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ANALYSIS OF ELASTOMER REFRIGERATION CYCLES

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Abstract

Refrigeration effects can be obtained from elastomers classified as "ideal rubber" by operating over a cycle similar to that of the Carnot cycle. The interesting properties of ideal rubber have long been recognized, with most investigations of potential thermodynamic cycles devoted to power cycles. This paper focuses on the development of refrigeration cycles constructed from ideal rubber refrigerants.

Thermodynamic properties of elastomers are presented. Similar to ideal gases, an ideal rubber "equation of state" involving force-length-temperature can be developed. Also, the specific heat at constant extension is shown to be an important property for achieving significant thermal effects.

Analysis of an elastomer refrigeration cycle is presented. The simplest cycle consists of four processes that are analogous to the ideal gas Carnot cycle. Two adiabatic, reversible processes are used to change temperature of the material as it moves to each thermal energy reservoir. Two isothermal, reversible processes are used for heat transfer to and from the thermal energy reservoirs. Estimates of the performance of the system, and the effects of irreversible processes are presented along with results from a simple demonstration cycle device.

Introduction

Elastomers have interesting thermodynamic characteristics that can be used to develop heat engine and refrigeration cycles. The primary purpose of this paper is to discuss the potential use of elastomers for refrigeration/heat pump cycles. The background section describes activities related to the thermodynamics of elastomers and various cycles derived from elastomers. A basic thermodynamic analysis of an elastomer-based refrigeration cycle is presented. Thermodynamic property testing results are presented, and experimental results from a simple elastomer refrigeration cycle are described. While significant improvements are needed in order to develop elastomers to a level where practical cooling levels are attained, such a cycle could result in high levels of performance, simplicity in construction, and an environmentally friendly refrigerant.

Background

Although the study of the thermodynamics of rubber and elastomers is an old field dating back to the original work of Joule (1859), little effort has been put into applying them to practical use. A rigorous theory of the kinetic behavior of bulk rubber including the interactions between molecular chains was developed by James and Guth(1943). The development of these theories is reviewed in Treloar (1975).

The thermodynamic behavior of elastomers has been viewed mainly as an intellectual curiosity or a teaching tool. The theory of ideal elastomer thermodynamics is mentioned in some general thermodynamics or physics textbooks (Feynman (1963), Hsieh (1975)). A number of brief articles describe classroom experiments that could be performed in undergraduate labs or lectures. The simplest experiment was performed by manually stretching a rubber band and then touching it to the sensitive skin of the lips to feel the increase in temperature (Calingaert (1952)). If the stretched rubber band cools to room temperature and the tension is then released, it will cool below room temperature. This also can be easily sensed with the lips. Several of the experiments involved hanging weights from a rubber band and heating it with a heat lamp (Brown (1963), Carroll (1963)). The contraction of the rubber band would raise the heavy weight. If the temperature and length of the rubber band and applied force were known, the constitutive equation of the rubber tested could be determined. This demonstration could also be used to qualitatively describe magnetic cooling by analogy (Paldy (1964)). The pedagogical goal of these demonstrations and experiments appeared to be expanding the students' concept of heat engines to systems other than the traditional gas phase expansion systems

Several elastomer cycle heat engine designs have been published. Wiegand (1925) proposes two designs. One design consists of a wheel with rubber band spokes. The spokes are connected to a ring that rotates around an eccentric axle. As the large wheel rotates, the length of the spokes varies. The spokes are heated in one region of the rotation and allowed to cool in another. This drives the expansion and contraction of the wheel and generates a torque. The other design consists of a rigid pendulum driven by the contraction of rubber bands. As the pendulum oscillates, the rubber bands are alternately exposed to a heat lamp or hidden by a shade. Wiegand constructed and operated prototypes of both designs and proposed using huge solar driven rubber engines to produce electricity. He also performed more detailed analysis and experiments with the pendulum engine in order to better characterize the Joule effect and fatigue during engine operation (Wiegand (1934)). The "Amateur Scientist" column of Scientific American published descriptions of demonstration engines that could be built using rubber bands and common objects (Hayward (1956) and Archibald (1971)). Both of Wiegand's designs were republished and appear to be the inspiration for the other designs. An oscillating engine in which the shade moves with the pendulum was presented (Hayward (1956)). Several rotary engines were also discussed (Archibald (1971)). Most use an eccentric wheel design. However, some use a horizontal axle, and the contraction of the rubber bands unbalances the wheel, causing it to rotate. These designs are simple, but inherently limited by gravitational acceleration. One novel design uses an axle that bends at an angle through a universal joint. The rubber bands are connected to disks on each side of the joint and form a cylinder. As the axles rotate, the lengths of the rubber bands change. Most of these demonstration engines were driven by placing part of the engine in a warm water bath or using a heat lamp and shade arrangement. Several of these designs were used for educational demonstrations (Matthews (1976), Meiners (1970) and Mullen (1975a)).

Farris (1977) and Mullen (1975b and 1975c) analyzed the theoretical performance of the Wiegand rotary engine without detailed elastomer property data. They showed that with proper material selection the efficiency could approach the Carnot limit. In addition the torque characteristics at low temperature differences are superior to similar gas cycle engines. Lyon et al. (1984) performed numerous tests of the thermodynamic properties of polyurethane-urea elastomers using a temperature controlled tensile tester. They also constructed a heat engine similar to the Wiegand design and found that its performance could be accurately modeled using the measured data.

Engine configurations that could be used for Joule effect engines have been developed for mechanochemical engines (Steinberg (1966), Sussmann (1973)). In these systems a collagen fiber shortens or lengthens as it enters electrolyte solutions of varying concentrations. The contraction of the collagen fiber is mechanically analogous to the thermally induced contraction of rubber. These designs could be adapted to Joule effect systems by substituting high and low temperature reservoirs for the high and low concentration reservoirs. Steinberg (1966) presents two elegant designs where a continuous band of fiber loops over pulleys of different diameters. The tension in the fiber creates a different torque on pulley of different diameters. By carefully arranging the belt's path, salt reservoirs, and in one design connecting pulleys with an auxiliary belt, rotary motion is produced. In Sussman (1973) the collagen belt repeatedly wraps around two cylinders that vary in diameter along their length. The cylinders are in a reservoir of high concentration and the belt exits this reservoir to enter the low concentration reservoir. The cylinders are rotated by the contraction of the fiber.

Several articles mention the use of elastomers as working substances in heat pumps. These papers indicate that the COP for such a system is potentially high (Farris (1977), Lyon (1984)). Lyon et al. claim a COP of 6 based on experimental studies of polyurethane-urea elastomers (Lyon (1984)). NASA patented a human powered heat pump based on the Archibald engine (Hutchinson (1971)). The system was designed for use in emergency situations when other forms of power are unavailable.

Cycle Analysis

An elastomer refrigeration cycle ideally follows the paths described by a Carnot cycle. Figure 1 is a simple schematic of an ideal gas Carnot cycle in which the four process paths of the cycle consist of two reversible, adiabatic work processes and two reversible, isothermal work processes. As in other common reversible cycles (e.g., Stirling and Ericsson), the most difficult processes to achieve in a practical manner are the isothermal processes. These process paths require the simultaneous transfer of heat and work.

Analysis of a refrigeration cycle requires an equation of state, a “TdS” relation, and for an ideal elastomer, a specific heat parameter. The equation of state is most commonly written as a relation between force, extension length (or ratio), and temperature. The TdS relation, analogous to that for an ideal gas, relates the material’s change of entropy to its internal energy and organized energy changes. Assuming an elastomer acts as “ideal rubber”, the material’s internal energy is only a function of its temperature, and therefore, a simple proportionality constant (specific heat at constant length) can be defined. This set of relations is shown below in equations 1, 2, and 3.

$$F = K\cdot T\cdot f\left(L/L_o\right) \quad (1) \qquad TdS = dU - FdL \quad (2) \qquad c_L = \left(\frac{\partial U}{\partial T}\right)_L \quad (3)$$

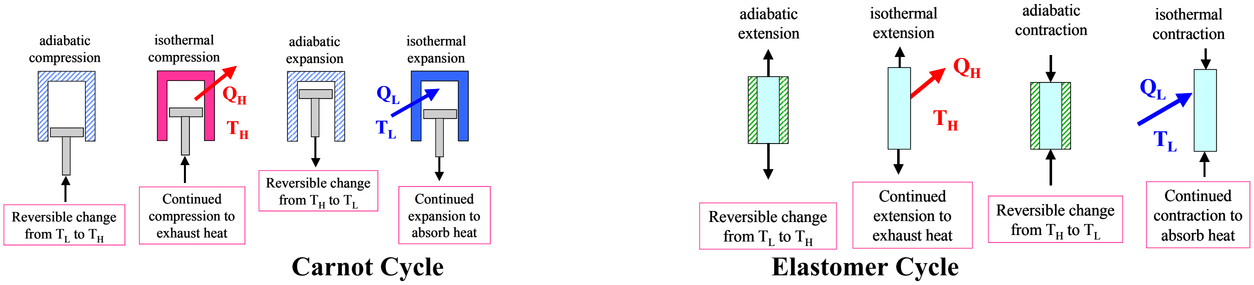

Figure 1 Schematic of the Carnot cycle and an ideal elastomer refrigeration cycle.

The four processes comprising the ideal elastomer cycle, as previously described, can be analyzed by using equations 1, 2, and 3. The two adiabatic, reversible process paths (the second and third schematics in Figure 1) require work in order to reversibly change the material’s temperature level from one temperature reservoir to the other. The work required for each of these process paths can be found by integrating the force over the extension length.

$${}_1W_2 = \int_1^2 K\cdot T\cdot f\left(L/L_o\right)dx \quad (4a) \qquad {}_3W_4 = \int_3^4 K\cdot T\cdot f\left(L/L_o\right)dx \quad (4b)$$

Alternatively, assuming ideal rubber characteristics, the work for these processes can be determined from the internal energy change. Note that the reversible, adiabatic work processes are ideally equal and opposite.

$${}_1W_2 = c_L\left(T_H - T_L\right) \quad (5a) \qquad {}_3W_4 = c_L\left(T_L - T_H\right) \quad (5b)$$

For the two isothermal processes, an ideal rubber material’s internal energy is unchanged, resulting in an equivalence of the heat and work transfers.

$${}_2Q_3 = {}_2W_3 = \int_2^3 K\cdot T\cdot f\left(L/L_o\right)dx \quad (6a) \qquad {}_4Q_1 = {}_4W_1 = \int_4^1 K\cdot T\cdot f\left(L/L_o\right)dx \quad (6b)$$

Process path 2-3, representing the isothermal extension process, rejects heat from the elastomer to the high temperature energy reservoir. Process path 4-1 for the isothermal contraction process, is the removal of heat from the low temperature energy reservoir. A cycle’s coefficient of performance (COP) for heat pump and refrigeration processes would be:

$$COP_{HP} = {}_2Q_3 \Big/ \left({}_1W_2 + {}_2W_3 + {}_3W_4 + {}_4W_1\right) \quad (7a) \qquad COP_{Rfg} = {}_4Q_1 \Big/ \left({}_1W_2 + {}_2W_3 + {}_3W_4 + {}_4W_1\right) \quad (7b)$$

Ideally, work processes for process paths 1-2 and 3-4, as noted above, are equal and opposite, canceling these terms. Substituting an equation of state and performing the above integrations for the work required in process paths 2-3 and 4-1 results in the Carnot limit of the cycle. Real effects, such as friction, temperature differences for the heat transfers and the difficulty to usefully feed work from the contraction processes into the extension processes result in less than ideal performance. As will be noted in the following sections, the equation of state for some example materials indicates a much more complicated material than is often assumed in literature with transient, viscoelastic effects.

Material Property Results

Experiments have been performed on some sample elastomer materials. Objectives of the experiments were to determine the thermodynamic properties of the sample elastomers (toy gum rubber balloons and amber pure gum rubber tubing). The balloons were selected because earlier tests had shown that they have a large temperature change during adiabatic stretches. The tubing had a similar composition, but showed a smaller temperature change.

The first experiment determined K, the elastomer equation of state constant. The experiment consisted of stretching a balloon next to a meter stick by suspending a known weight to its lower end while fixing the upper end as shown in Figure 2. A small gauge thermocouple was inserted inside the balloon so that it was always in contact with the balloon walls. The equilibrium values of force, temperature and length were measured. The value of K [Newtons/Kelvins] was calculated by minimizing the sum of the squares of the difference between the calculated and measured forces.

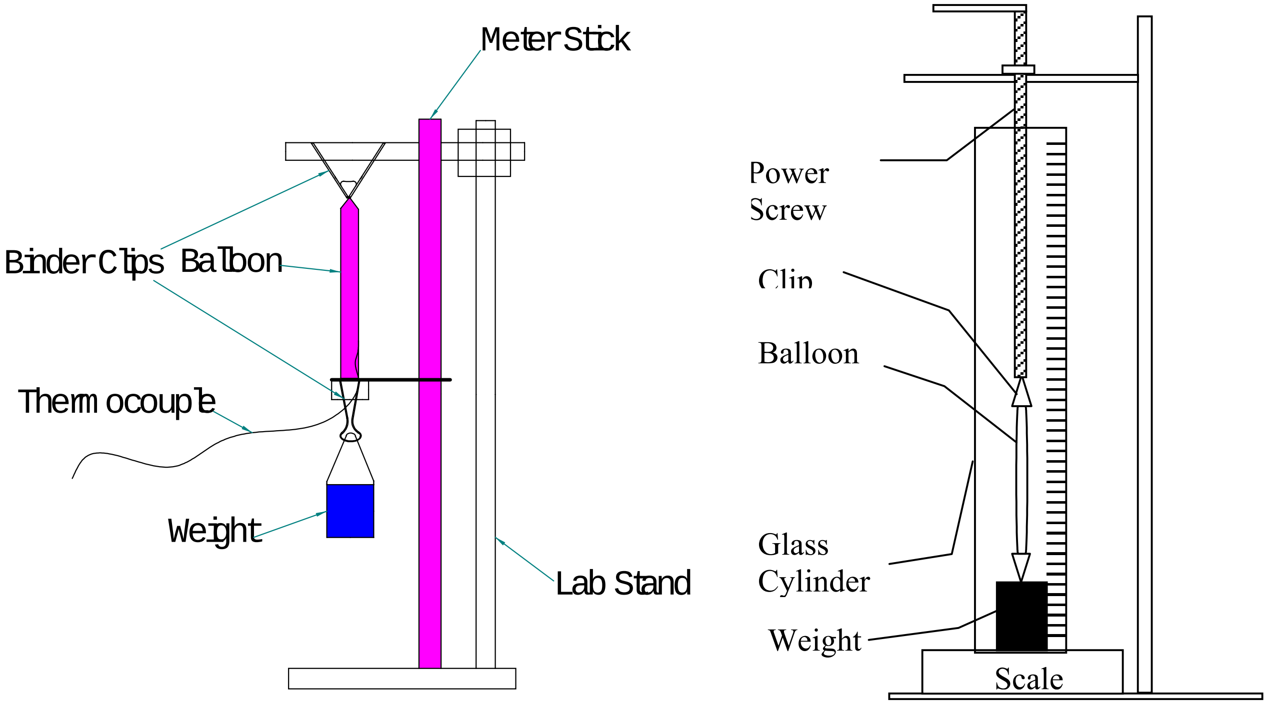

Figure 2 Right: Constant Temperature Experimental Setup, Left: Constant Length Experimental Setup

With the same setup the balloon was stretched adiabatically in a controlled temperature chamber in order to calculate its specific heat. For each load, the peak temperature value and the corresponding stretched length were recorded. Under adiabatic conditions, the change in internal energy is equal to the work done on the balloon, which can be calculated from the following equation,

$$\Delta U = W = \int F dL = K\overline{T}\, L_0 \left(\lambda^2 / 2 + 1/\lambda \right) \tag{8}$$

where $\lambda = L/L_0$ and $\overline{T}$ is the average temperature between the beginning and end of the isentropic process. L_0 is the unstretched length and L is the stretched length. This equation is derived from an equation of state that includes a λ^{-2} correction term subtracted from the λ term. The specific heat C_L was calculated as the ratio between the change in internal energy to the change in temperature as shown in equation 3b.

$$C_L = \frac{\Delta U}{\Delta T} \tag{3b}$$

The setup shown in Figure 2 was used to determine the relation between force and length at different temperatures. The specimen was placed in a glass cylinder filled with water to ensure isothermal conditions at all times. The specimen lower end was held in place by a large weight. The upper end of the specimen was attached to a power screw mechanism, which allowed a controlled change in length. The tension on the elastomer was measured by a platform balance. As the tension increased on the specimen, the reading on the scale decreased by the same amount. The isotherms obtained from this experiment showed the correct trends, but multiple tests indicated significant variations caused by transient creep of the material, material nonuniformities among samples, and effects related to the cyclic variation of a specific sample.. Sample results are shown in Figure 3.

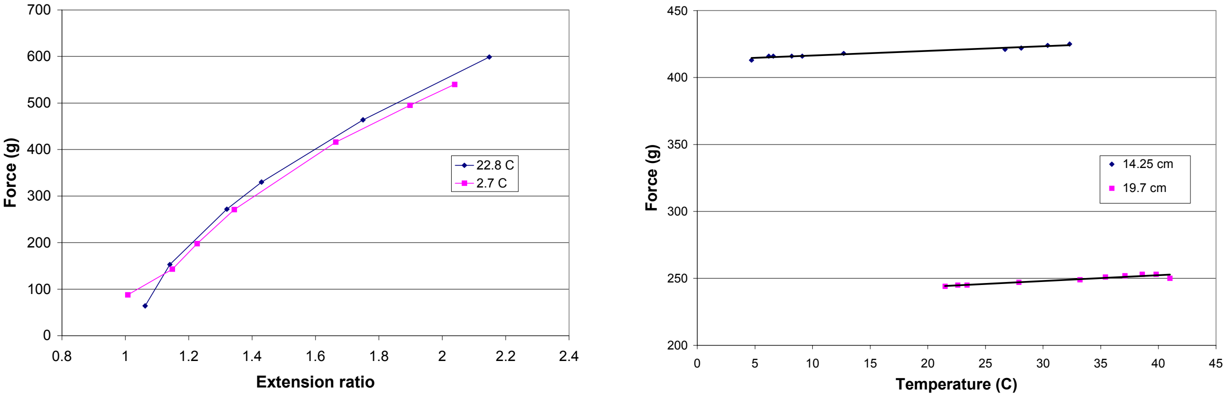

Figure 3. Right: Elastomer Isotherms for gum rubber tubing, Left: Constant Length curves

After estimating the experimental error in the previous experiment, it became evident that another experiment was necessary to notice a temperature effect more explicitly. In order to observe this behavior, the previous setup was used with the length of the specimen held constant during the experiment. A strip type heater was placed on the outer walls of the cylinder to heat the water-specimen system. Temperature and force were recorded as time elapsed, as shown in Figure 3.

From the above experiments the values of K and C_L for the balloon were determined. The balloon used is approximately 9 cm long, 3.4 cm in circumference and 0.2 mm thick. The average and standard deviation for the calculated values for C_L were approximately of the same magnitude. Therefore, the value of C_L can only be considered correct to the order of magnitude. The values obtained for K and C_L were 0.00243 N/K and 0.4 J/K, respectively.

The force versus length behavior of the elastomer tested fits the equation used above. However, the effect of temperature is less clear. The data shows the predicted trend in both constant length and constant temperature tests. However, the scatter in the data is of similar magnitude to the variation due to temperature. As Figure 3 shows the increase in tension due to an increase in temperature is fairly small. Therefore, any inaccuracy in other variables can overshadow this effect. In some tests, the length of the balloon increased with time during the tests. Therefore, creep, strain rate, and the time history of the sample may be significant factors that are not included in the equation. In addition, the inaccuracy in the length measurement is a more significant fraction of the total length at small elongation ratios.

Proof of Concept Prototype Tests

A simple proof of concept prototype was constructed. This prototype was designed to closely follow the ideal cycle of adiabatic and isothermal processes. Several long rubber balloons were connected to a crankshaft at 180 degrees from each other (Figure 4). The other ends were connected to a stationary rod. As the crankshaft rotated the balloons alternately stretched and contracted. At their shortest length they were nearly fully relaxed (λ=1) and at their longest length they stretched two to three times (λ=2 to 3). As the balloons moved they alternately came into contact with two aluminum plates. As the balloon stretched against one plate it rejected heat nearly isothermally. As it contracted against the other plate it absorbed heat isothermally. The plates were hinged at their base. The weight of the top plate and a counter weight on the bottom plate maintained nearly continuous contact with the rubber. The brief period when the rubber band was transferring from one plate to the other corresponds to the adiabatic processes in the ideal cycle. The plates were outfitted with thermocouples and insulated.

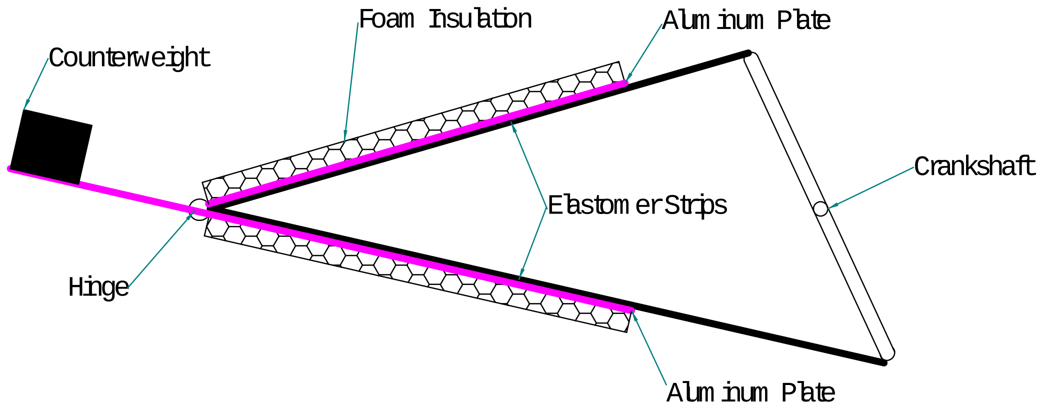

Figure 4. Schematic of elastomer refrigeration prototype

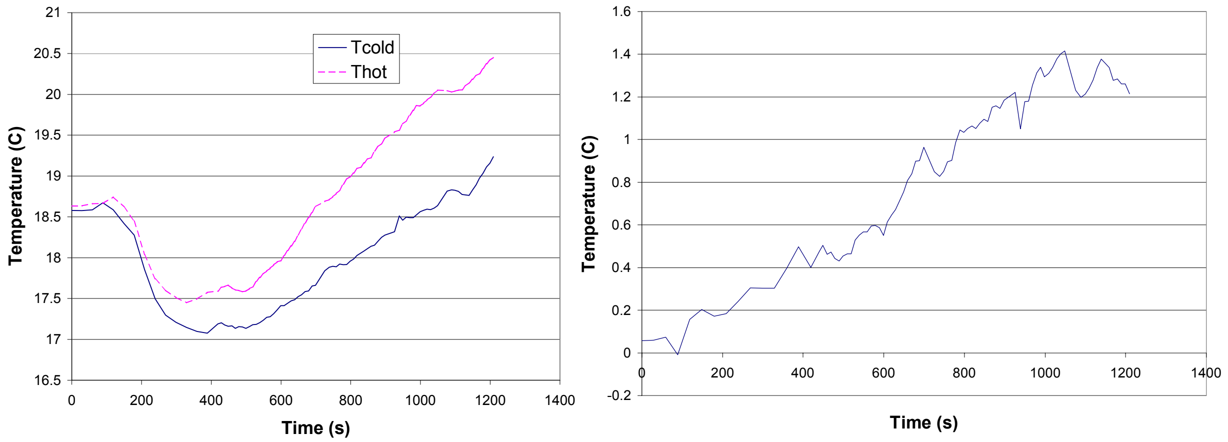

Figure 5. Proof of concept test: Left: plate temperatures versus time, Right: Temperature of heated plate minus the temperature of the cooled plate

The prototype demonstrated heat transfer between the two plates. However, friction from the rubber sliding against the plates increased the temperature of both plates. As shown in Figure 5, the temperature of the heat rejection plate increased faster than that of the heat absorption plate. The initial decrease in temperature was due to a decrease in ambient air temperature. At the startup of the test, the temperature difference between the plates increased approximately linearly with time (See Figure 5). This demonstrates that the cycle transferred heat as predicted.

Attempts at lubricating the rubber-aluminum interface improved performance. However, lubrication is a difficult question, as many petroleum-based oils will cause deterioration of the rubber. Soap water improved performance, but dried out. Graphite powder, glycerin, and a graphite-glycerin mix did not noticeably improve performance.

These tests prove that heat can be transferred against a thermal gradient using elastomers as the working substance. Further tests with improved lubrication or a different prototype design may show a temperature decrease below

Further Work

Elastomer cooling systems have the potential for improved efficiency. As they have not been studied extensively, there is much room for further work. Identification of elastomers with potential for use and accurate measurement of their thermodynamic properties needs to be performed. In addition, a wider variety of physical embodiments of elastomer cooling cycles could be developed , analyzed, and tested.

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