dot{H}$ for an ideal gas in any region of an open system is

$$\dot{H} = \dot{m}h = \dot{m}c_pT, \tag{1}$$

where $\dot{m}$ is the mass flow rate through the region, h is the specific enthalpy, c_p is the specific heat at constant pressure, which for an ideal gas is constant, and T is the temperature. For an oscillating flow the time average of the enthalpy flow over one period is

$$\langle\dot{H}\rangle = c_p/\tau \int_0^\tau \dot{m}\, T\, dt. \tag{2}$$

According to the first law of thermodynamics the average heat flow rate $\langle\dot{Q}\rangle$ into a region is related to the change in enthalpy flow through that region $\Delta\langle\dot{H}\rangle$ and to the average work rate $\langle\dot{W}\rangle$ produced in the region, by

$$\langle\dot{Q}\rangle = \Delta\langle\dot{H}\rangle + \langle\dot{W}\rangle. \tag{3}$$

For a pulse tube, equation (2) cannot be used directly but T may be determined from the pressure P by use of the equation of state for an ideal gas:

$$T = P/R\rho. \tag{4}$$

Thus an alternative and often more useful equation for the enthalpy flow becomes, using (2) and (4),

$$\langle\dot{H}\rangle = \left(c_pA_g/R\tau\right) \int_0^\tau u\, P\, dt \tag{5}$$

where $\dot{m}$ has been replaced by $\rho A_g u$, and where A_g is the cross-sectional area perpendicular to the gas flow direction and u is the gas velocity. Since both eqs (2) and (5) are cyclic integrals, only the dynamic temperature T_d and pressure P_d need be used in those equations. Consider a sinusoidal pressure wave, P_d, with amplitude P_{do} superimposed on the average pressure P in a pulse tube

$$P_d = P_{do} \sin \omega t \tag{6}$$

This leads to a flow velocity u, mass flow rate $\dot{m}$, and dynamic temperature T_d, given by

$$u = u_o\sin(\omega t + \phi), \tag{7}$$

$$\dot{m} = \dot{m}_o \sin(\omega t + \theta), \tag{8}$$

$$T_d = T_{do} \sin(\omega t + \alpha) \tag{9}$$

where ϕ, θ, and α are the phase angles by which each of these waves leads the pressure wave. The assumption of sinusoidal behavior follows from the assumption that (P_d/P) and (T_d/T) are both small compared to unity. The integrals in eqs. (2) and (5) are of the form

$$I = (K/\tau) \int_0^\tau \sin(\omega t)\sin(\omega t + \delta)dt, \tag{10}$$

(K = constant terms) which becomes

$$I = (K/2) \cos \delta \ . \tag{11}$$

Thus, $\langle\dot{H}\rangle$ is a maximum when u and P_d (eq. 5) or $\dot{m}$ and T_d (eq. 7) are in phase (δ=0) and is zero when the phase angle between them is $\pi/2$.

We now consider three ranges of heat transfer between the gas and the walls. For adiabatic conditions $(\omega\tau_t \gg 1)$ $\phi=\pi/2$, $\theta=\pi/2$, $\alpha=0$, and from eq. (5) $\langle\dot{H}\rangle=0$. For isothermal conditions $(\omega\tau_t \ll 1)$ $T_d=0$ and from eq. (2) $\langle\dot{H}\rangle=0$. For intermediate conditions $(\omega\tau_t \approx 1)$, θ and ϕ are less than $\pi/2$ and α becomes nonzero. The phase angle between $\dot{m}$ and T_d then is less than $\pi/2$, so by eqs. (2) and (11) $\langle\dot{H}\rangle$ is nonzero.

The enthalpy flow as a function of position is shown in Figure 3 for the basic pulse tube. A positive $\langle\dot{H}\rangle$ means the enthalpy flow is to the right. The enthalpy flow at the left (cold) end of the pulse tube is initially greater than that on the right (hot) end because $\dot{m}$ is greater there, whereas T_d is the same on both ends. The abrupt changes in $\langle\dot{H}\rangle$ at the pulse tube boundaries give rise to heat flow terms according to eq. (3), since no work crosses the rigid boundary. If the net heat input at the left end is less than $\dot{Q}_c$, that end of the pulse tube cools until equilibrium is reached. At that time $\langle\dot{H}\rangle$ will become constant for all x within the $\omega\tau_t \approx 1$ region and heat flows occur only at the boundaries. A first-law analysis shows that $\dot{Q}_c = \dot{Q}_H$ at equilibrium, which means that a measurement of $\dot{Q}_H$ gives the gross refrigeration power of the pulse tube.

The basic pulse tube relies on heat transfer to the walls to bring about a phase angle between u and P_d different from $\pi/2$. In the orifice pulse tube the orifice at the warm end is the phase shifting mechanism between u and P_d, by analogy to an RC electrical circuit. Heat transfer along the walls is still possible with the orifice pulse tube, but we have found that the amount of heat transferred there should be less than that in the basic pulse tube for best results. Therefore the orifice pulse tube works better at higher frequencies than the basic pulse tube, for tubes of the same diameter.

Basic Pulse Tube

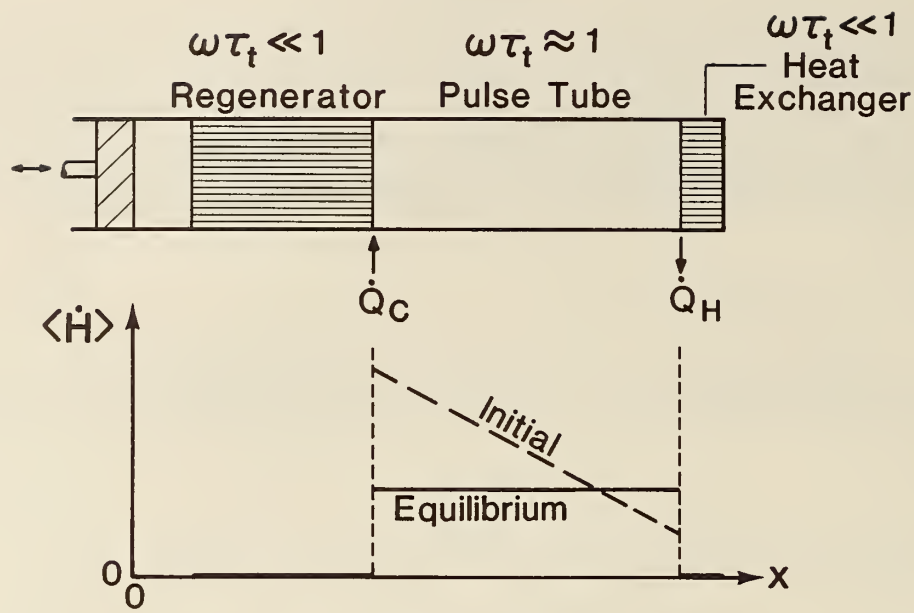


Fig. 3 Enthalpy Flow in the basic pulse-tube refrigerator

The enthalpy flow analysis is easily extended to the Stirling refrigerator (Fig. 4). Because $\omega\tau_t \ll 1$ in the regenerator section, $\langle\dot{H}\rangle = 0$. The sections on each end of the regenerator can have any value of $\langle\dot{H}\rangle$ in practice. If $\omega\tau_t \gg 1$ (adiabatic), the movement of the piston causes a phase shift between u and P_d away from $\pi/2$ to a phase angle of approximately zero. The enthalpy flow according to eqs. (5) and (11) is then a maximum and heat flows occur at the discontinuities in $\langle\dot{H}\rangle$ at each end of the regenerator. The term $\langle\dot{H}\rangle$ goes to zero at the boundary with the piston which means the First Law in eq. (3) is satisfied by balancing $\Delta\langle\dot{H}\rangle$ with the work flow $\langle\dot{W}\rangle$. If $\omega\tau_t \ll 1$ (isothermal) in the sections between the regenerator and the pistons, the enthalpy flow is zero. The energy balance at the piston boundary is then satisfied by having $\langle\dot{Q}\rangle = \langle\dot{W}\rangle$ at the boundary. The similarity between the Stirling refrigerator and the pulse tube refrigerators is now evident when the cold piston or displacer is viewed simply as a mean of shifting the phase between the velocity and pressure waves, just as intermediate heat transfer or flow through an orifice causes such a phase shift in the pulse tubes. However, a phase shift of as much as $\pi/2$ cannot be reached in the pulse tubes except in some asymptotic fashion where $T_d \to 0$ or $\dot{m} \to \infty$.

Some quantitative comparisons between the pulse tube refrigerator and the Stirling refrigerator will be given later.

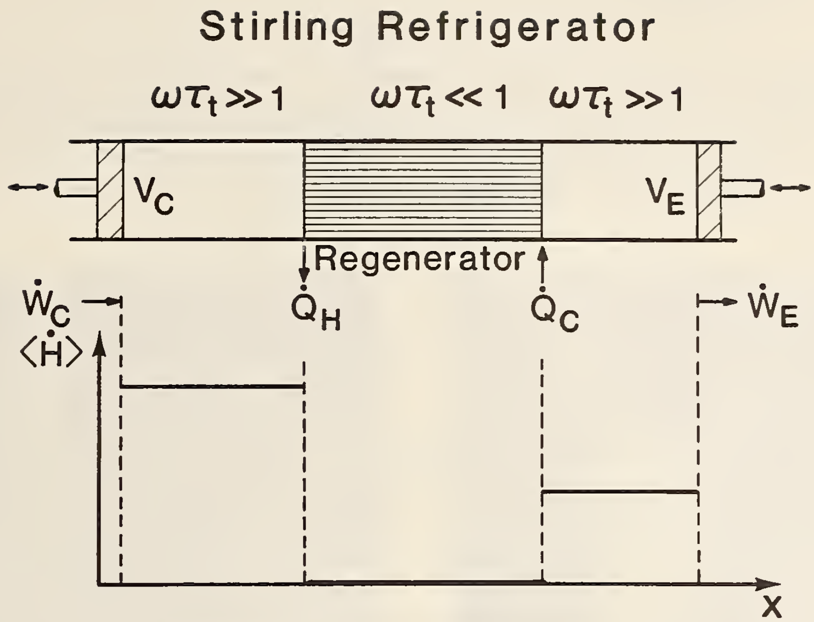


Fig. 4 Enthalpy flow in the Stirling refrigerator

3. Test Apparatus

The pulse-tube test apparatus provides a means for measuring the relevant parameters for calculating efficiency, refrigeration power and mass flow. Photographs of the apparatus are given in Figure 5 and Figure 6. Also a schematic diagram of the system is given in Figure 7. The pulse tube test apparatus is surrounded by a radiation shield held at 77 K by the use of liquid nitrogen. In addition, a vacuum of 10^{-3} Pa (10^{-5} torr) is maintained throughout the whole test apparatus.

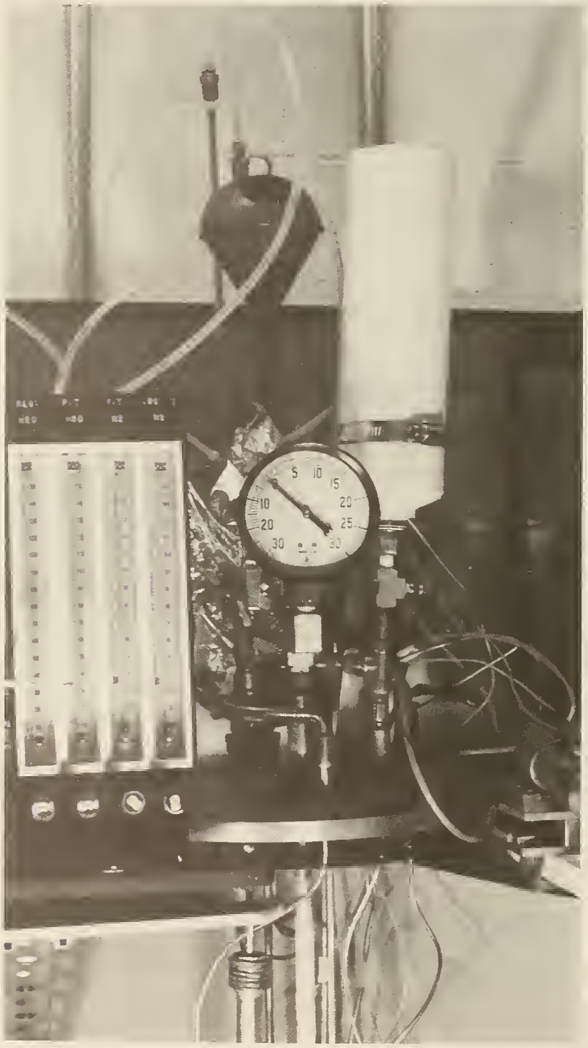


Fig. 5 Photograph of the pulse-tube refrigerator test apparatus showing the reservoir volume and orifice

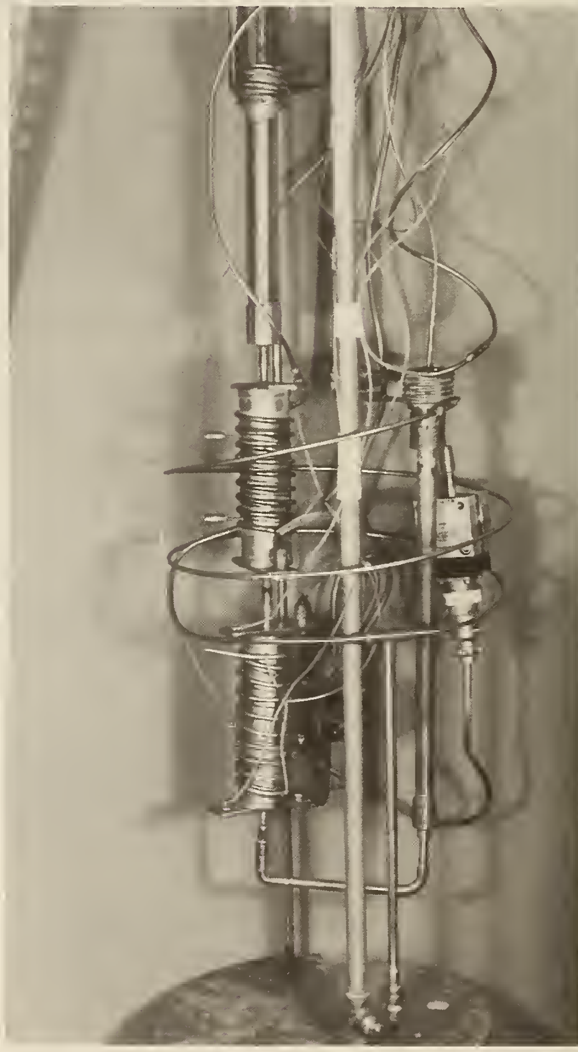


Fig. 6 Photograph of the pulse-tube refrigerator test apparatus showing the pulse-tube, the regenerator, and the two isothermalizers

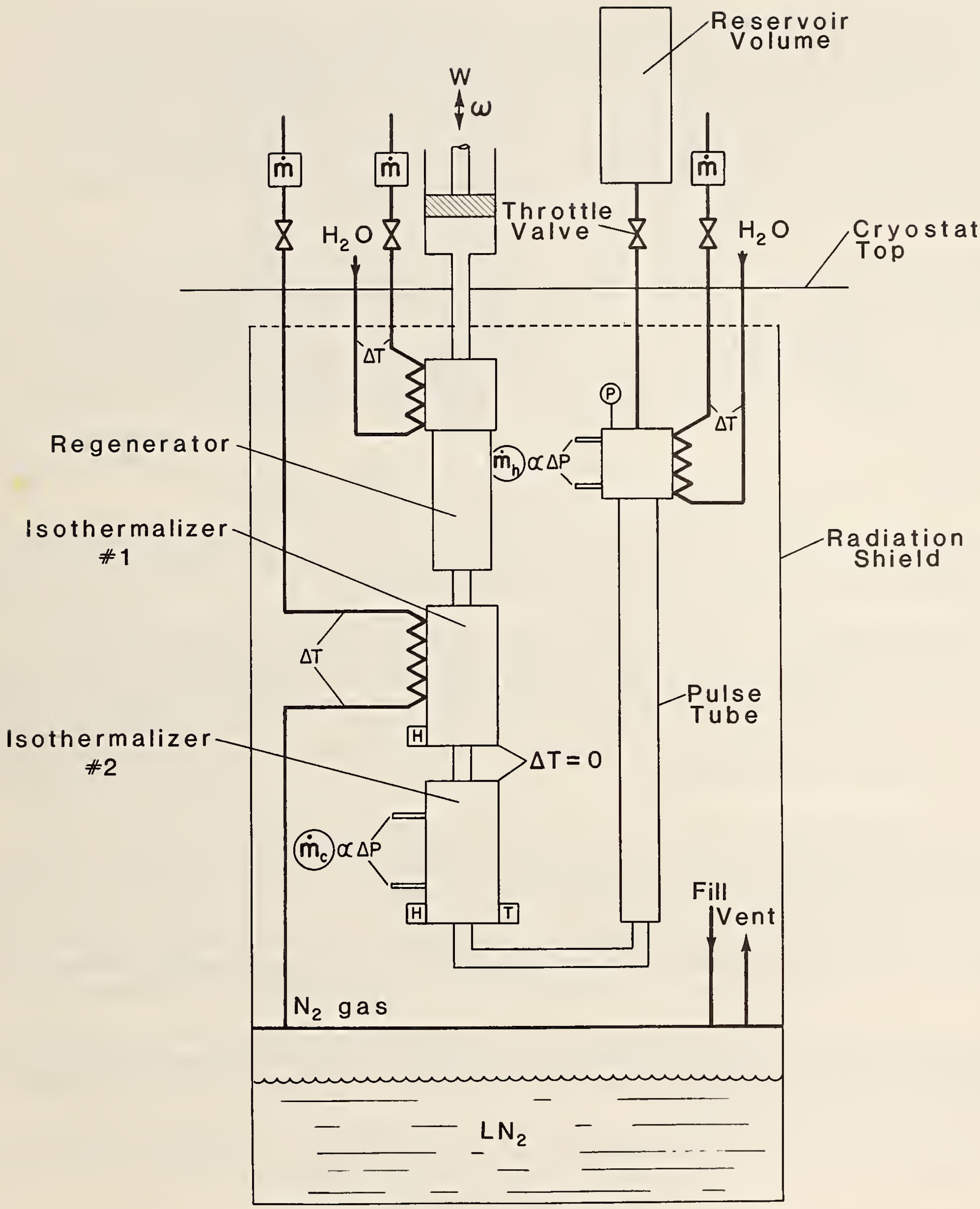


Fig. 7 Schematic diagram of the test apparatus

Previous measurements of the pulse tube behavior were made in systems where the regenerator loss was mixed with the refrigeration effect. In an attempt to separate the regenerator loss term from the intrinsic refrigeration, paired isothermalizers have been employed here: isothermalizer #1 is adjacent to the regenerator, and #2 is next to the pulse-tube. The isothermalizers have excellent heat transfer between the working gas and the body of the isothermalizer and a high heat capacity to eliminate temperature oscillation at the working frequency. The two isothermalizers are thermally isolated from each other; but if they are maintained at the same temperature by external means, the cooling power required by the #1 isothermalizer should equal the regenerator loss, and the heat input to isothermalizer #2 should equal the intrinsic refrigeration power of the pulse tube. The natural tendency is for #1 isothermalizer to be warmer than #2 isothermalizer when no cooling from the boil-off nitrogen vapor is provided to the #1 isothermalizer. Cooling of the #1 isothermalizer was balanced by increased heating required by the #2 isothermalizer. The heat flow to the cooling water at the top end of the pulse tube was not affected since the total gross heat input to the cold end was not changed when cooling was provided to the #1 isothermalizer. However, it was found that the two isothermalizers could not be maintained at the same temperature. With no cooling temperature differences were around 7 K. With the maximum cooling power available the difference was reduced to only about 4 K and the heat input to the #2 isothermalizer was then much greater than the heat rejected at the hot end. This behavior is not understood at present, so the measurements reported have used the heat rejected at the hot end as a measure of the gross refrigeration power.

The major loss term in these experiments are the regenerator conduction and the regenerator ineffectiveness. By using the liquid nitrogen boil-off gas to cool the bottom of the regenerator when the pulse tube was not operating, it was found that the regenerator conduction could be represented to within ±20% by 2.5(W) - 0.0086(W/K)*T. At 100 K the conduction is then 1.6 W. Theoretical calculations based on curves of effectiveness vs. heat transfer units in Kays in London [9] for the regenerator ineffectiveness gave an equation to represent the regenerator loss term for 6 Hz and a mass flow of 2g/s by 15(W) - 0.05(W/K)*T. At 100 K the regenerator loss is then 10.4 W.

During this work experiments were done with three different pulse tubes, all of type 304 stainless steel. Dimensions of these tubes are given in the next section.

For good heat transfer the ends of the pulse tube were made of copper containing a few layers of copper screen to provide a large surface for the heat transfer. The volume of each of the isothermal ends was about 10% of the pulse tube volume

The orifice consisted of a 15-turn needle valve and the reservoir volume above the orifice was approximately 1L. The valve flow coefficient C_v for 1 or more turns is given by -2.025E-10(m*s*√K)+2.825E-10(m*s*√K)*turns. The regenerator was a stainless steel tube 19 mm in diameter by 127 mm long filled with 1050 discs of 150 mesh phosphor bronze screen.

For all pulse tubes the losses due to conduction along the steel tube length were smaller than 1% and could be neglected.

The refrigeration power of the pulse tube was determined by measuring the electrical power input to isothermalizer #2, as well as the mass flow rate, $\dot{m}$, and the ΔT of the cooling water flowing around the hot end of the pulse tube. The water measurement gives the gross refrigeration power, since $\dot{Q}_c=\dot{Q}_H$ at equilibrium.

All absolute temperatures were measured by commercial diode thermometers which are accurate to ± 1 K. The temperature difference between isothermalizer #1 and #2 and the temperature rise of the cooling water were measured with copper-constantan thermocouples.

The mass flow rate at the cold end of the pulse tube, $\dot{m}_{pt}$, was determined from measurements of the pressure drop across the laminar flow element of isothermalizer #2. The construction of the isothermalizer is shown in Figure 8. For laminar flow of an ideal gas the mass flow rate is given by

$$\dot{m}_{pt}=C_K P_{pt} \Delta P_I / T_c R \quad (12)$$

where C_K is a flow coefficient, ΔP_I is the pressure drop across the laminar flow channel in the isothermalizer, P_{pt} is the pressure in the pulse tube, R is the ideal gas constant and T_c is the temperature at the cold end of the pulse tube. The coefficient C_K was determined in a separate experiment where helium gas flowed continuously at room temperature through the isothermalizer and a calibrated hot-wire flow meter. The variation of C_K was less than 10% over a factor of ten in flow rate. There was a directional dependence of about 10-20% in the flow coefficient. Laminar flow occurs in the isothermalizer for flow less than about 2.5 g/s. The largest average mass flow rates were about 2.9 g/s for the largest volume pulse tube at 9.5 Hz frequency and at 80 K. Peak values were somewhat higher, although the same flow coefficient was used to calculate $\dot{m}$ in all cases since the flow rate was less than

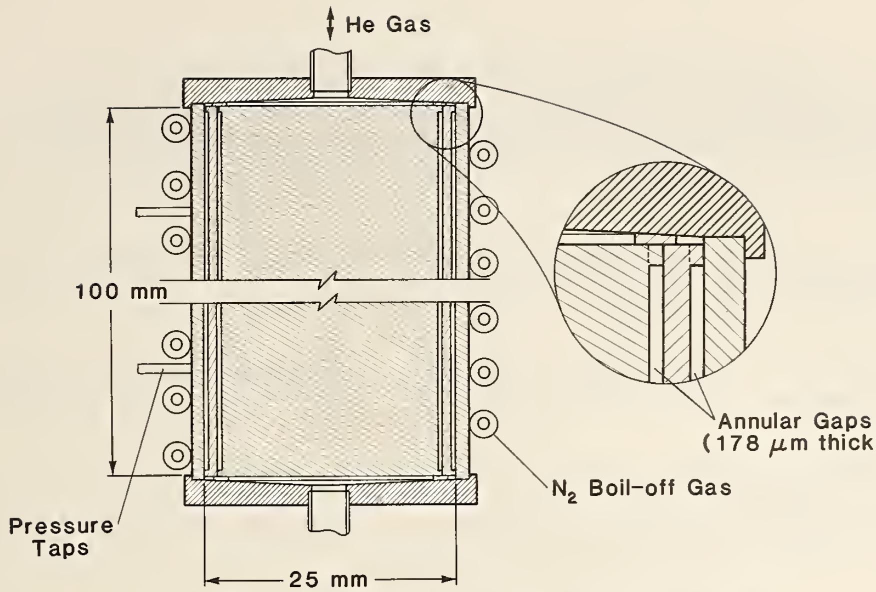


Fig. 8 Design diagram of the isothermalizer

2.5 g/s for most other situations. In the experiments the mass conservation law was used to calculate an exact ratio for forward and reverse flow coefficients in every measurement.

A variable reluctance pressure transducer of 50 kPa full scale was used to measure ΔP_I. The cavity volume on each side of the diaphragm is about 0.07 cm³. The transducer was mounted on the side of the isothermalizer to keep the length of 1.5 mm diameter pressure lines to a minimum to allow for fast response times. To determine if both cavities of the transducer respond equally to a rapidly changing pressure, the isothermalizer was capped off at the bottom end so very little mass flow would occur during pressure oscillations. Careful adjustments of lengths of 1.5 mm diameter pressure taps were required to balance the transducer for zero mass flow.

Since the pressure transducer is at the temperature of the isothermalizer, the temperature dependence of the transducer sensitivity was measured in a separate experiment but found to vary by less than 13% between 300 K and 77 K. Because of the uncertainty of other measured parameters, we decided to ignore the variation of transducer sensitivity with temperature. However, the zero setting on the transducer changed with temperature more rapidly and it was necessary to stop the compressor momentarily and adjust the zero setting for each new temperature.

The pulse tube pressure P_{pt} was measured with an absolute pressure transducer of the variable reluctance type attached to the top end of the pulse tube. A similar transducer was installed next to the compressor to observe the pressure P_c at that point in the system.

The mass flow through the orifice was determined by measuring the pressure variation in the reservoir volume with a piezoresistive pressure transducer. The mass flow rate through the orifice averaged over one-half period is then calculated by

$$\langle \dot{m}_o \rangle = 2\Delta m_o/\tau = 2V_r \Delta P_r/\tau R T_o \qquad (13)$$

where τ is the cycle period, V_r is the reservoir volume, ΔP_r is the difference between the maximum and minimum pressure in the reservoir, Δm_o is the change of mass of the gas, R is the gas constant, and T_o is the reservoir temperature.

The compressor used to operate the pulse tube apparatus is quite large (~7 kw motor) to allow for volume throughout the versatile control panel. Measurement of electrical power input to the compressor motor is then not a fair comparison with other systems that are better matched to the capacity of the compressor. The best method of comparing the efficiency of the pulse tube refrigerator with other pulse tubes and with other refrigeration techniques is to consider the efficiency of only the cooling process and neglect losses associated with the regenerator and the compressor. The ideal thermodynamic work input to drive the pulse tube is determined from measured $\dot{m}_{pt}$ and P_{pt}. The instantaneous mass within an ideal compressor with no dead volume between it and the cold end of the pulse tube is given by

$$m_{pt}(t) = \int_o^t \dot{m}_{pt}(t)\ dt. \tag{14}$$

Applying the equation of state for an ideal gas again we can calculate the volume variation V(t) of the ideal compressor

$$V_{pt}(t) = m_{pt}(t) \cdot R \cdot T_o / P_{pt}(t) \tag{15}$$

For a closed cycle the work input is

$$W = \oint P dV \tag{16}$$

By using $P_{pt}(t)$ and $V_{pt}(t)$ the equation becomes

$$W_c = \int_o^\tau P_{pt}(t) \frac{dV_{pt}(t)}{dt} \cdot dt, \tag{17}$$

which is the work input over one cycle. To obtain the average work input rate we multiply this by the frequency,

$$\dot{W} = W_c \cdot f \tag{18}$$

The average mass flow $\langle \dot{m}_{pt} \rangle$ is given by

$$\langle \dot{m}_{pt} \rangle = 2f(m_{ptmax} - m_{ptmin}) = 2f\Delta m_{pt}\ , \tag{19}$$

The thermodynamic efficiency η of the various types of pulse tube refrigerators is used for cycle comparisons. This efficiency considers only the basic refrigeration element and neglects regenerator and compression losses. The efficiency relative to Carnot is expressed as

$$\eta = \dot{Q}(T_o - T_c)/\dot{W}T_c \tag{20}$$

where T_o is the ambient temperature, T_c the temperature of the cold end of the pulse tube, $\dot{Q}$ is the refrigeration power, and $\dot{W}$ is the work input.

The quantities P_C, P_{pt}, P_r, and $\dot{m}_{pt}$ were measured with a digital oscilloscope with 12 bit resolution and recorded on floppy disc. A program was written for the digital oscilloscope which carried out all the calculations in eqs. 12-20.

Measurements of pressures could be made to within ±2% but due to uncertainties in calibration of the laminar flow element the uncertainty of the mass flow is about ±15%. Measurements of the refrigeration power are accurate to about ±5%. The efficiency calculations use the refrigeration power and mass flow data therefore the inaccuracy of these values will be about the same as mass flow inaccuracy.

4. General Description of the Experiments

All experiments were done with the same equipment so that the results can be compared without any restrictions. The only part changed in the apparatus was the pulse tube. However for each pulse tube the same design for the bottom and top was used to guarantee equal heat transfer at the ends of each tube.

Each pulse tube was constructed from type 304 stainless steel to keep the losses due to conduction along the tube as low as possible. These losses were less than 1% and could be neglected. The sizes and corresponding numbers for the three pulse tubes are listed here.

Pulse tube I : 240mm length, 12.7mm O.D., 0.51 mm wall
Pulse tube II : 240mm length, 6.4mm O.D., 0.30 mm wall
Pulse tube III: 120mm length, 12.7mm O.D., 0.51 mm wall.

The most exhaustive experiments were done with pulse tube I to study all the general properties of the pulse tubes. Pulse tube II was used to demonstrate the influence of the cross-sectional area on refrigeration power and efficiency. Pulse tube III was one half the length of pulse tube I in order to investigate the dependence of refrigeration power and efficiency on length.

An average pressure of approximately 1 MPa and a pressure ratio of 2.6 was used for measurements of each pulse tube. The value of 1 MPa seemed to be the best pressure and the pressure ratio of 2.6 was the maximum that could be achieved with the available compressor. Helium gas was used for all runs. The frequency range varied from 3 Hz to 11.5 Hz. It was not feasible to go to higher frequencies with the existing compressor because of excess vibrations.

Measurements on the different pulse tubes were made at the following frequencies:

Pulse tube I : 3 Hz, 6 Hz, 9.5 Hz, 11.5 Hz
Pulse tube II : 3 Hz, 6 Hz, 9.5 Hz, 11.5 Hz
Pulse tube III: 6 Hz, 9.5 Hz

The temperatures ranged from approximately 270 K to the lowest possible temperature for the given frequency. Data were taken at different points throughout the entire temperature range.

The time required to realize the lowest possible temperature was especially long for pulse tube II because of its very small refrigeration power. Some runs took roughly 12 hours in order to obtain all the required data for the given frequency.

Special care was taken to obtain all data only at steady state conditions.

In the following section the individual results for each pulse tube and each frequency will be discussed. A summary of the most interesting and important results is given at the end of this report.

5. Experiments

5.1 Pulse Tube I; F = 3 Hz

As Fig. 9 illustrates, the highest relative efficiency is approximately 90% of Carnot efficiency when the orifice is completely closed. In this case the orifice pulse tube is equivalent to the basic pulse tube. The more the orifice is opened the lower the efficiency.

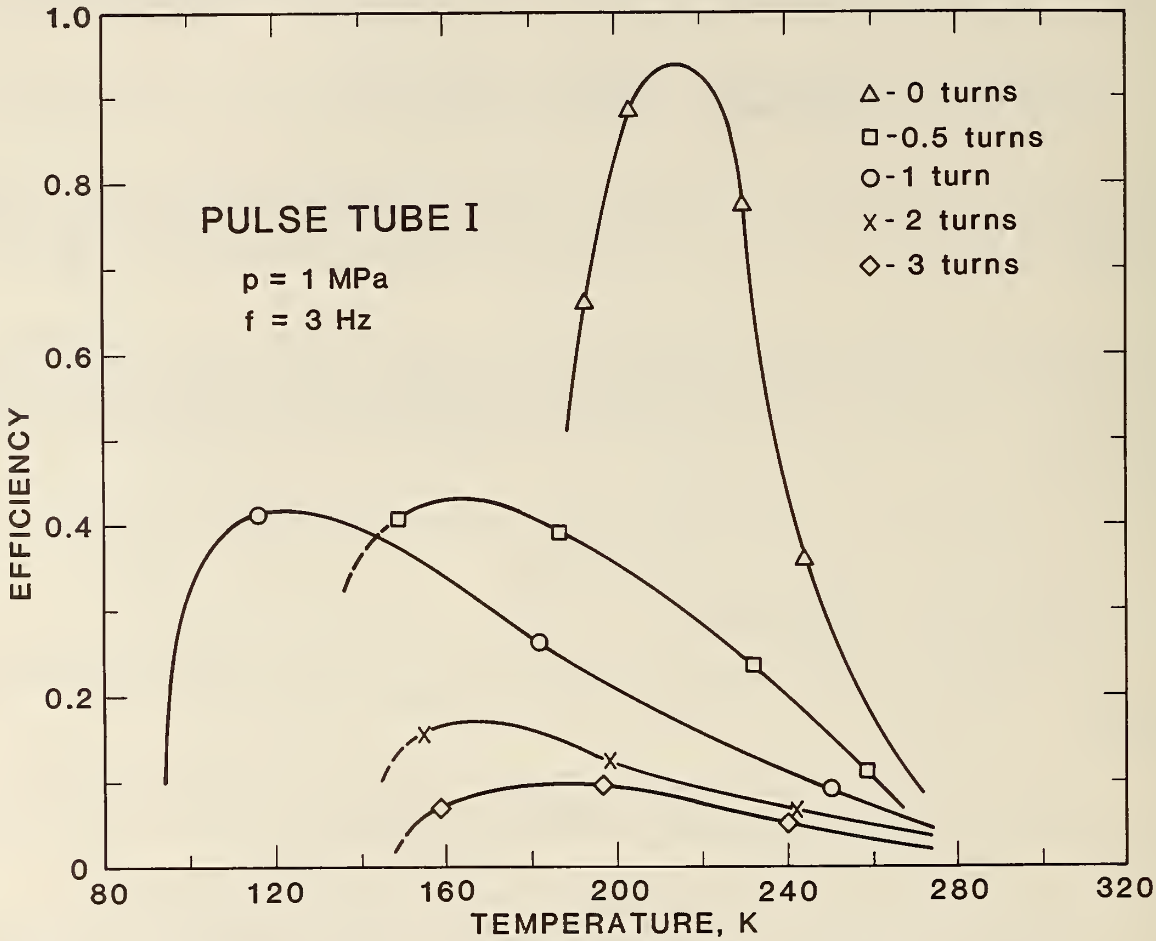


Fig. 9 Efficiency relative to Carnot vs temperature for pulse-tube I at 3 Hz

At a frequency of 3 Hz, our results indicate that an orifice opening of 1 turn gives the best results for the refrigeration power in the interesting temperature range, as shown in Fig. 10. The lowest temperature for this frequency of approximately 90 K was achieved with this orifice setting. For a larger orifice opening the mass flow through the orifice becomes too large. With an orifice opening of 3 turns, the mass flow through the orifice is roughly equivalent to the mass flow into the pulse tube, as shown in Fig. 11. This means that the orifice does not produce much phase shift for this case.

The mass flow into the pulse tube ranged from 0.4 g/s to 0.6 g/s depending on the orifice setting. It varies little with temperature. The ratio of refrigeration power to mass flow rate is shown in Fig. 12.

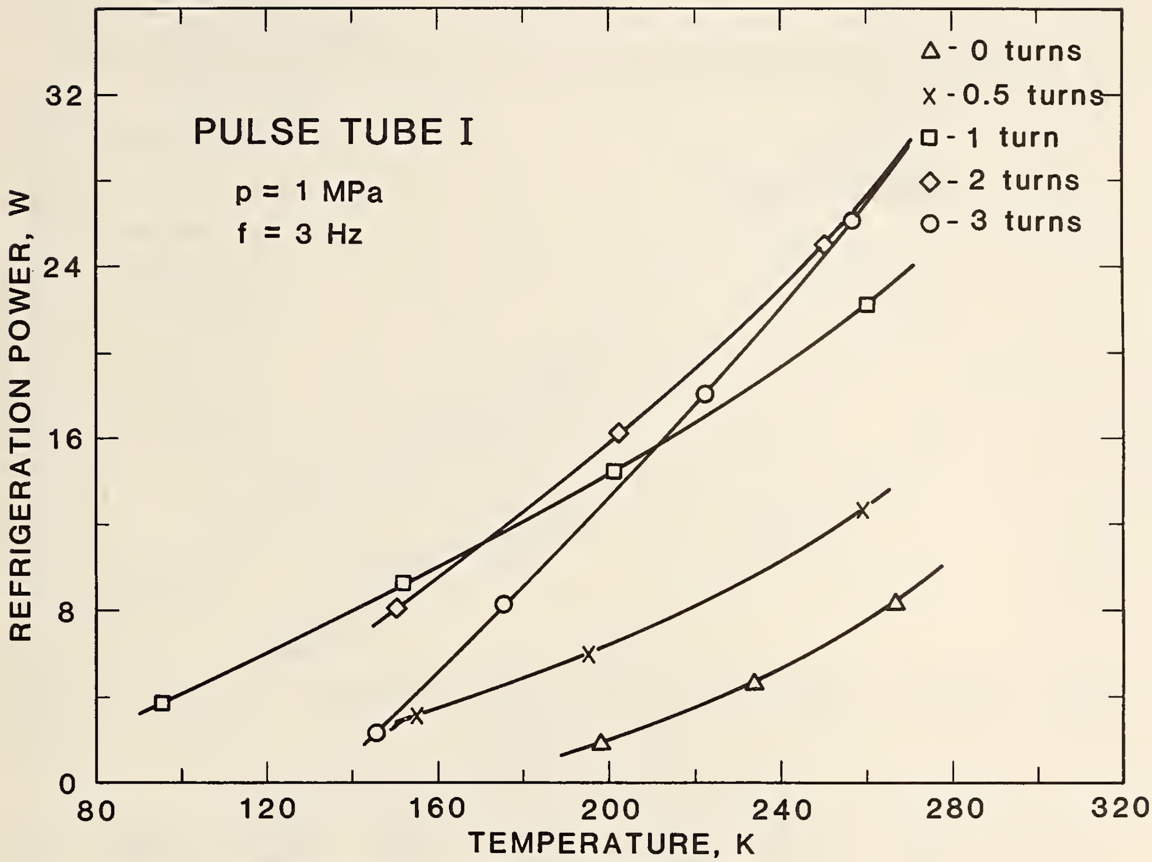


Fig. 10 Refrigeration power vs temperature for pulse-tube I at 3 Hz

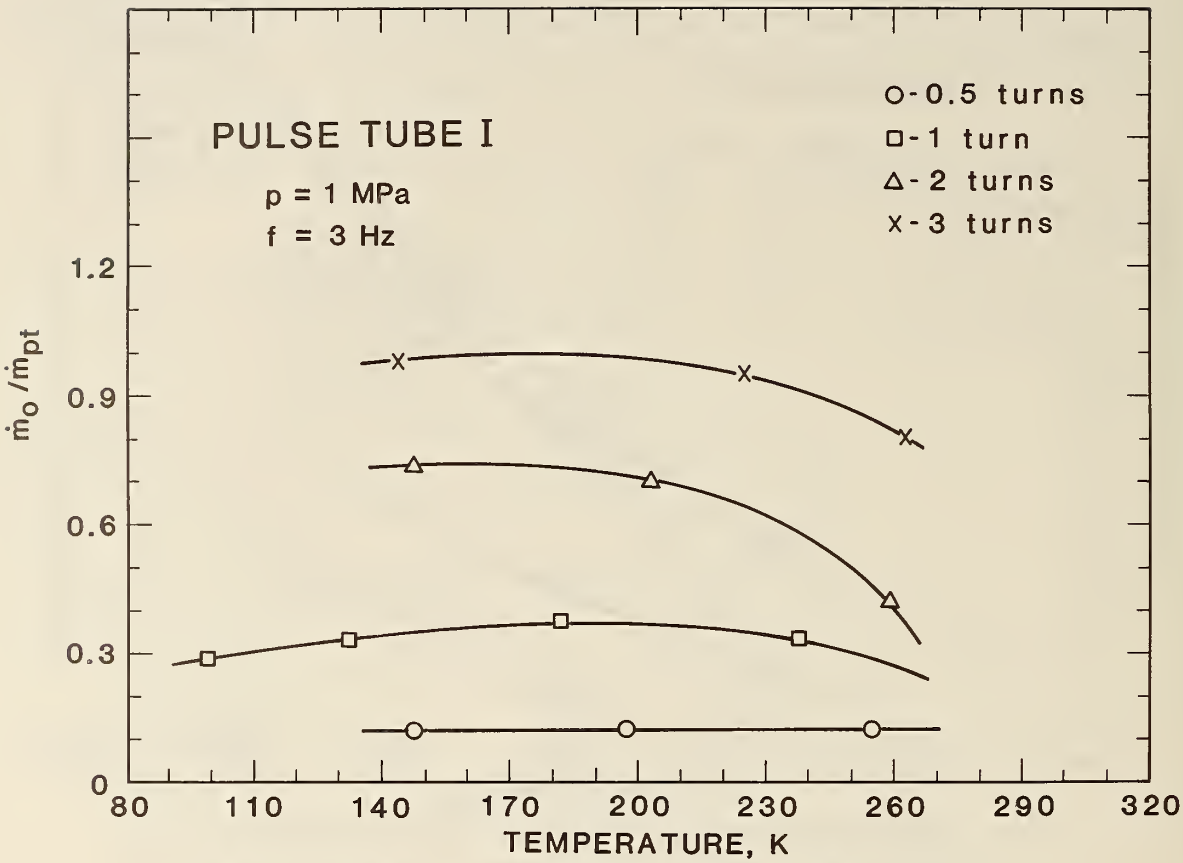


Fig. 11 $\dot{m}_o/\dot{m}_{pt}$ vs temperature for pulse-tube I at 3 Hz

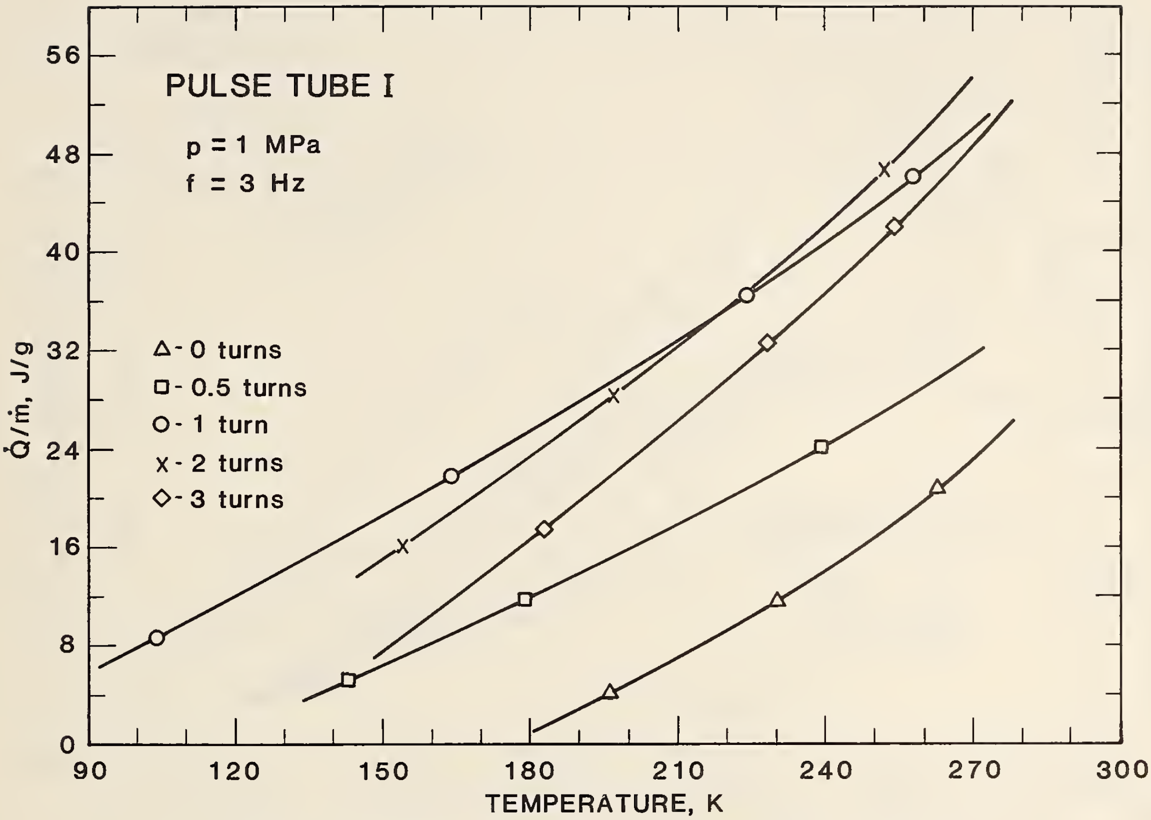


Fig. 12 $\dot{Q}/\dot{m}_{pt}$ vs temperature for pulse-tube I at 3 Hz

5.2 Pulse Tube I; F = 6 Hz

The lowest temperature recorded with this pulse tube (75 K) was accomplished with a frequency of 6 Hz and an orifice setting of 2 turns. It is at this frequency that the best combination of low temperatures and large relative efficiencies are realized. (Fig. 13). An astonishing efficiency of almost 90% Carnot was obtained with an orifice setting of 1 turn at a temperature of about 120 K. However, the refrigeration power at this setting was too low to bring about a further decrease in temperature. As Fig. 14 shows the highest refrigeration power can be achieved either with 2 or 3 orifice turns, depending on the temperature range.

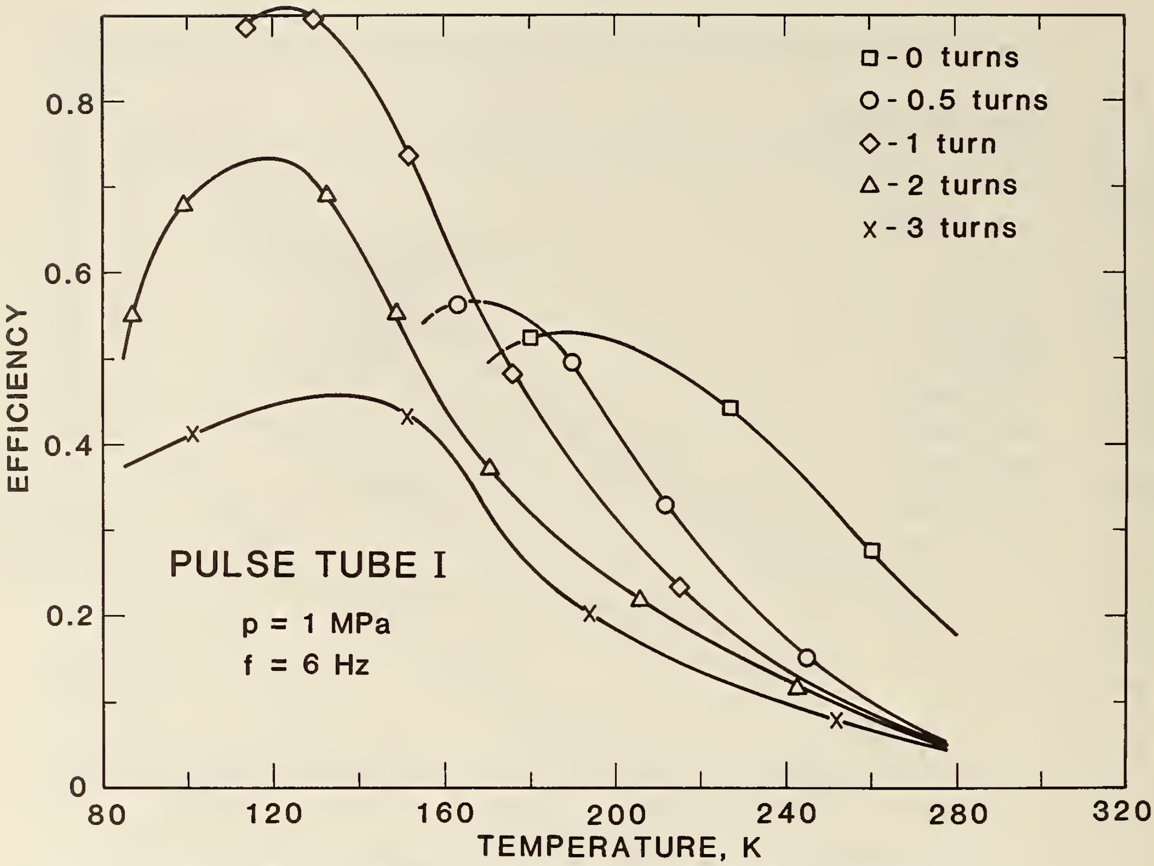


Fig. 13 Efficiency relative to Carnot vs temperature for pulse-tube I at 6 Hz

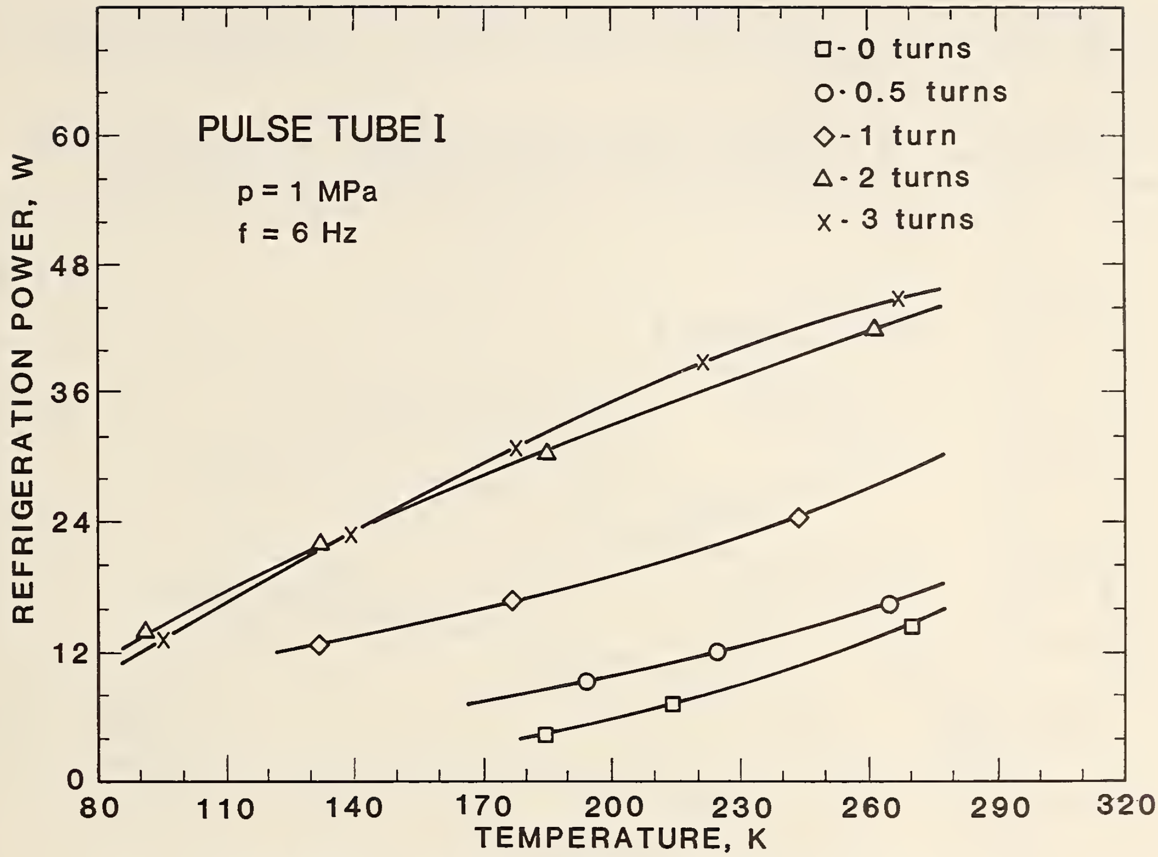


Fig. 14 Refrigeration power vs temperature for pulse-tube I at 6 Hz

For the basic pulse tube (orifice closed) a frequency of 6 Hz is already too high to get sufficient heat transfer between the gas and the tube walls. The refrigeration power in this case is too low to be useful.

As can be seen from Fig. 15 the ratio of $\dot{m}_o/\dot{m}_{pt}$ drops significantly below about 140 K and it falls into a reasonable range between 30% and 40% for 2- and 3-turn orifice openings. This explains the peak values of the efficiencies for orifice settings.

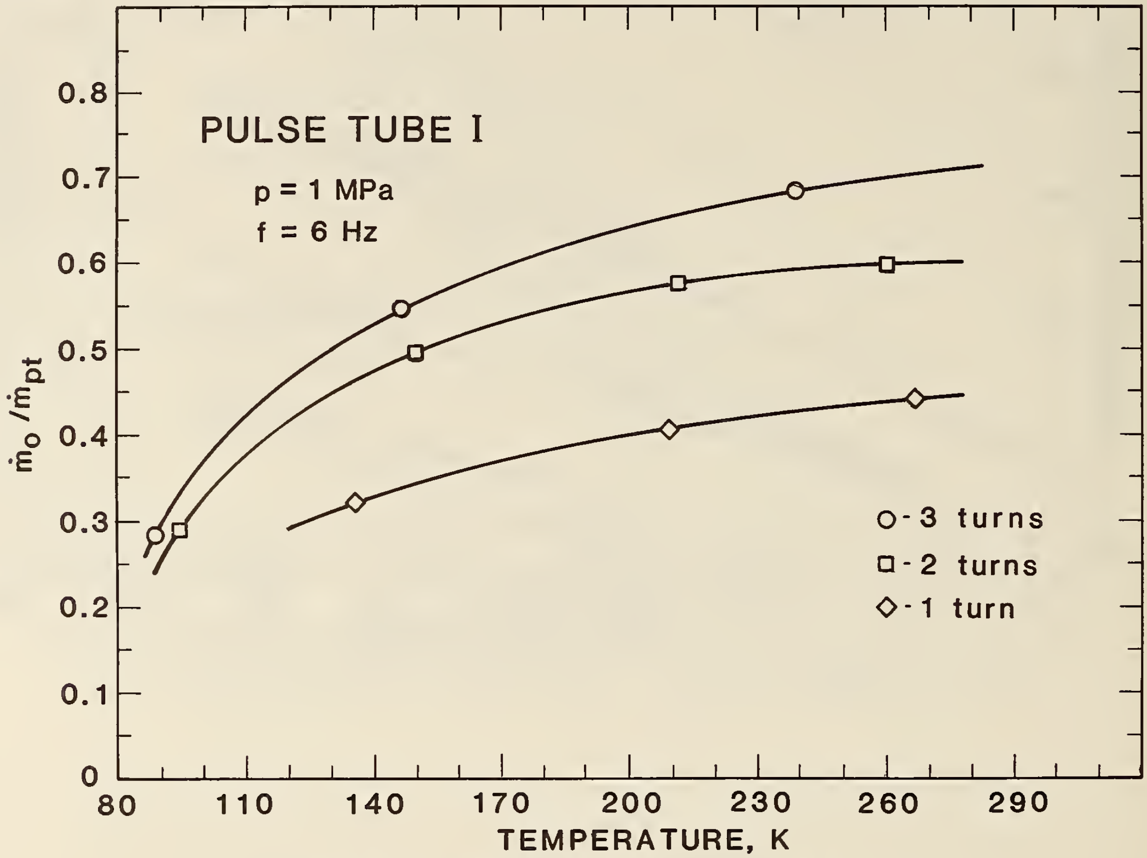


Fig. 15 $\dot{m}_o/\dot{m}_{pt}$ vs temperature for pulse-tube I at 6 Hz

The mass flow at a frequency of 6 Hz into the pulse tube is now more dependent on the temperature than at the lower frequency and varies from approximately 1.9 g/s to 0.9 g/s. It is found to be an approximately linear function of the temperature. The variation of the mass flow with the orifice setting is less than 10%.

The values for the heat transport per unit mass flow $\dot{Q}/\dot{m}_{pt}$ are not significantly different compared to values at the lower frequency of 3 Hz (Figs. 12 and 16).

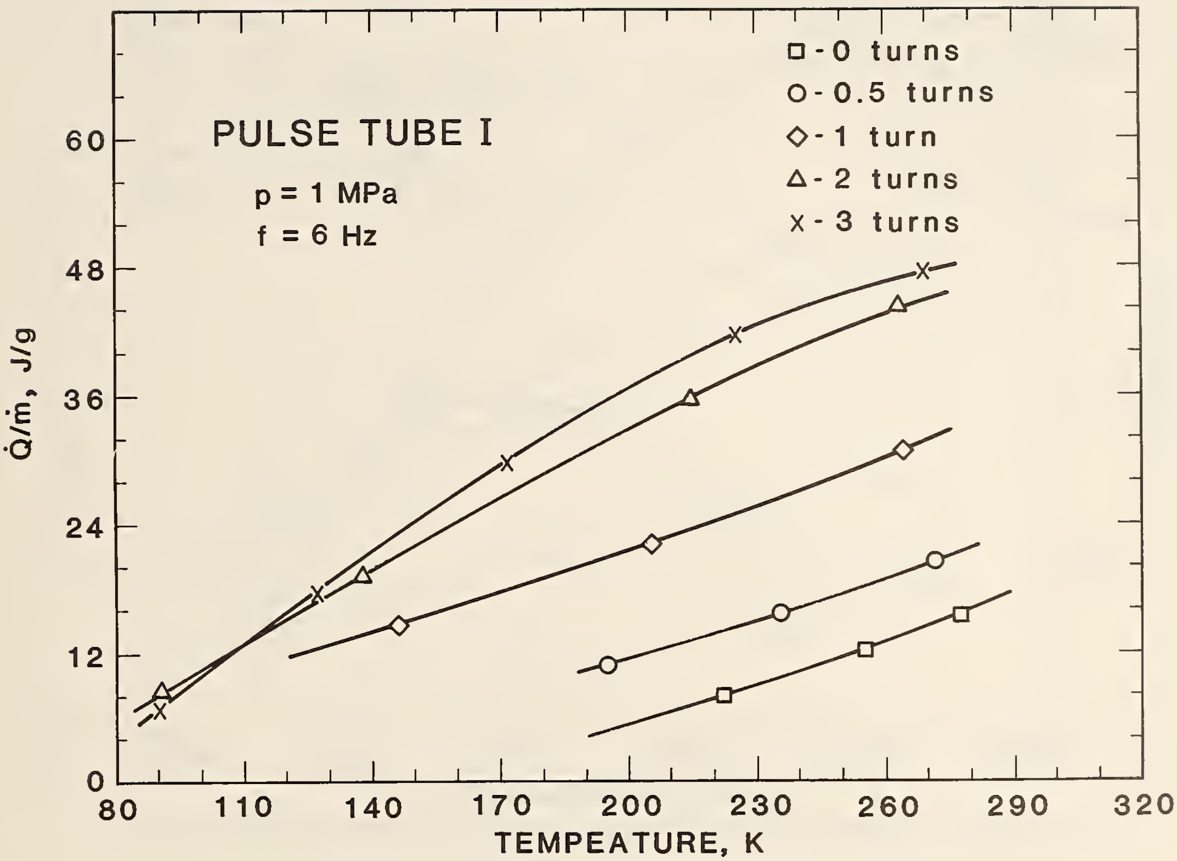


Fig. 16 $\dot{Q}/\dot{m}_{pt}$ vs temperature for pulse-tube I at 6 Hz

Considering all the tested frequencies, 6 Hz appears to be the best for application with this pulse tube size. By going to higher frequencies the refrigeration power is increased in the higher temperature range (>120 K) but only at the expense of a lower relative efficiency. Below 100 K the frequency of 6 Hz yields not only the best relative efficiency but also the highest refrigeration power.

5.3 Pulse Tube I; F = 9.5 Hz

The frequency of 9.5 Hz yielded the lowest relative efficiencies for pulse tube I (Fig. 17). These efficiencies are less than half of the efficiencies at 6 Hz without improving the refrigeration power (Fig. 18). The peak relative efficiency was only 34% of Carnot at a temperature of about 90 K and an orifice setting of 3 opening turns. In addition the lowest possible temperature was about 5 K higher than the lowest temperature achieved with a driving frequency of 6 Hz. However, relatively high refrigeration powers were achieved below 100 K making this frequency more useful for applications than the frequency of 3 Hz in spite of its much lower relative efficiency.

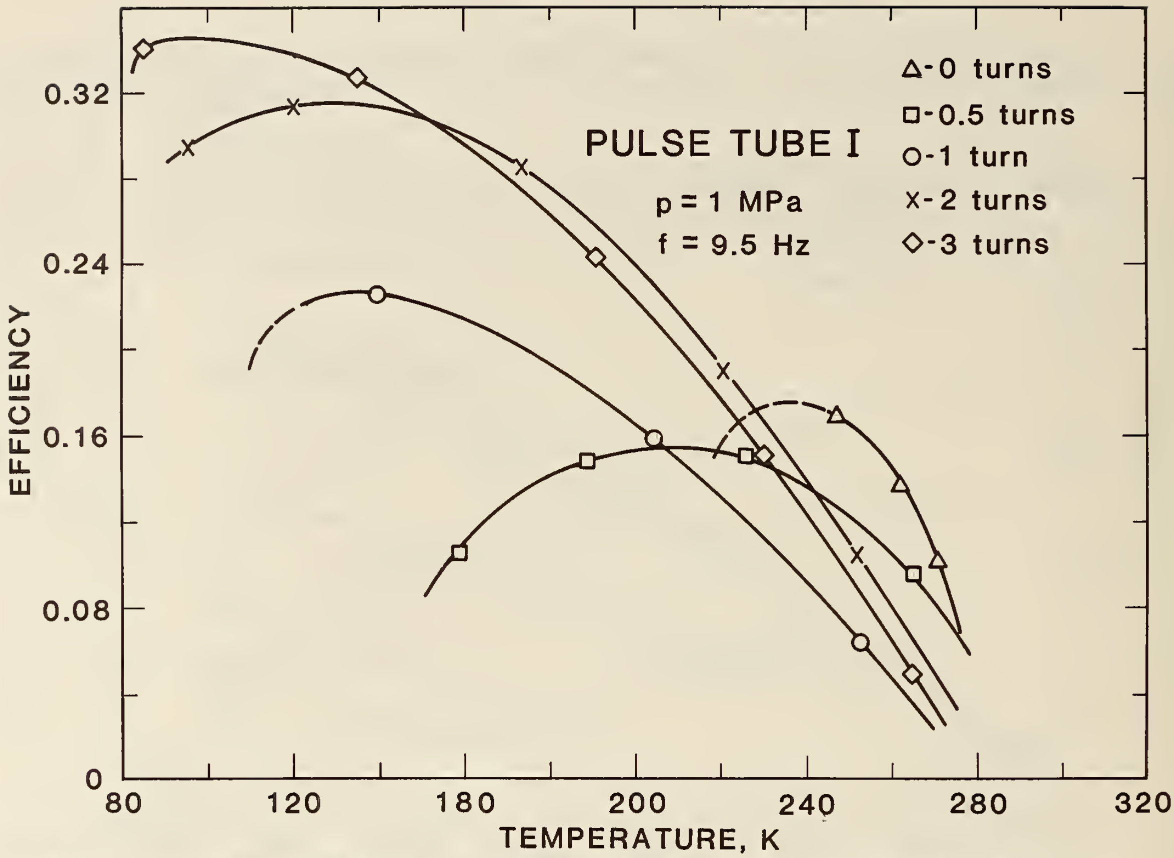


Fig. 17 Efficiency relative to Carnot vs temperature for pulse-tube I at 9.5 Hz

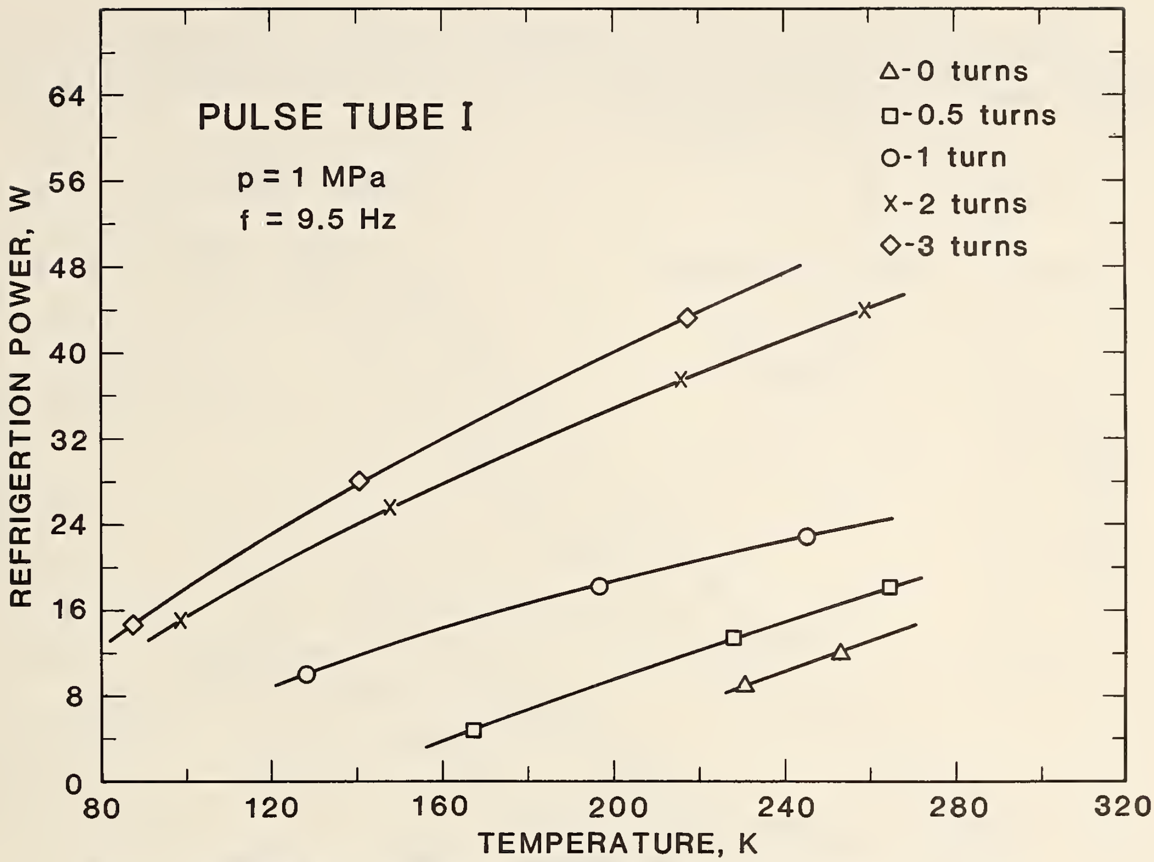


Fig. 18 Refrigeration power vs temperature for pulse-tube I at 9.5 Hz

The mass flow into the pulse tube is increased significantly in comparison to the 6 Hz frequency and the dependence on the orifice setting is even less significant than for 6 Hz. The flow ranges from approximately 1.2 g/s at 265 K to 2.9 g/s at 80 K and is approximately a linear function of the inverse temperature.

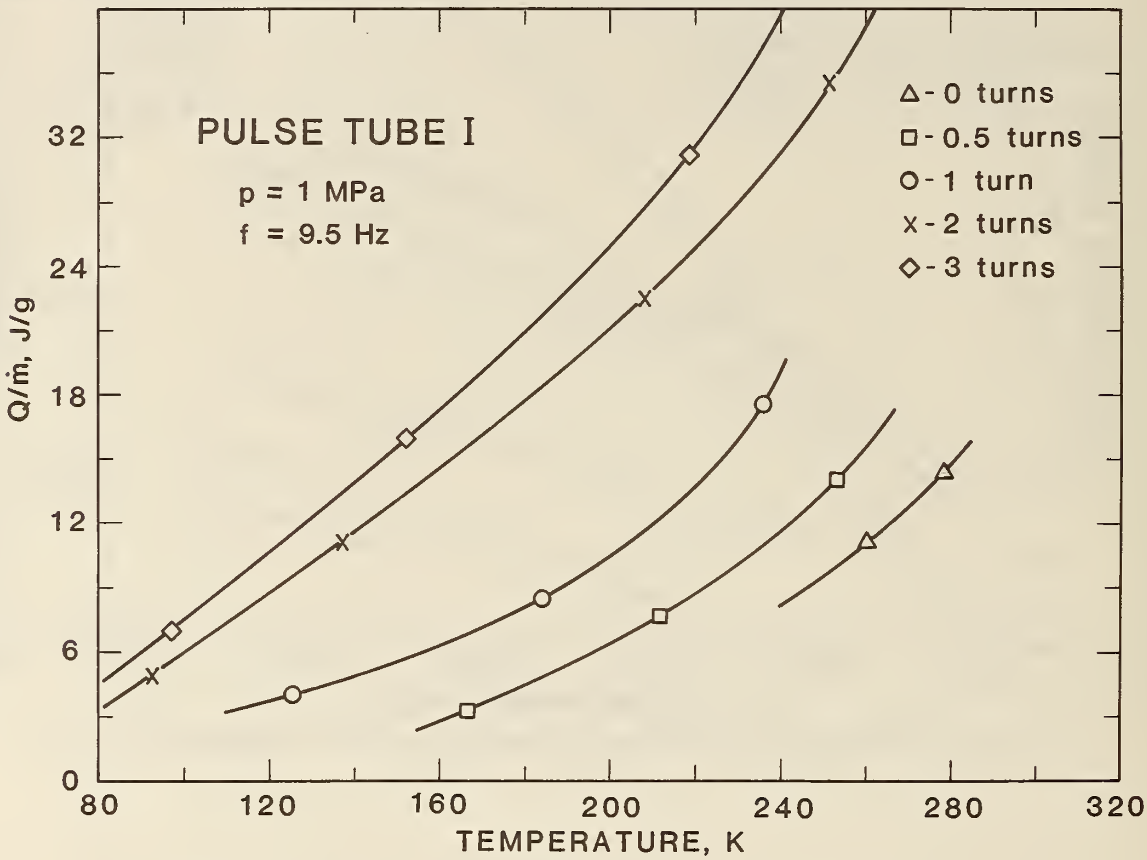


Fig. 19 $\dot{Q}/\dot{m}_{pt}$ vs temperature for pulse-tube I at 9.5 Hz

The ratio of mass flowing through the orifice to mass flowing into the pulse tube, $\dot{m}_o/\dot{m}_{pt}$, diminished and is only approximately 18% at 100 K (Fig. 20). This is the lowest ratio recorded with pulse tube I and could be an explanation for the relatively poor characteristics of this pulse tube at 9.5 Hz.

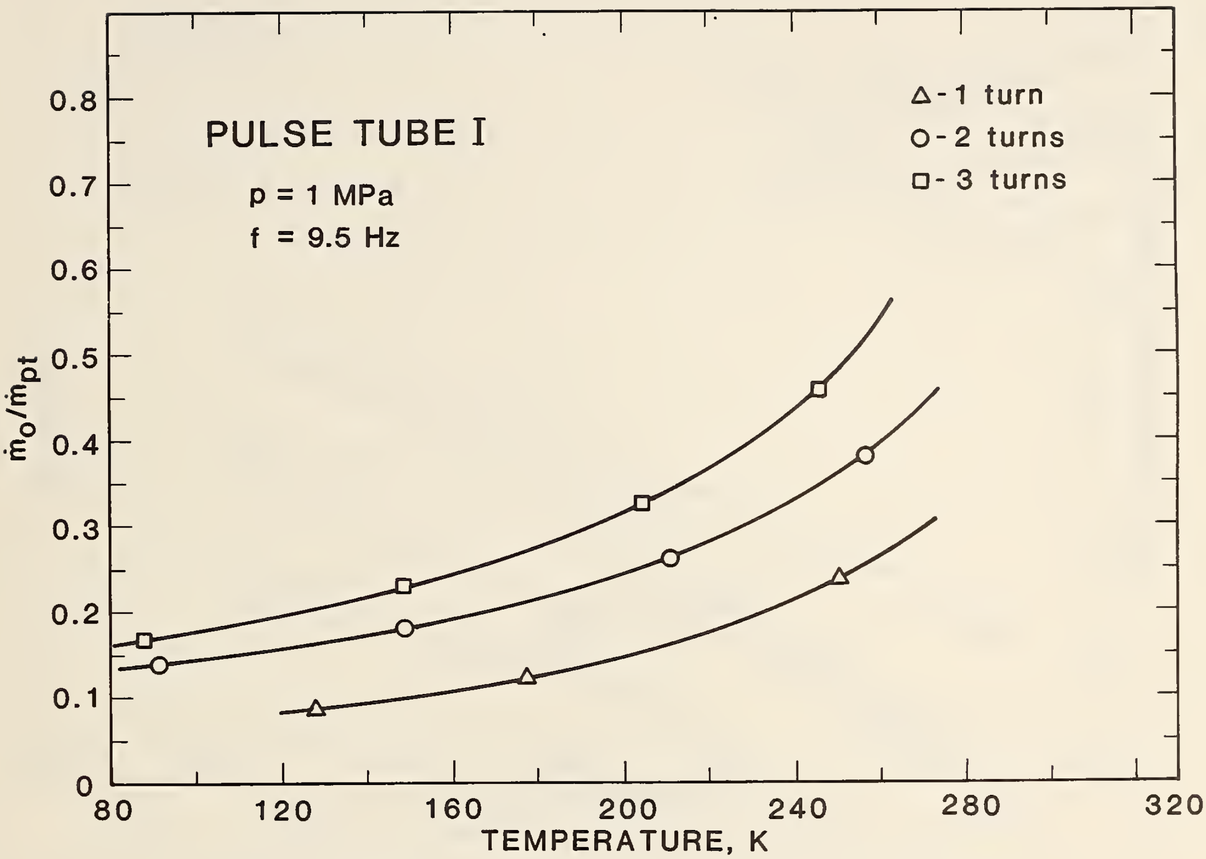


Fig. 20 $\dot{m}_o/\dot{m}_{pt}$ vs temperature for pulse-tube I at 9.5 Hz

5.4 Pulse Tube I; F = 11.5 Hz

In comparison to the results for 9.5 Hz, the results achieved at 11.5 Hz are better. In relation to a frequency of 6 Hz the only advantage at this frequency is in the high temperature range above 180 K, where there is a higher refrigeration power. Below this temperature the refrigeration power is almost identical to the power produced with a driving frequency of 6 Hz (Fig. 21) but can only be achieved with a much lower efficiency (Fig. 22). The peak in the relative efficiency is approximately 47% of Carnot at a temperature of around 120 K with an orifice setting of 3 turns. It is possible that some resonance phenomenon is responsible for this relatively high efficiency because 11.5 Hz is nearly the first harmonic of 6 Hz. Recall that a frequency of 6 Hz gave the overall best results for this pulse tube and yielded a relative efficiency of 90% of Carnot at 120 K.

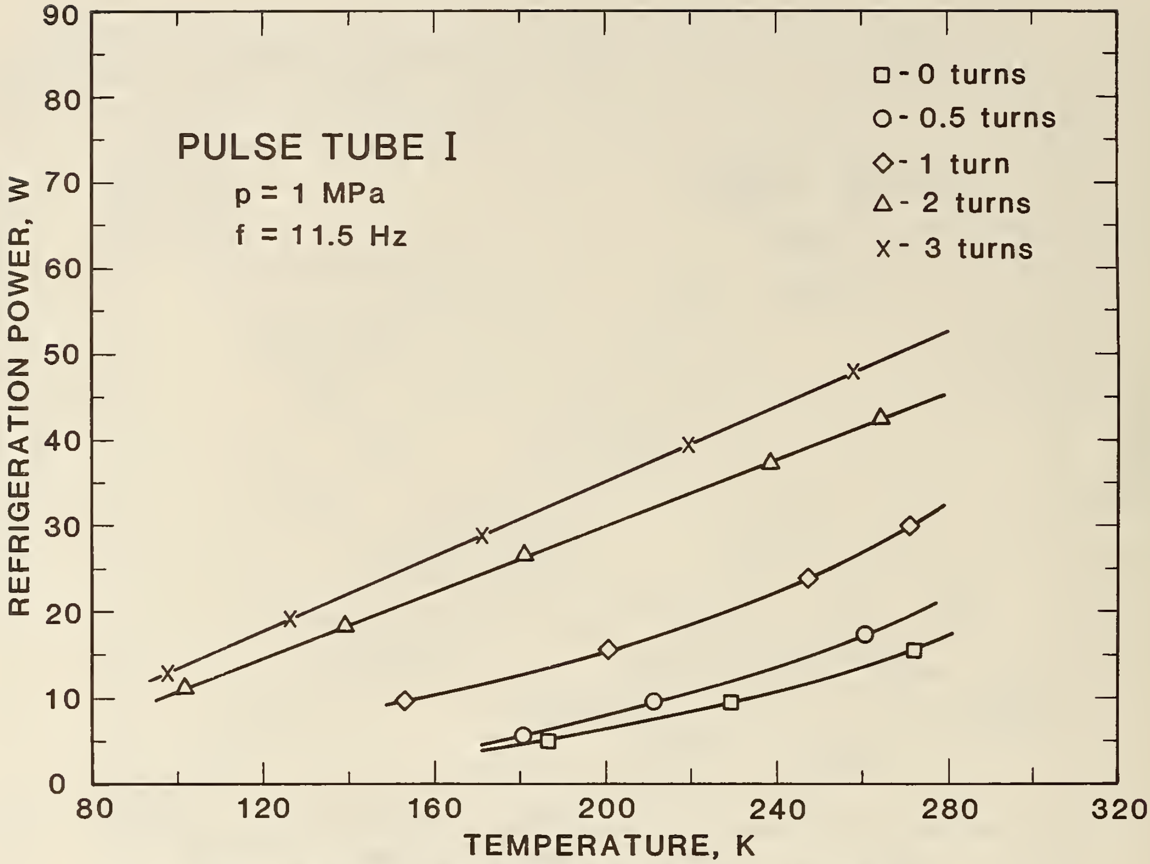


Fig. 21 Refrigeration power vs temperature for pulse-tube I at 11.5 Hz

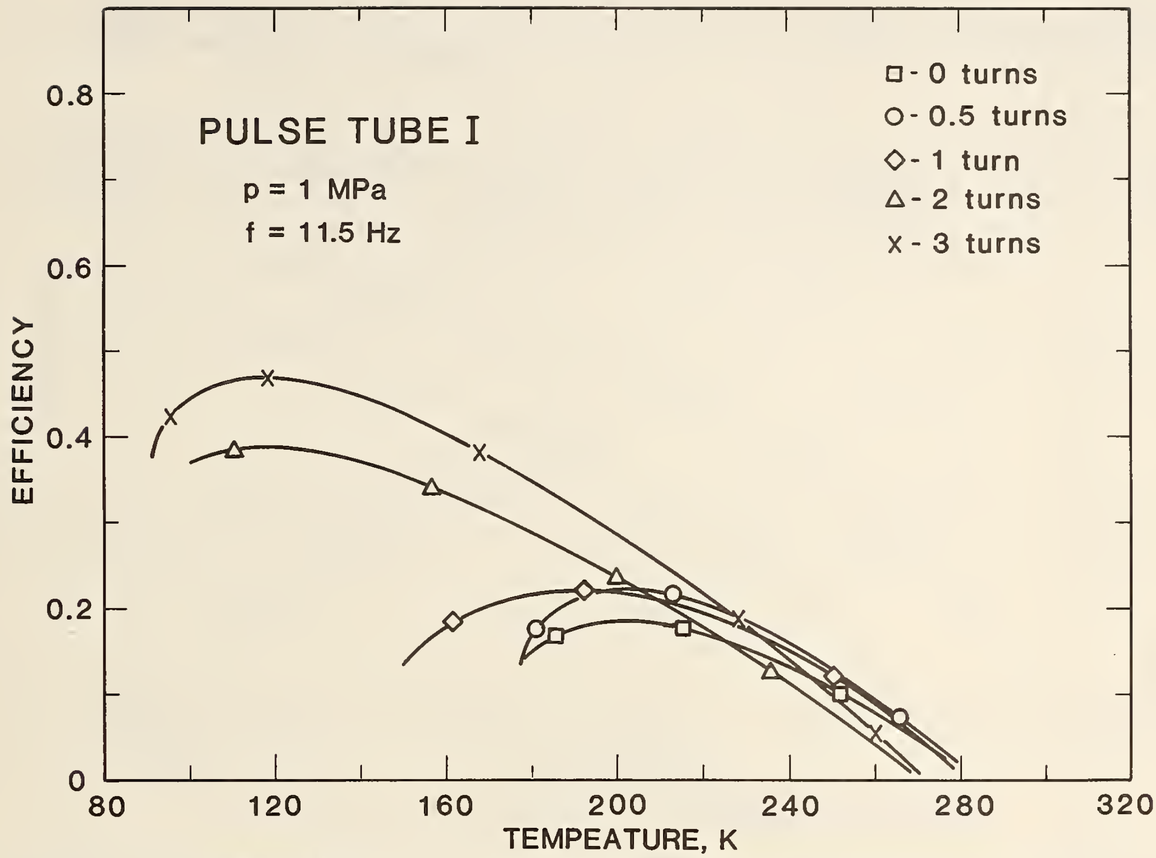


Fig. 22 Efficiency relative for Carnot vs temperature for pulse-tube I at 11.5 Hz

The lowest temperature obtained at this frequency was about 90 K, with an orifice setting of 3 turns. It appears that by increasing the frequency the lowest possible temperature is also increased. Unfortunately, it was impossible to run experiments with this test apparatus at higher frequencies to study this phenomenon more exactly.

The mass flow into the pulse tube at a frequency of 11.5 Hz was between 1.5 g/s for 270 K and 2.3 g/s for 90 K. The relation between mass flow and temperature is absolutely linear and almost no dependence on the orifice setting was exhibited, although the ratio of $\dot{m}_o/\dot{m}_{pt}$ increased significantly compared to the frequency of 9.5 Hz (Fig. 23). This can also be explained by the previously hypothesized resonance phenomenon.

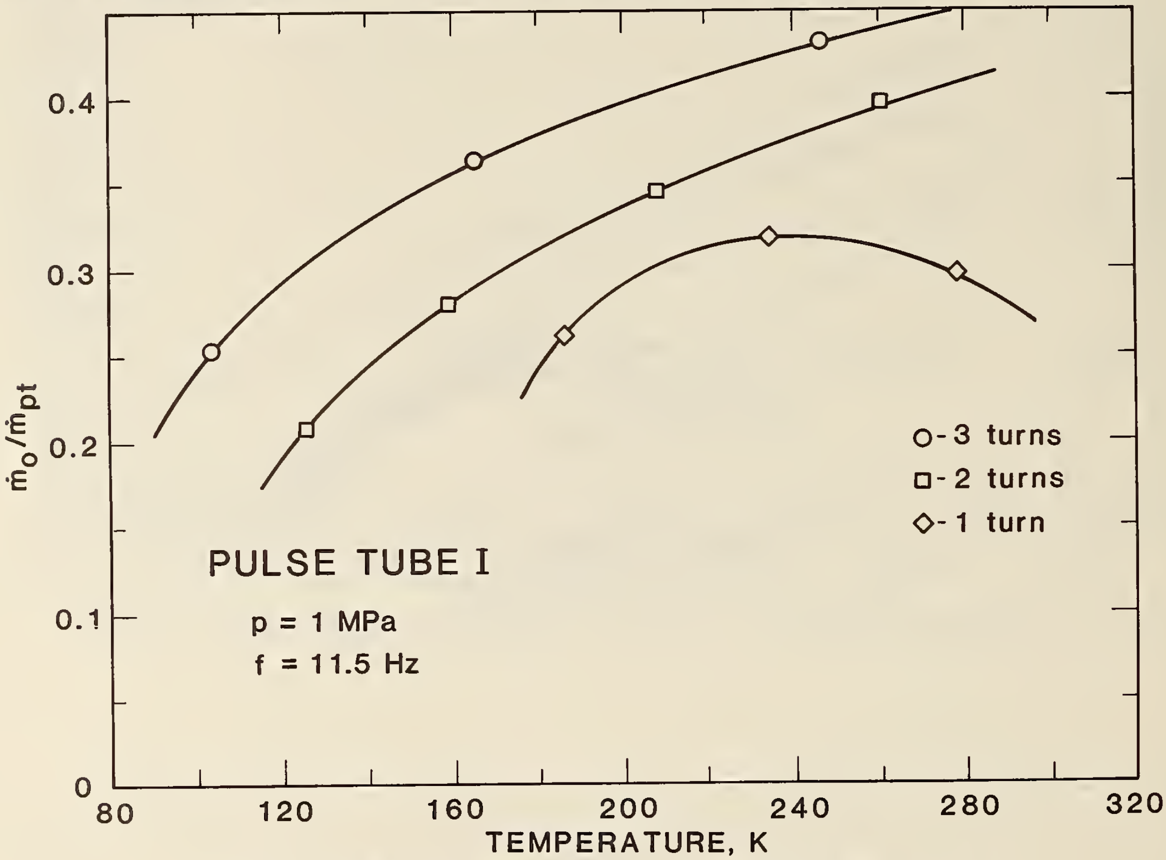


Fig. 23 $\dot{m}_o/\dot{m}_{pt}$ vs temperature for pulse-tube I at 11.5 Hz

Because of the increased mass flow into the pulse tube and comparable refrigeration power the curves for the refrigeration power per unit mass flow have their lowest value for this frequency (Fig. 24). This is the only parameter which decreases with increasing frequency.

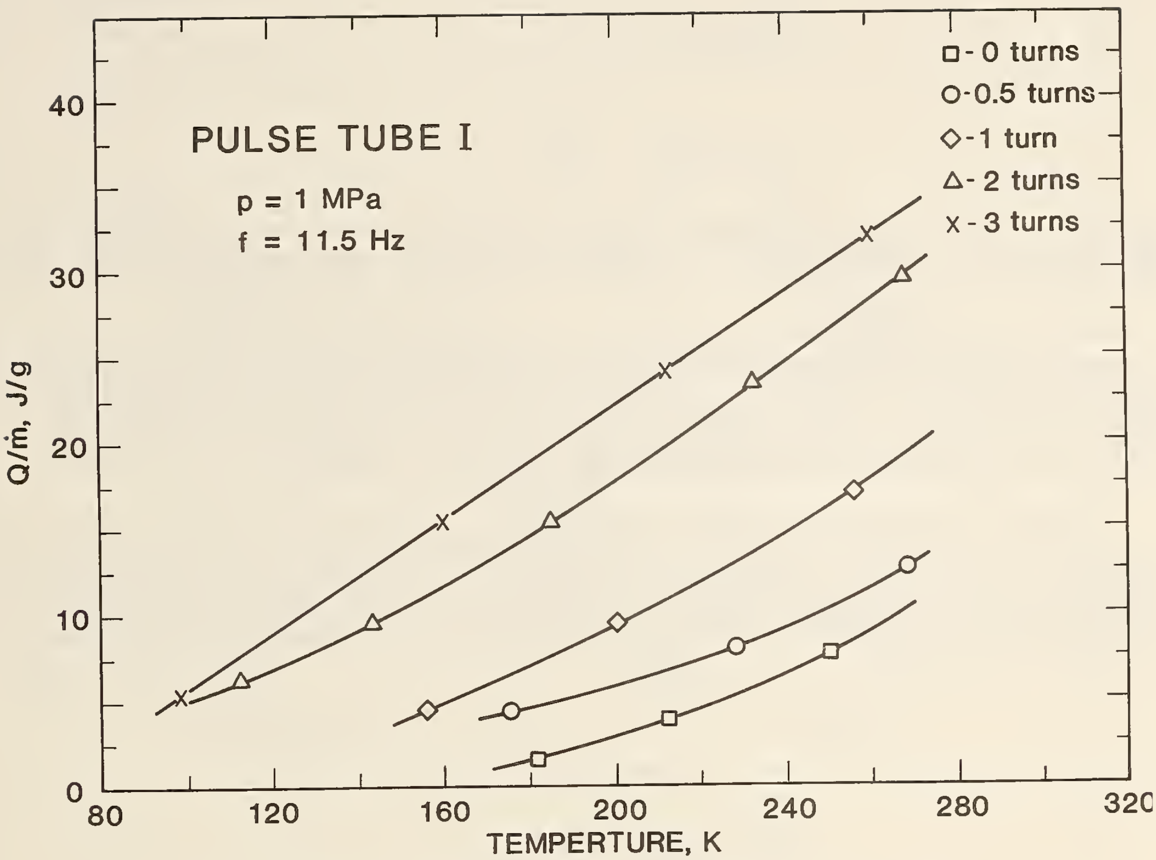


Fig. 24 $\dot{Q}/\dot{m}_{pt}$ vs temperature for pulse-tube I at 11.5 Hz

5.5 Summary for Pulse Tube I

The experiments described above for different frequencies reveal the importance of choosing the right frequency in order to get the best results. Although many experiments were done at various frequencies it is still not clear why some frequencies yield lower values for the refrigeration power and the efficiency. Nevertheless, some other conclusions can be formulated and some suggestions made in earlier works can be confirmed.

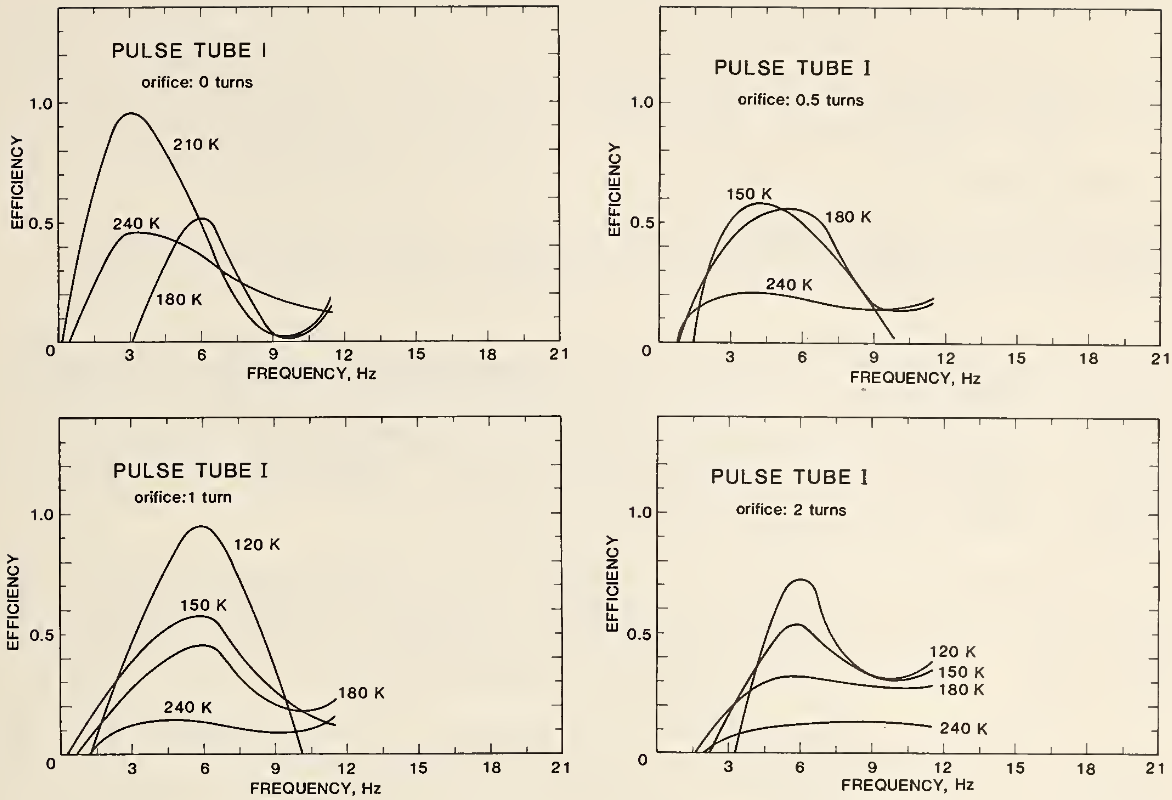
The basic pulse tube (closed orifice) works best at lower frequencies; however, at these frequencies its refrigeration power is much lower than the power of an orifice pulse tube. The basic pulse tube has the highest relative efficiency throughout its complete temperature range. The lowest temperature achieved with the basic pulse tube in this work was roughly 190 K and is therefore much higher than temperatures achieved with the orifice pulse tube.

As already mentioned in an earlier work [8], the heat transport per unit mass flow for each pulse tube is relatively low. This was confirmed by these experiments. Because the mass flow in the pulse tube does not depend on the orifice setting at the higher frequencies the $\dot{Q}/\dot{m}_{pt}$ value is especially low for the basic pulse tube. In the low temperature range there is little variation in these values at the different frequencies.

For the orifice pulse tube 6 Hz was the best frequency of all those tested and the lowest temperature of 75 K was achieved at 6 Hz. This tube yielded a low temperature of 60 K when run without the isothermalizers [8]. Operation of the orifice pulse tube at 6 Hz also yielded the greatest efficiency values and the highest refrigeration power in the low temperature range. A frequency of 11.5 Hz produced reasonable refrigeration power curves and efficiencies but the efficiencies were smaller by a factor of two than those measured at 6 Hz. The good results at this frequency may be a result of a resonance phenomenon because 11.5 Hz is almost the first harmonic of 6 Hz. The poorest results of all were measured between these two frequencies, at 9.5 Hz. The highest efficiency at this frequency was only 34% of Carnot. This frequency also yielded the lowest ratio of $\dot{m}_o/\dot{m}_{pt}$, which may account for the low refrigeration power and efficiency. The low $\dot{m}_o/\dot{m}_{pt}$ ratio indicates that little phase shifting by the orifice has occurred, and confirms the theory that for the orifice pulse tube most of the phase shift is caused by the orifice and not by heat transfer along the tube walls.

With increasing frequency the mass flow of gas into the pulse tube becomes more and more a linear function of the temperature and is almost independent of the orifice setting at the higher frequencies. However, it is difficult to see a relation between frequency and the amount of mass flow. It seems that the mass flow is also affected by the resonance phenomenon because the experiments yielded peak values for the mass flow at a frequency of 9.5 Hz. This frequency gave the highest mass flow rate at temperatures below 200 K.

To show the frequency-dependent properties of the pulse tubes, the relative efficiencies at particular temperatures and orifice settings were plotted against frequency in Fig. 25 through 29. These plots clearly show the peak values of the efficiency at 6 Hz for the orifice pulse tube and at 3 Hz for the basic pulse tube. These plots also illustrate that choosing the right frequency is especially important for low temperatures, where most applications would occur.



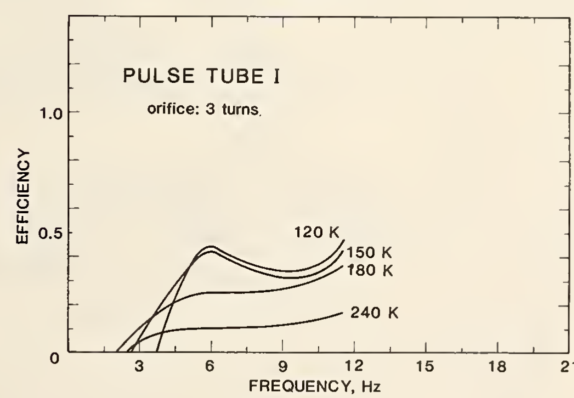


Fig. 25-29 Efficiency relative to Carnot vs frequency for different orifice settings

The experiments demonstrated that in the lower temperature range smaller values are designed for the ratio of mass flow through the orifice to mass flow into the pulse tube. To achieve optimal results these values should be around 20%. At higher temperatures, values of 40% or more yield the best results. In general, by choosing the optimal orifice setting the ratio of $\dot{m}_o/\dot{m}_{pt}$ is automatically in the best range for the corresponding temperature.

5.6 Pulse Tube II

Before describing the experiments done with pulse tube II, preliminary suppositions regarding pulse tube behavior are stated which describe the most important differences between pulse tube I and pulse tube II.

Since the diameter of pulse tube II is only one-half the diameter of pulse tube I the cross sectional area is one-fourth that of pulse tube I. Therefore it was assumed that the refrigeration power would be one-fourth that of pulse tube I. Also because of the larger ratio of wall surface to cross sectional area a much lower efficiency is expected at the same frequency. As a result of the diminished refrigeration power the temperature minima are expected to be greater than the low temperatures recorded with pulse tube I. No assumptions were made concerning the optimal frequencies. It is now interesting to see how the experimental results agree with the theoretical predictions.

For pulse tube II a frequency of 3 Hz was much too low. With the basic pulse tube our test apparatus was not sensitive enough to measure any refrigeration power. Operation of the orifice pulse tube also produced values too low to be considered reliable. Consequently no plots were made for this frequency. Therefore, it appears that a smaller diameter tube requires higher frequencies in order to obtain reasonable results.

At a frequency of 6 Hz measurable data were achieved. The most conspicuous result was the lowest achievable temperature of only 180 K with an orifice setting of 1.5 turns. Also, the refrigeration power was very low in fact, far below the expected value for this frequency (Fig. 30).

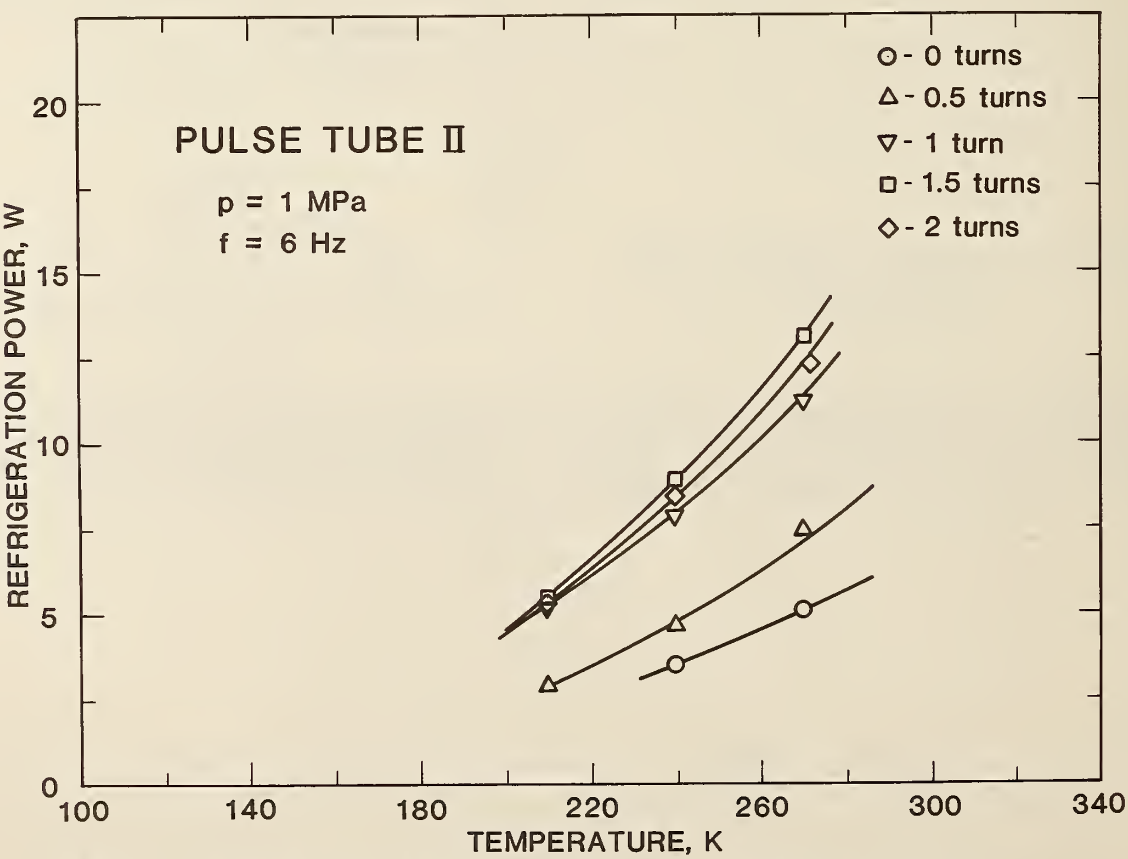


Fig. 30 Refrigeration power vs temperature for pulse-tube II at 6 Hz

The peak of the relative efficiency was roughly 14% of Carnot efficiency with a closed orifice, at a very high temperature of 240 K. This efficiency is much lower than the comparable value for pulse tube I (Fig. 31).

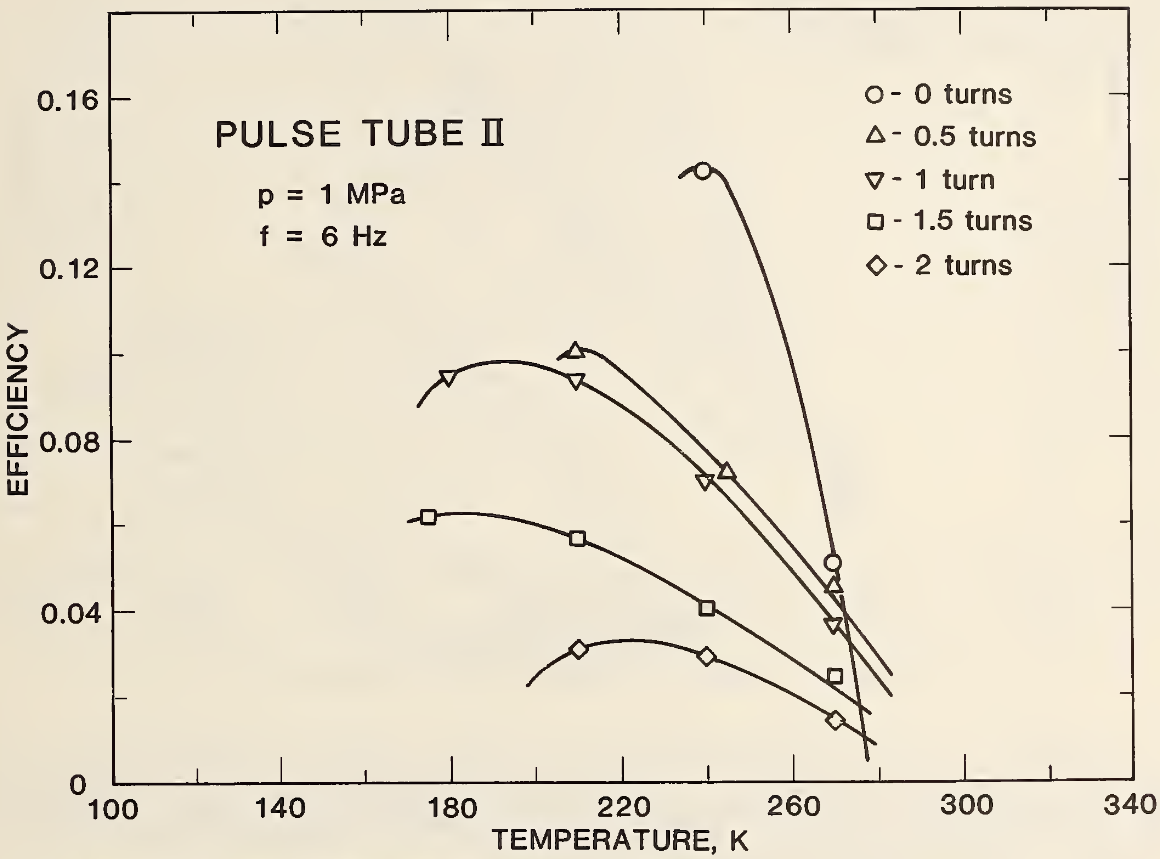


Fig. 31 Efficiency relative to Carnot vs temperature for pulse-tube II at 6 Hz

The mass flow ranged between 0.52 g/s for 270 K and 0.62 g/s for 180 K and did not depend on the orifice setting. Mass flow values varied with temperature in a linear fashion and were approximately one-half of the comparable values from pulse tube I. Since the refrigeration powers are less than one-fourth those of pulse tube I, the maximum $\dot{Q}/\dot{m}_{pt}$ values for pulse tube II drop to values of 12 J/g at 270 K and 3.2 J/g at 210 K at a frequency of 6 Hz and an orifice setting of 1.5 turns.

Since the values for the mass flow into pulse tube II were much lower, smaller orifice openings caused higher values for $\dot{m}_o/\dot{m}_{pt}$. The optimum adjustment for pulse tube II at a frequency of 6 Hz was 1.5 turns, which gave a $\dot{m}_o/\dot{m}_{pt}$ ratio of 0.51 at 270 K and 0.48 at 180 K. The temperature dependence of $\dot{m}_o/\dot{m}_{pt}$ may be neglected for all orifice settings since the measurements were performed only in the high temperature range. A two turn opening gave a ratio of about 0.68 and 1 turn yielded a ratio of roughly 0.34, although total mass flow into the pulse tube was not affected by the valve setting. Mass flow ratios were not measurable with a 0.5 orifice opening and orifice settings of more than two turns proved as useless since the mass flow into the orifice was too large.

A frequency of 9.5 Hz already produced an important improvement in comparison with the frequency of 6 Hz. The refrigeration power was increased by almost a factor of two although the efficiency decreased slightly. At a frequency of 9.5 Hz the refrigeration power was much higher than the theoretical estimate of one quarter but the comparison is not very well grounded since this frequency rendered a surprisingly low value for the refrigeration power using pulse tube I (Fig. 32).

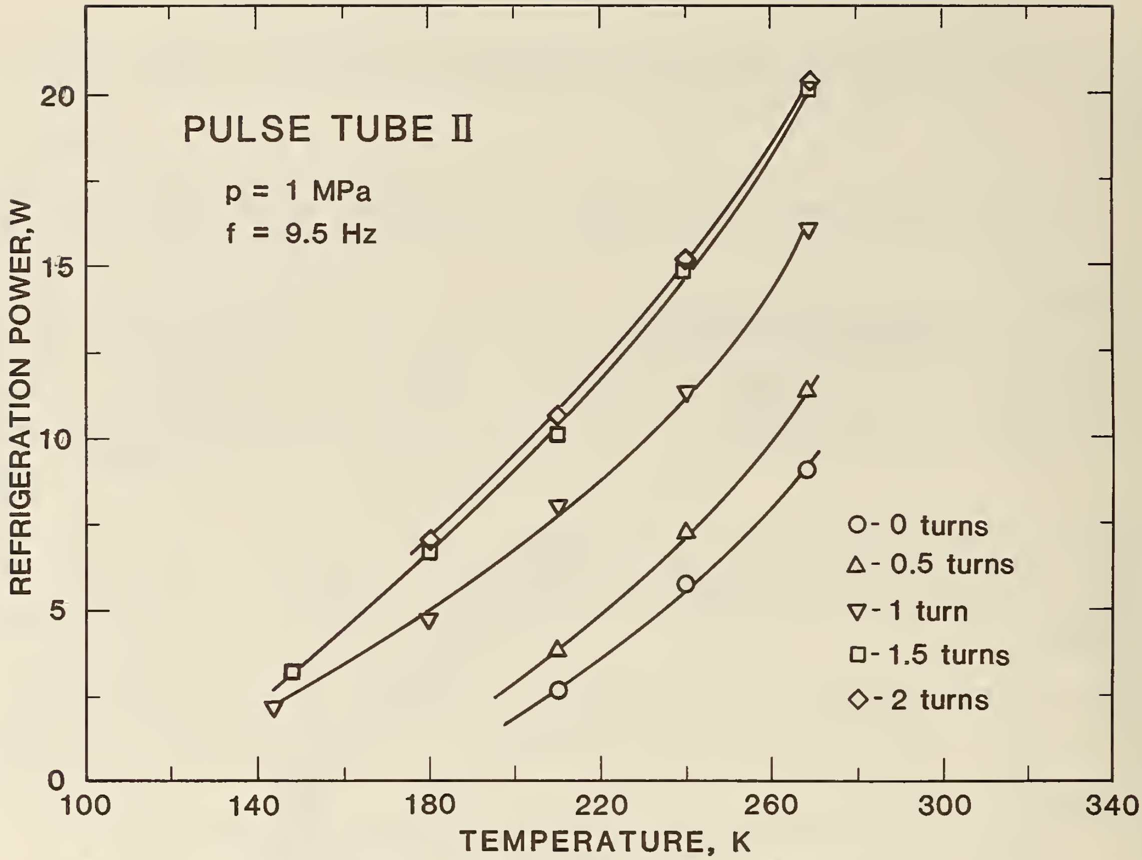


Fig. 32 Refrigeration power vs temperature for pulse-tube II at 9.5 Hz

The peak of the relative efficiency was around 12% of Carnot a a temperature of 210 K (Fig. 33). It was achieved with an orifice setting of one turn whereas the basic pulse tube (orifice closed) at this temperature yielded a value of only 10.5% of Carnot. The higher refrigeration power allowed lower temperatures, and the lowest possible temperature for 9.5 Hz was 140 K with an orifice setting of 1.5 turns.

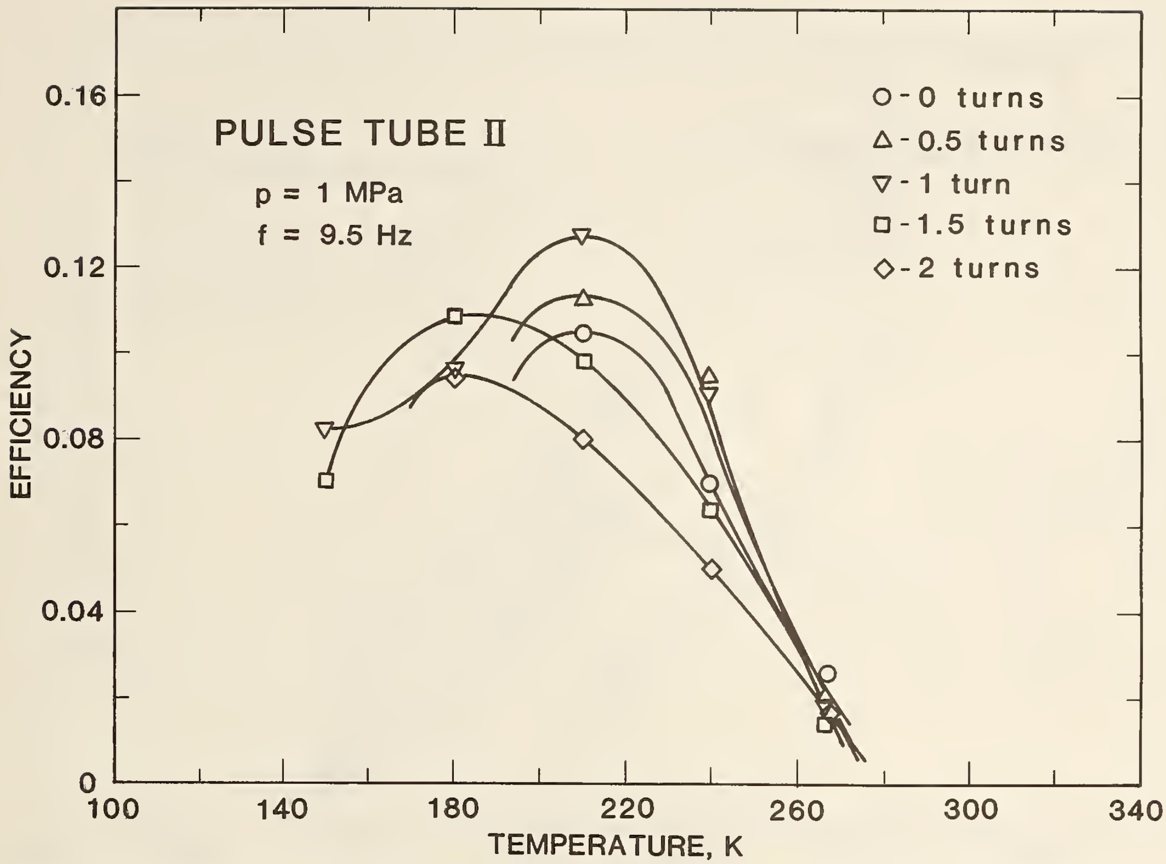


Fig. 33 Efficiency relative to Carnot vs temperature for pulse-tube II at 9.5 Hz

The mass flow into the pulse tube at 9.5 Hz was more dependent on the orifice setting and varied by about 10%. The mass flow ranged from 0.87 g/s at 270 K to 1.2 g/s at 145 K. No useful relation regarding the mass flow values obtained with pulse tube I at 9.5 Hz could be found.

The best ratio of $\dot{m}_o/\dot{m}_{pt}$ at a frequency of 9.5 Hz was slightly greater using pulse tube II. This ratio was obtained with an orifice setting of 1.5 turns which delivered values for $\dot{m}_o/\dot{m}_{pt}$ of 0.25 at 150 K to 210 K and 0.32 for the higher temperature range. Ratios of 40% or greater are too high to be considered reasonable for applications.

As the results demonstrate, the resonance phenomenon present at pulse tube I is not evident when using pulse tube II.

The highest values for refrigeration power and efficiency were obtained using pulse tube II at a frequency of 11.5 Hz. These results support the theoretical proposition which predicted optimum results at higher frequencies.

The peak of the relative efficiency was 35% of Carnot at a temperature of 180 K and an orifice setting of 1.5 turns (Fig. 34). Also a relatively high value of 28% of Carnot was achieved for the basic pulse tube at a temperature of roughly 240 K.

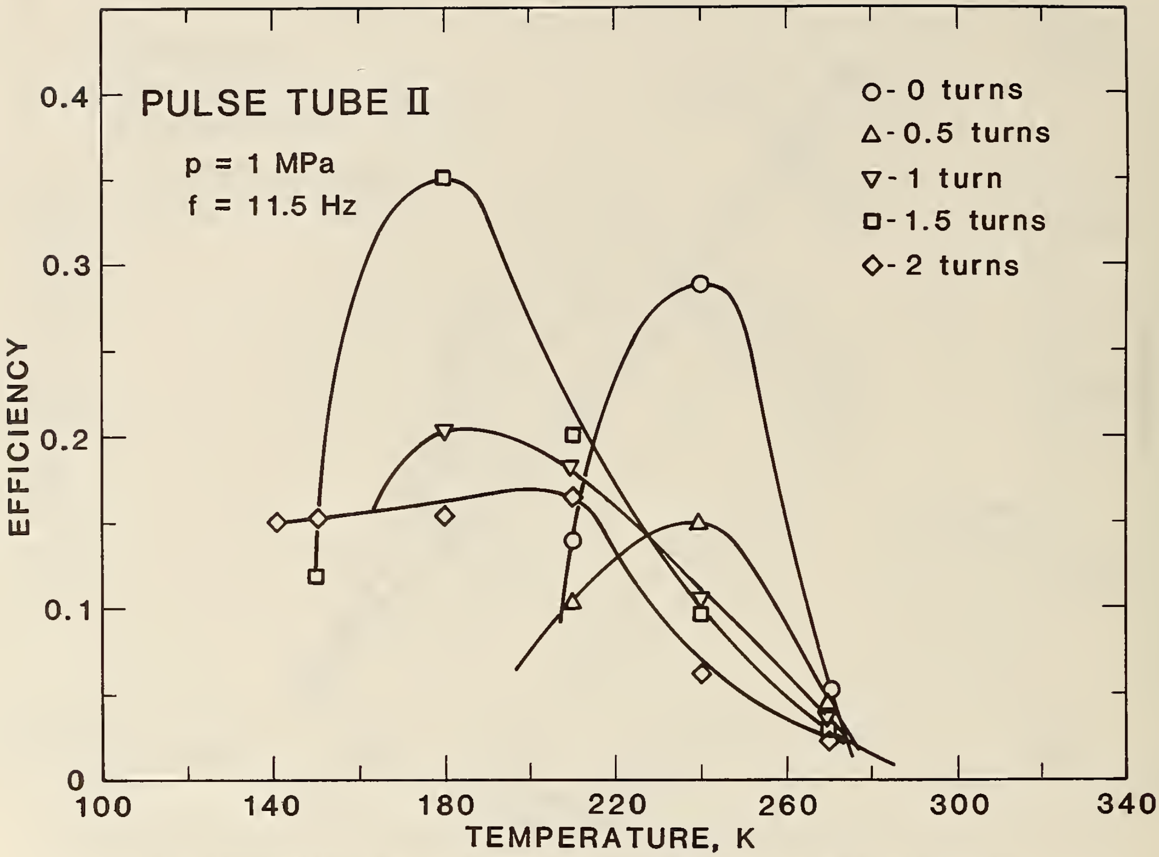


Fig. 34 Efficiency relative to Carnot vs temperature for pulse-tube II at 11.5 Hz

At this frequency the assumption that the refrigeration power of pulse tube II is about one-fourth the power of pulse tube I was verified (Fig. 35). The frequency of 11.5 Hz yielded the highest refrigeration power for pulse tube II and the best result was obtained with an orifice setting of 2 turns. Also the lowest temperature of 140 K was achieved with this orifice setting.

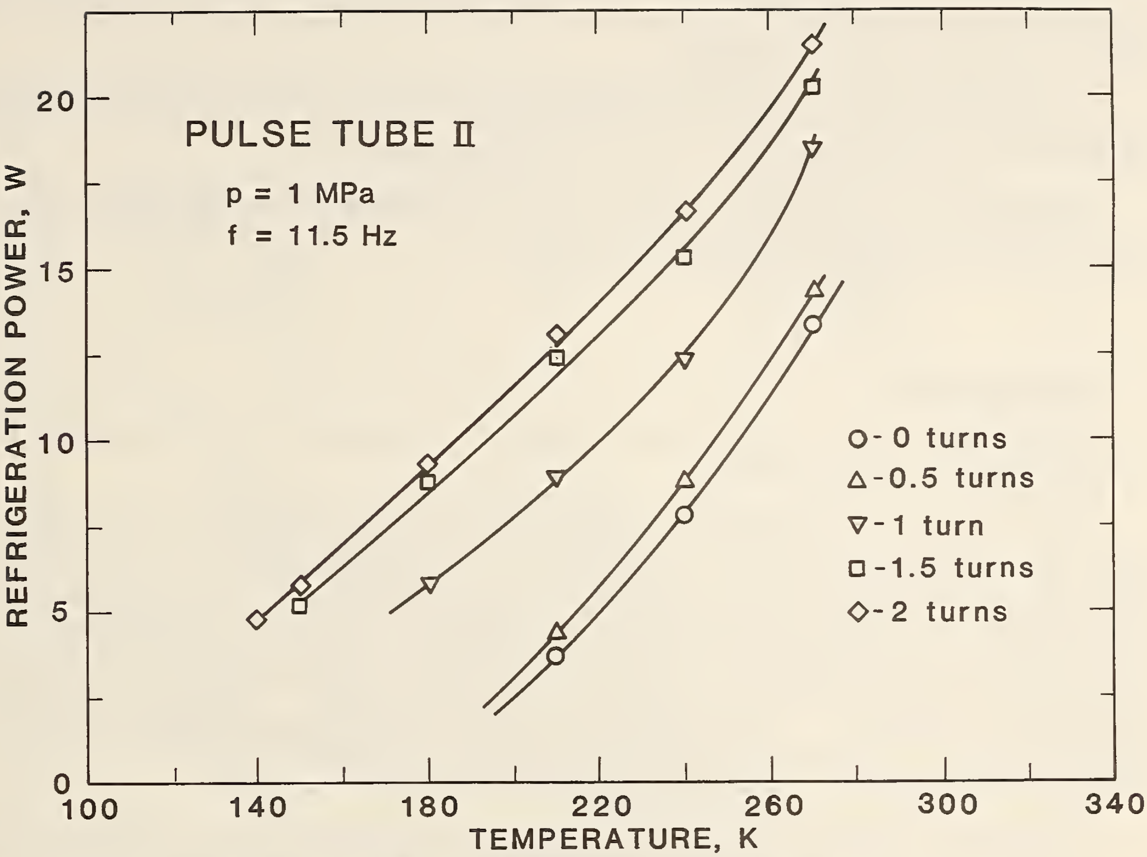


Fig. 35 Refrigeration power vs temperature for pulse-tube II at 11.5 Hz

The mass flow into the pulse tube was relatively independent of the orifice setting at this frequency and can be approximated by a linear function of the temperature. The mass flow ranged from 1.0 g/s at 270 K to 1.4 g/s at 140 K. Analogous to previous frequencies no reasonable relation between the mass flow for pulse tube I and pulse tube II at the equivalent frequencies can be established.

The optimum ratio for mass flow through the orifice and mass flow into the pulse tube was obtained with pulse tube II at a frequency of 11.5 Hz with an orifice setting of 2 turns. Values of 0.35 in the higher temperature range and 0.27 in the lower temperature range were measured. These values are below the optimum values for pulse tube I.

5.7 Summary for Pulse Tube II

The experiments demonstrate that the relation between different pulse tube diameters is not as simple and direct as assumed. Unfortunately no experiments could be performed above a frequency of 11.5 Hz due to apparatus limitations.

Therefore some interesting work can be done in the future using this pulse tube size with higher frequencies. Nevertheless some conclusions concerning the influence of the diameter on pulse tube behavior can already be formed.

For smaller pulse-tube diameters a higher frequency is necessary in order to get optimum results. Also the basic pulse tube functions better at a higher frequency when a smaller diameter is used.

The influence of irreversibilities is much greater for the smaller tube and therefore much lower efficiency values can be achieved. In this work 11.5 Hz delivered the optimum efficiency but it is possible that at higher frequencies this tube would be even more efficient.

The lowest possible temperature was much higher for this pulse tube. Only 140 K could be achieved with a frequency of 11.5 Hz. It is also possible that lower temperatures can be obtained by increasing the frequency.

The proposed relation between the refrigeration power for the two pulse tube diameters could only be justified at 11.5 Hz. At this frequency the power of pulse tube II was roughly one-fourth the power of pulse tube I at corresponding temperatures.

Because pulse tube II yielded optimum values at much higher frequencies than pulse tube I the assumption was verified that within the orifice pulse tube only little heat could be transferred between the tubing wall and the gas.

5.8 Pulse Tube III

As with pulse tube II, theoretical suppositions will be stated first, describing the main properties of pulse tube III.

Pulse tube III had the same tube diameter as pulse tube I suggesting that optimum results for pulse tube III might be obtained also at a frequency of 6 Hz. The length of pulse tube III was one-half that of pulse tube I. Because a frequency of 3 Hz provided relatively low refrigeration power, no experiments were administered for pulse tube III at this frequency. In addition the refrigeration power for pulse tube III was expected to be slightly smaller than the power produced by pulse tube I. Since the length of this tube is shorter than for the original pulse tube, the temperature gradient along the shorter tube must be steeper in order to achieve the same minimum temperature. Therefore a higher minimum temperature was expected. Furthermore the efficiency will probably be slightly lower than for pulse tube I. In addition the experiments should also indicate whether the length or diameter has the greatest influence on the properties of the pulse tube.

The first run of pulse tube III was conducted at a frequency of 6 Hz. The results were as expected. The lowest possible temperature was 110 K with an orifice setting of 2 turns.

The relative efficiency was astonishingly high using the basic pulse tube (orifice closed). A value of almost 85% of Carnot was achieved at a temperature of 220 K. With the orifice pulse tube a value of 55% of Carnot was obtained at a low temperature of 120 K with an orifice setting of 1 turn (Fig. 36).

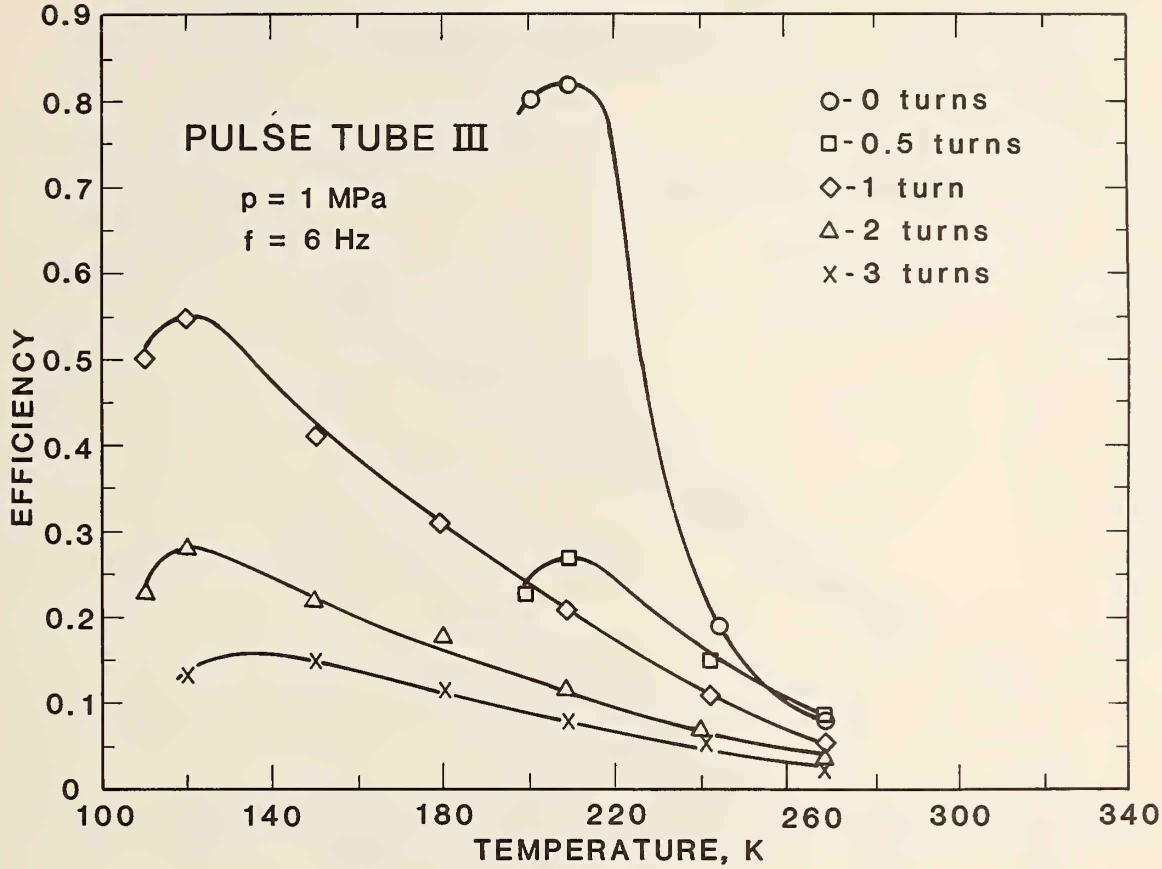


Fig. 36 Efficiency relative to Carnot vs temperature for pulse tube III at 6 Hz

The refrigeration power was approximately one half the power produced by pulse tube I at the same frequency (Fig. 37). Similar to the case with pulse tube I, the best result was obtained with 2 turns.

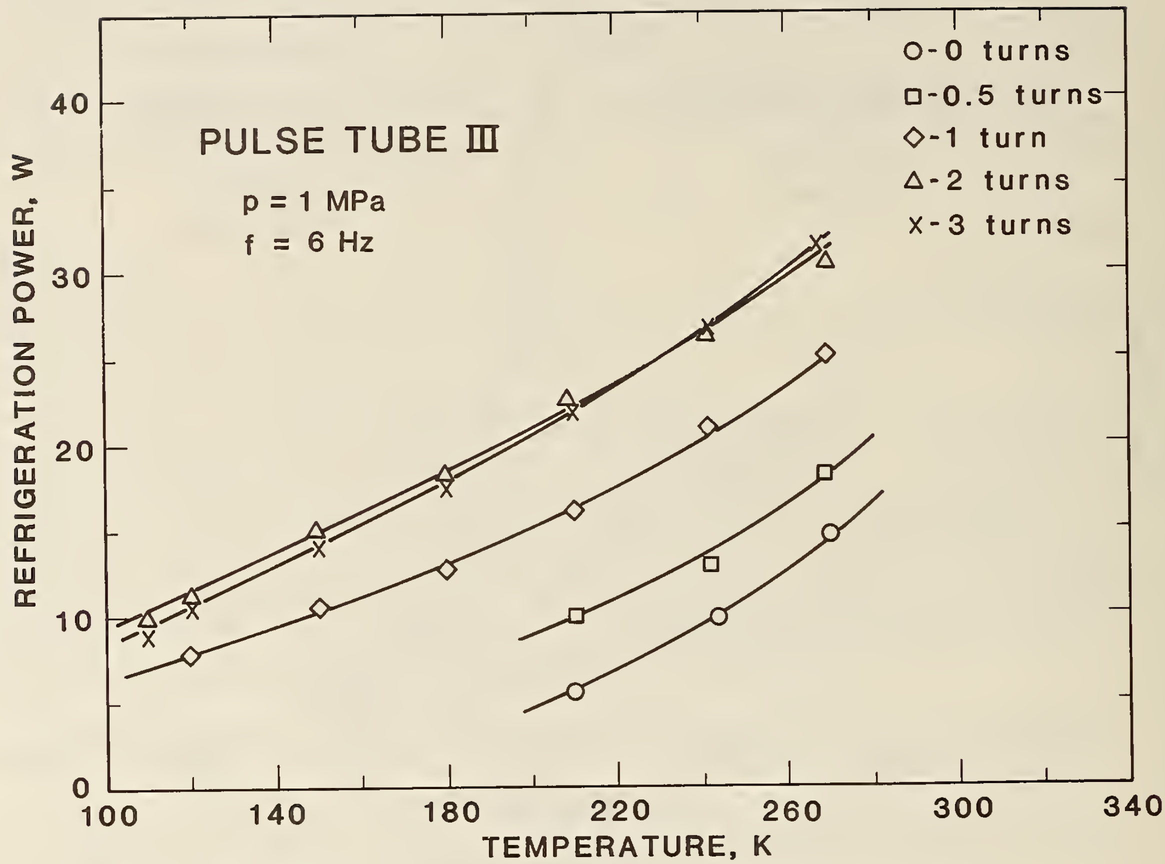


Fig. 37 Refrigeration power vs temperature for pulse-tube III at 6 Hz

The mass flow into the pulse tube was also lower for pulse tube III than with pulse tube I. The range extended from 0.71 g/s at 270 K with a closed orifice to 1.05 g/s at 110 K with an orifice opening of 2 turns. The dependence of the mass flow on the orifice setting was much more evident with this pulse tube than with pulse tube I. A mass flow variation of 15% was observed between the basic pulse tube and an orifice setting of 3 turns. However using the same orifice settings as employed with pulse tube I, equivalent values for the ratio of mass flow through the orifice to mass flow into the pulse tube were recorded. Therefore Figure 15 of pulse tube I is also applicable for pulse tube III. The heat transport per unit mass flow values were about 20% below the values obtained with pulse tube I at equivalent temperatures.

The data acquired with pulse tube III at 6 Hz showed that all the theoretical estimates were appropriate and a comparison between pulse tube I and pulse tube III is easier to realize than between pulse tube I and pulse tube II. The behavior of pulse tube III is similar to the behavior of pulse tube I at this frequency. The second point of interest was to ascertain how the values for refrigeration power and efficiency change by going to a frequency of 9.5 Hz.

The results for pulse tube III at 9.5 Hz clearly show the expected drop of the relative efficiency values compared to the values at 6 Hz (Fig.38). The highest efficiency of 35% of Carnot was obtained with an orifice setting of 2 turns at a temperature of 120 K. The basic pulse tube yielded efficiency values below 20% of Carnot at all temperatures. The behavior of the efficiency curves and refrigeration power for pulse tube III are qualitatively the same as those of pulse tube I.

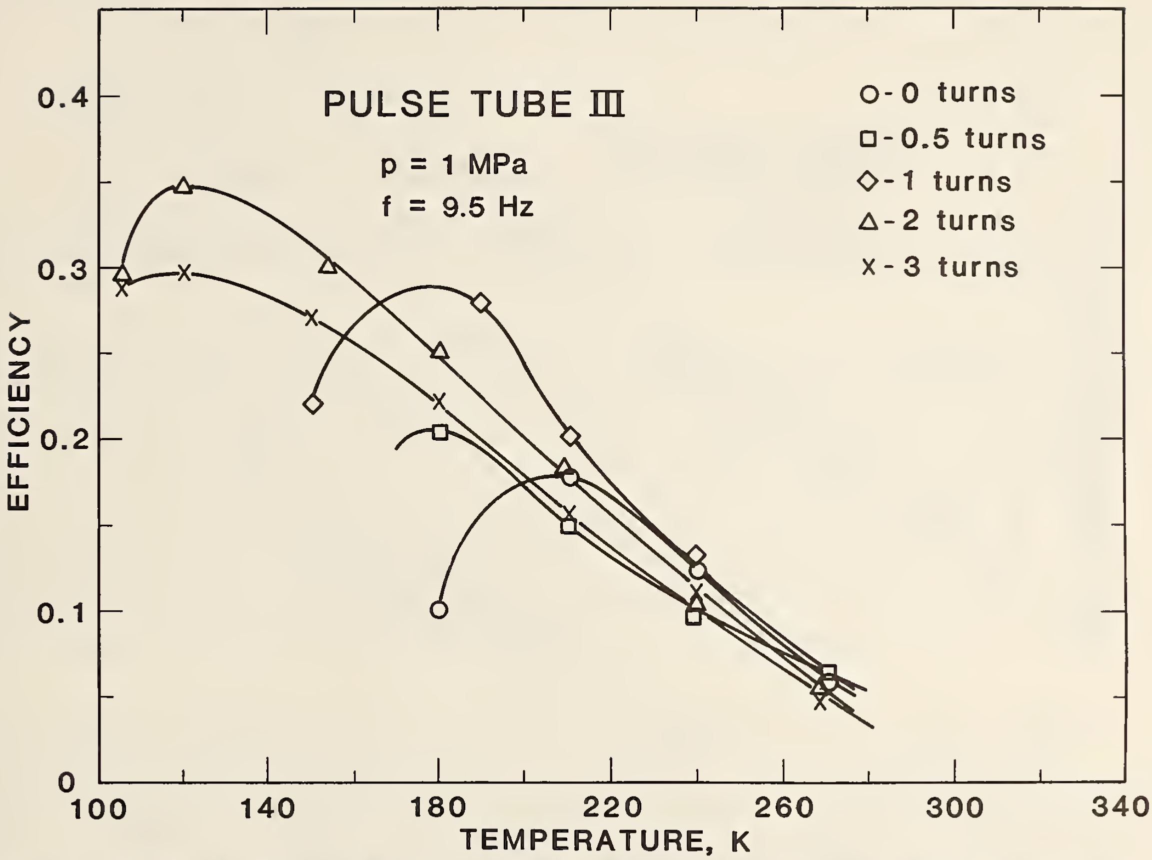


Fig. 38 Efficiency relative to Carnot vs temperature for pulse-tube III at 9.5 Hz

For both tube I and tube III, the refrigeration power increased in going from 6 Hz to 9.5 Hz. However the increase was more notable with pulse tube III. The optimum refrigeration power for pulse-tube III at 9.5 Hz was obtained with an orifice setting of three turns (Fig. 39).

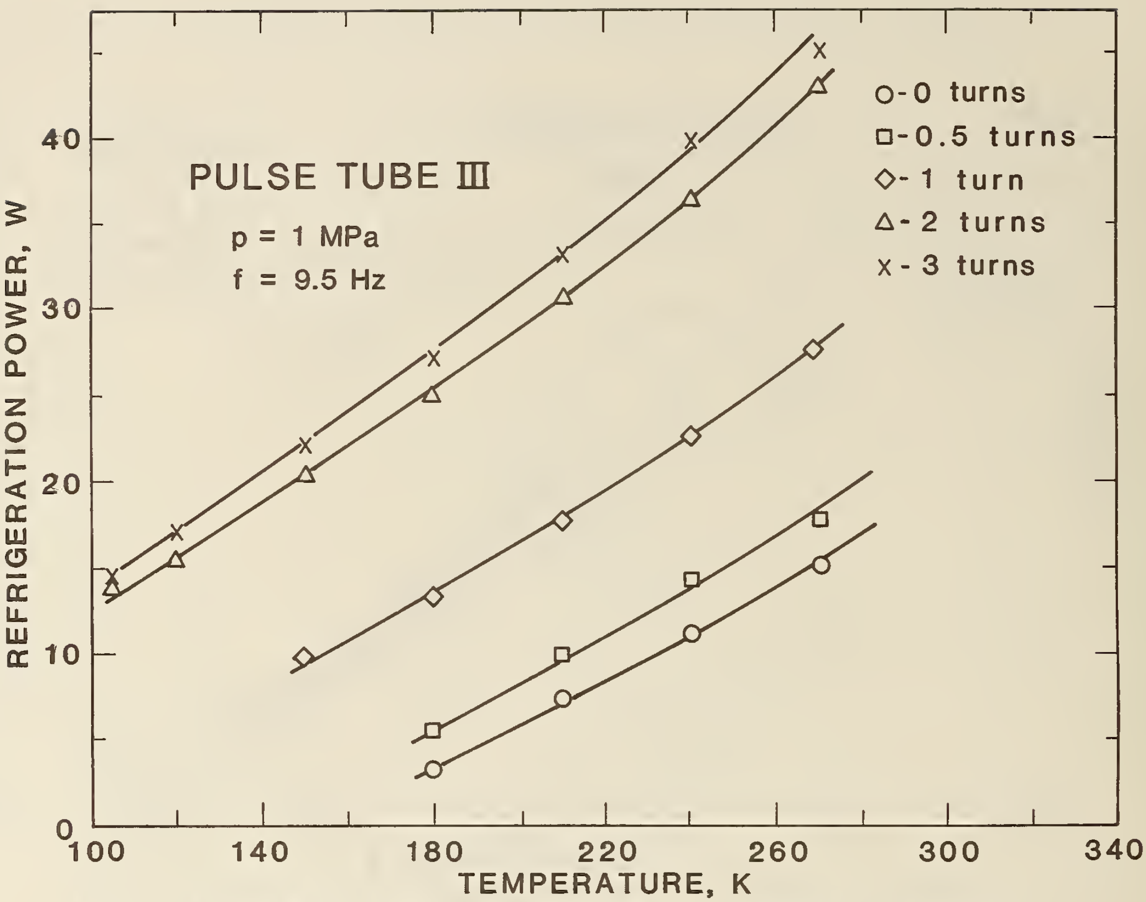


Fig. 39 Refrigeration power vs temperature for pulse-tube III at 9.5 Hz

Contrary to pulse tube I the lowest temperature for pulse tube III was achieved with 9.5 Hz. It was possible to attain a minimum temperature of 105 K with both 2 and 3 turns.

The values for the mass flow into pulse tube III were slightly smaller than those of pulse tube I at low temperatures but were about the same in the high temperature range. The mass flow ranged from 1.2 g/s at 270 K to 1.9 g/s at 110 K. Since the dependence on the orifice setting is insignificant for this frequency the mass flow can be approximated by a linear function of the temperature. Similarly to the case with a frequency of 6 Hz, equivalent orifice setting yielded the same values for $\dot{m}_o/\dot{m}_{pt}$ using pulse tube I as with pulse tube III. Therefore Figure 20 is also suitable for pulse tube III. Since the $\dot{Q}/\dot{m}_{pt}$ values of pulse tube I and pulse tube III correspond well, accurate values for pulse tube III can also be obtained from Figure 19.

5.9 Summary for Pulse Tube III

The results confirmed the predicted behavior of pulse tube III and showed that the behavior of pulse tube I and pulse tube III were qualitatively similar at each experimental frequency. Therefore, it may be reasonable to predict behavior paralleling that of pulse tube I for frequencies not measured with pulse tube III. Refrigeration power and efficiency were lower for pulse tube III than for pulse tube I but exhibited the same dependence on the frequency. The contrast in the efficiencies of the two pulse tubes is much less than the difference in the refrigeration power. The refrigeration values produced by pulse tube III are one half those of pulse tube I. Also, behavior at the same orifice settings is roughly equal for both tubes. The lowest possible temperature for pulse tube III is significantly above the minimum temperature achieved with pulse tube I.

6. Comparison and Discussion of the Three Pulse Tubes

As expected, the best results among the three pulse tubes were acquired with pulse tube I. This same pulse tube size was used at NBS in earlier work to achieve a record low temperature of 60 K [8].

In these experiments, the lowest temperature achieved was 75 K at a frequency of 6 Hz. A possible reason that 60 K could not be obtained is because of the isothermalizers in the test apparatus. These have a small but finite gas volume (2.7 cm^3) and cause a pressure drop. The most surprising phenomenon of pulse tube I was the frequency dependence. The pulse tube I achieved the best results for efficiency, roughly 90% of Carnot, at a frequency of 6 Hz. By increasing the frequency up to 9.5 Hz the efficiency dropped significantly down to a peak value of only 34% of Carnot. Going to a higher frequency of 11.5 Hz, the efficiency increased to a peak value of about 48% of Carnot. In contrast the refrigeration power increased steadily with increasing frequency for a temperature range above 120 K. As the frequency was increased the orifice had to be opened more and more in order to achieve optimum results. Therefore the basic pulse tube (closed orifice) worked best at the lowest frequency of 3 Hz where it yielded a peak in relative efficiency of 90% of Carnot. Also the minimum temperature obtained with the basic pulse-tube was found at 3 Hz.

Examination of the data reveals that a reduction of the pulse tube diameter has more influence on behavior than shortening the length. Results showed that a tube of smaller diameter requires higher frequencies to operate most efficiently. The values for both refrigeration power and efficiency were much lower for pulse tube II than they were for pulse tube I. The peak value of efficiency using pulse tube II was achieved at a frequency of 11.5 Hz and was only about 35% of Carnot. It is possible that greater relative efficiencies can be obtained at higher frequencies. The lowest temperature for pulse tube II was measured at this frequency and was only 140 K. The refrigeration power for pulse tube II was largest at 11.5 Hz. The ratio of refrigeration powers for pulse tube I to pulse tube II at this frequency was nearly equivalent to the ratio of the cross sectional areas, although the mass flow into pulse tube II was more than one-fourth the mass flow into pulse tube I for each frequency setting.

The refrigeration power and especially efficiency of pulse tube III was better than those for pulse tube II. A temperature of 110 K could be achieved with pulse tube III at a frequency of 9.5 Hz which sets the minimum temperature of pulse tube III less than that of pulse-tube II. The behavior of pulse tube III at the various frequency settings was similar to pulse tube I. The best values for efficiency were obtained at a frequency of 6 Hz, yielding relative efficiency values of 55% of Carnot with optimum orifice setting and 82% of Carnot with the basic pulse tube. The refrigeration powers delivered by pulse tube III are roughly half those of pulse tube I in the temperature range tested here. The mass flow into the pulse tube was slightly less using pulse tube III than with pulse tube I. A direct comparison of pulse tube II with pulse tube III is not useful because their behaviors at the various frequencies are completely different.

P-V diagrams (Fig. 40) for pulse tube I and an ideal Stirling refrigerator point out the most important difference between these refrigerators. The flat shape illustrated in the diagram of the pulse tube reveals its small power per unit mass in comparison to an ideal Stirling refrigerator which has a much greater area of work input from the same size compressor. From this diagram the difference between the orifice pulse tube and the basic pulse tube can also be compared. Both diagrams of the pulse tubes were produced with pulse tube I at a frequency of 6 Hz and a temperature of 210 K. For the orifice pulse tube the orifice setting was 3 turns. The ideal Stirling refrigerator was calculated from a Schmidt analysis [10].

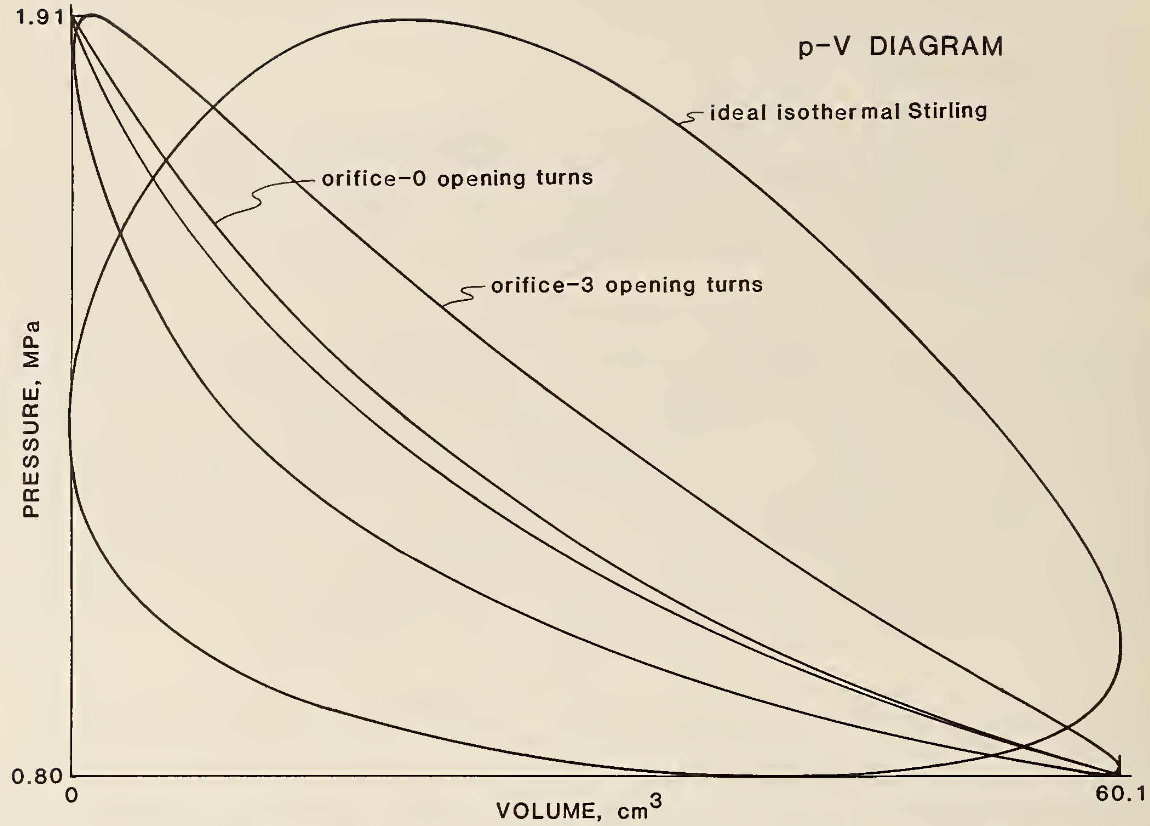


Fig. 40 p-V-diagram for basic pulse tube, orifice pulse tube, and Stirling refrigerator

7. Conclusions

The experiments performed here gave detailed performance data for three different orifice pulse tubes which incorporated the same basic design but were of different sizes. The refrigeration power, efficiency, and refrigeration per unit mass flow measured in these experiments were the first such results obtained on orifice pulse tubes, but they are by no means a complete set of measurements from which detailed modeling can be developed. They do serve as a guide to future work. The orifice pulse tube is more useful for future applications than the basic pulse tube since its refrigeration power can be an order of magnitude greater. Also much lower temperatures can be achieved with the orifice. The only disadvantage in comparison to the basic pulse tube is the lower efficiency of the orifice pulse tube.

The diameter of the pulse tube has the greatest influence on the characteristic behavior of the refrigeration power and efficiency curves at various frequencies, whereas the length of the tube plays only a subordinate role. Nevertheless, a change of either length or diameter has a substantial effect on the refrigeration power.

The optimum frequency of the larger diameter tube (12.7 mm) was 6 Hz whereas the optimum frequency for the smaller diameter tube (6.4 mm) could be above the highest tested frequency of 11.5 Hz.

The most important results of this work are listed below:

- The lowest temperature measured was 75 K, which was achieved with pulse tube I at a frequency of 6 Hz.
- The best frequency for the 12.7 mm diameter orifice pulse tube was 6 Hz, which gave the highest efficiency values of almost 90% of Carnot.
- The basic pulse tube also yielded an efficiency of 90% of Carnot but at a frequency of 3 Hz.
- A decrease in the diameter of the tube degraded the efficiency and refrigeration power.
- Smaller diameter tubes work better at higher frequencies.
- The refrigeration power is approximately proportional to the tube length.
- The tube length has less influence on the efficiency than does the tube diameter.
- The optimum frequency is independent of the tube length.
- The optimum orifice setting depends on the diameter of the tube.
- The basic pulse tube works better at lower frequencies than the orifice type.

The primary advantages of any pulse-tube refrigerator over other refrigeration cycles are:

- Only one moving component (at room temperature).
- Uses modest pressure and pressure ratios.
- Possible to achieve temperature ratios of greater than four in one stage.
- Works with an ideal gas, which implies one fluid for all temperatures.
- A large orifice will not collect impurities at the high temperature part of the cycle.
- Large refrigeration powers in the orifice type.
- Good intrinsic efficiency.
- Several stages can be operated form the same pressure wave generator.

The one disadvantage of a pulse tube is the low refrigeration rate per unit mass flow which means better regenerators are required.

8. Acknowledgments

Construction of much of the apparatus was done by Dr. David R. Smith and is greatly appreciated. We acknowledge the careful revising of this report by Mary P. Russell and Dr. David R. Smith.

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Pulse-tube or thermoacoustic refrigerators have the potential for high reliability since they require only one moving part--an oscillating piston or diaphragm at room temperature.

If a tube is closed at one end and connected to a pressure wave generator at the open end, and if the phase angle between mass flow and pressure is shifted from 90°, then refrigeration occurs at the open end. The shift in phase angle can be realized by thermal relaxation between the gas and the tube walls or by an orifice at the closed end. A low temperature of 60 K using helium gas in a one stage orifice pulse tube has been achieved at NBS. This report describes the first measurements of the efficiency, refrigeration power, and refrigeration power per unit mass flow, for three pulse-tube refrigerators. Three tube sizes, differing in length and diameter, were studied over a frequency range of 3 to 11.5 Hz. Cooling efficiencies as high as 90% of the Carnot efficiency were obtained when compressor and regenerator losses are neglected. With the optimum orifice setting, gross refrigeration powers of 14 W were measured at a temperature of 100 K in a tube of 12.7 mm diameter and 240 mm length at a pulse frequency of 6 Hz. The influence of pulse frequency, orifice setting, diameter, and length of tube are discussed in relation to some theoretical understanding of pulse-tube behavior.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

cryocooler; cryogenics; efficiency; pulse-tube refrigerator; refrigeration power; refrigerator; regenerative refrigerator.

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