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A High Performance Linear Compressor For CPU Cooling

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Power dissipation and power density of computer CPUs have been constantly increasing with the increase in performance as defined by "Moore's Law". In the foreseeable future it will become difficult, if not impossible, to manage the high-end CPUs heat dissipation with conventional air-cooling or with non-chilled liquid cooling. Lately, CPU spot refrigeration has been receiving more attention from system designers as a viable option for the thermal management of high performance computers. IBM has been shipping such refrigerated CPU computers for several years.

One of the main obstacles for introducing CPU spot refrigeration into commercial computers is the unavailability of a small size compressor with low power consumption (for high COP refrigeration system), low vibrations, long life and very low cost.

This paper introduces a compact compressor technology and design developed by Sunpower in collaboration with Sun Microsystems to meet stringent performance, size, cost and life requirements for cooling multiple CPUs in server computer applications. The system thermal performance goal set for this compressor development program was an implementation of a vapor compression cycle (Rankine) that can remove a 1200 W of heat load from a temperature of 20^{o} C to an ambient temperature of 50^{o} C. The compressor must fit into a 2U-rack mount form factor, i.e. maximum diameter of 75 mm; must have a COP of at least 3 and L-10 life of better than 100,000 hours, and must be cost competitive with existing vapor compression cycle compressors. In order for the compressor to be applicable in a computer environment, additional requirements, including minimal vibration and orientation independence, must be met.

This design utilizes Sunpower's free-piston linear compressor technology [1, 2], in which a gas bearings system replaces traditional oil lubricated bearings. A dual counter piston configuration placed in a tight shell lowers vibrations and size, and enables improved heat removal. A variable frequency driver-controller is utilized for maximum performance and efficiency. Several prototypes were fabricated and tested. This paper includes the design considerations, analyses and test results of the compressors developed.

This paper only addresses the linear compressor of the vapor compressor system. It does not address solutions and optimization of the entire cooling system, including the evaporator and condenser heat exchangers.

Thermodynamic Requirements

The following were the initial system operating specifications:

Evaporating temperatures (cold side)	0^{o} C to 25^{o} C
Condensing temperatures (warm side)	50^{o} C to 60^{o} C
Cooling capacity	800 W to 1400 W

In order to meet Sun's criteria and requirements, Sunpower added some design safety margins, resulting in the following specifications:

Evaporating Temperature	$20^{o}C$
Condensing temperature	$60^{o}C$
Cooling capacity	1500 W
Ambient	$45^{o}C$

R134a[3] was chosen as the refrigerant for this application.

Upon plotting the basic cycle on a pressure enthalpy diagram, the performance of the system was calculated initially using Refprop[4], developed by NIST. For mapping the required performance it was assumed that the evaporating conditions varied from $15^{o}C$ to $25^{o}C$. Increments of $5^{o}C$ were used for the calculations. Condensing temperatures were assumed to be either $50^{o}C$ or $60^{o}C$. Cooling capacity was set as constant at 1500 W.
The cycle then was analyzed using Sunpower's in-house compressor design codes. This analysis includes losses such as the pressure drop across the valves, seal leakage, and heat transfer losses. These models have been extensively calibrated using different refrigerants such as R600, R22 and R134a, and applied to compressor ranging in size from <10 W to over 1 kW electrical input, and to applications ranging from low temperature food freezing to heat pumps. These models have also been calibrated using data independently generated by Sunpower's clients.

Free Piston Linear Compressor Configuration

The configuration of the linear compressor is axi-symmetric. The compressor is comprised of a piston reciprocating in a cylinder and coupled directly to a linear motor. Since there is no conversion of rotating motion, all the forces of the linear compressor act along a single axis, the axis of the piston motion.
This operation along a single axis and the direct coupling between the motor and piston generates minimal side loads and allows the use of a gas bearings system that prevents contact between the piston and cylinder. If oil lubrication is the method of choice, then the oil can be of a low viscosity, to minimize friction losses.

Compressor Size and Performance as a Function of the Operating Frequency

There are several factors that need to be considered regarding the frequency of operation. Neglecting losses, compressor capacity is linearly proportional to frequency. Therefore, capacity per unit volume or power per unit volume should benefit from high operating frequency. Again, if flow losses are neglected, for a given mass flow rate, the required swept volume will be smaller as the operating frequency is increased. However, there are other issues that prevent the frequency from being arbitrarily set too high.
The linear compressor is a resonant machine. The moving mass (piston) of the compressor is the mass component of a mass-spring system that is designed to have a natural frequency close to the operating frequency of the compressor. The spring rate required can be provided in two ways: 1) by the working gas exerting a force on the face of the piston during compression/expansion, and 2) by dedicated mechanical springs. Since gas springs typically cause unacceptable losses and increased manufacturing costs, dedicated mechanical springs usually provide most of the spring rate required by the system. The resonance frequency of the compressor is described by the following equation:

$$\omega_n = \sqrt{\frac{k_{working\_gas} + k_{dedicated}}{m}}$$

For the natural frequency of the compressor to remain essentially constant over a range of operating conditions, it is important that the total spring stiffness remain essentially constant. However, the spring provided by the compression workspace varies with operating conditions. Therefore, the fraction of the total spring rate provided by the dedicated mechanical spring must be large when compared with the spring rate provided by the compression workspace. That is:

$$k_{dedicated} > k_{working\_gas}$$

As the design operating frequency is increased for a fixed inlet and discharge pressure, and with a fixed volumetric flow rate, the required piston diameter is reduced.

$$D = \sqrt{\frac{4\dot{m}}{\pi(2X_p)f}}$$

Where:

$D = diameter$

$\dot{m} = flowrate$

$f = frequency$

X_p = *piston amplitude*

And therefore the spring provided by the working gas is reduced. The amount of mass that can be resonated by the working gas is also reduced with increasing frequency as follows:

$$mass = \left(\frac{D}{f}\right)^2 \frac{\Delta P}{32\pi X_p}$$

The net result is:

$$mass \propto \frac{1}{f^3}$$

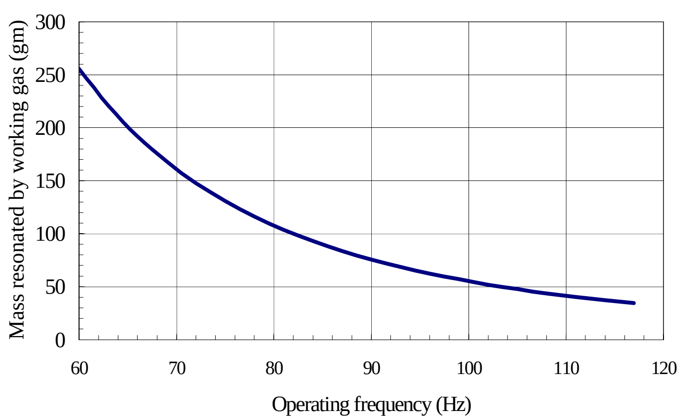

Figure 1. Mass resonated by the working gas at varying operating frequency.
Pressure ratio and flowrate remain fixed.

Sunpower makes use of planar springs, which are formed from a flat sheet of material. Figure 2 shows such a planar spring. The springs are analyzed using FEA methods and have been tested extensively in real machines and on accelerated life test rigs.

The planar springs are connected to the piston through a compliant member to minimize the transfer of radial forces due to misalignment and tolerance stack-up[5]. This feature is fundamental to achieving a manufacturable linear compressor design.

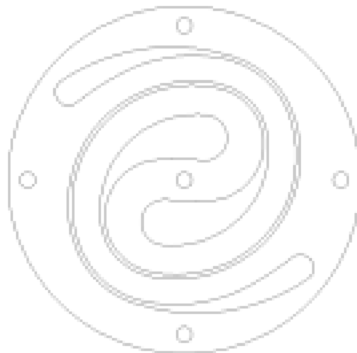

Figure 2. A typical planar spring.

The operating frequency also has a strong effect upon the size of the electric linear motor employed in the linear compressor. For a fixed piston stroke, power is proportional to velocity and velocity is proportional to frequency. Therefore, for a fixed power the motor size is inversely proportional to the frequency.

Valves

Valves can be the traditional flapper-valves mounted on a common valve-plate and usually facing the top of the piston. Another option is an axial-flow arrangement where the suction valve is situated on the face of the piston and moves with it, and the discharge valve is mounted on the valve plate on top of the cylinder. In such an arrangement the gas flows through the piston (suction valve), compression space and discharges valve without changing direction. The axial flow arrangement reduces the losses due to heat transfer from the exiting gas to the incoming gas that is common in a conventional configuration. The linear compressor lends itself well to this configuration due to the compressor's simple mechanical layout.
When the suction valve is mounted on the face of the piston it could be an inertia type. Sliding on a guide, the coned-shape valve is free to move as shown in Figure 3 below.

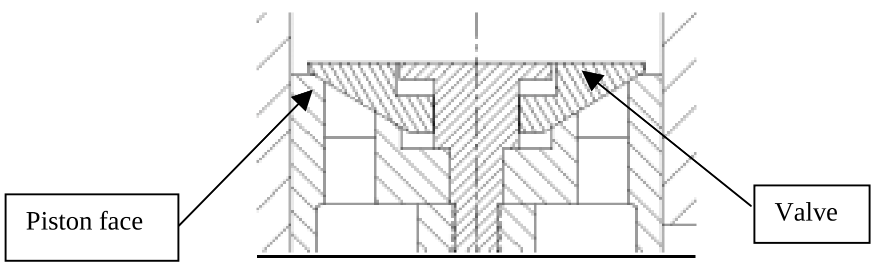

Figure 3. Piston face with inertia valve [6].

Valve dynamics are strongly influenced by operating frequency and this can have a significant effect on compressor performance and operation.

Noise and vibrations

The linear compressor is a mechanical oscillator that induces high vibration forces into its surrounding structure. These vibrations can be dealt with through two basic methods:

A. Isolation – where the compressor and all the connections into it (electrical wires, tubes) allow relative motion between the compressor and a stationary casing without fatigue and without transmitting forces.

B. Cancellation – Since the operation of the compressor is along one axis, a system that produces an opposition to these forces can be employed. One such system is a mass - spring arrangement (passive absorber) that, with the proper tuning, can typically cancel the fundamental frequency and thus bring the overall vibration to an acceptable level. A lower vibration option is an active system where all the frequencies and forces are dealt with. In this case a system can be constructed of two identical compressors operating in opposite directions from one another. These compressors can share suction and discharge processes and electrical connections. When arranged in this way, the two separate compressors run essentially perfectly in phase. Sunpower has demonstrated Stirling engines, coolers and linear compressors with this configuration that have achieved vibration levels of less than 10 μm.

Noise comes from two main sources: Gas pulsation and friction between moving components.
The mechanism for noise generation due to gas pulsation is the opening and closing of the inlet and discharge valves. Here the linear compressor is no different from other reciprocating compressors. However, with non-contact operation achieved through gas bearings, there is no generation of noise due to the motion of parts. Multiple Sunpower machines have demonstrated the resulting reduction in noise.

Oil lubrication and Gas bearings

Every refrigeration compressor in today's market uses oil as the lubricant material for the moving parts. The technology and mechanism associated with oil lubrication are well documented. As new refrigerants are developed, oil compatibility is always a concern. As with new refrigerants, new lubricants have to cause minimal damage to the environment.
The linear compressor is essentially free of side loads. Gas bearing technology [7], which employs the working gas as the lubricating material, replaces the traditional oil lubricants. In such system, some of the high-pressured gas is channeled back into the piston cylinder arrangement to form gas cushions that prevent contact between the moving parts. The typical energy consumption of a gas bearings system is in the range of 1~ 2% of that of the compressor, which is lower then what is typically dissipated through friction from oil lubrication systems.

Variable Frequency Square Wave Driver

A typical Sunpower linear compressor controller uses a feedback loop to maintain a known piston stroke. The piston stroke must be controlled for three reasons. The first is to make it independent of fluctuations in power line voltage. The next reason is to make the compressor stroke independent of variations in the external operating conditions such as ambient temperature or heat load. The third reason is to have the ability to vary the cooling power of the compressor to match the load requirements. The simplest approach to controlling the stroke of the linear compressor is to modulate the voltage that is applied to the motor terminals.
An alternative approach to using the line voltage for the control of the linear compressor is a square wave driver. The square wave drive controller rectifies the AC input power into a DC voltage. The DC link voltage is then applied to the motor at various duty cycles by an inverter to control the RMS value of the motor voltage. One advantage of the square wave driver is that the frequency of the motor current can be varied independently from the AC input frequency. This permits the compressor to be driven at a frequency that is different than the line frequency. It also permits the compressor drive frequency to be varied, enhancing the control capabilities and compressor performance over a wider range of operating conditions. The position of the piston can be measured directly using a variable inductance sensor. The sensor measures the top-dead-center position of the piston.
The stroke can also be calculated using Sunpower's technique known as reconstruction [8]. Reconstruction requires measuring the motor terminal voltage and current and using this information, along with the physical parameters of the motor (inductance, resistance, and back EMF constant) to calculate the stroke of the piston. This method requires no additional sensors inside of the pressure vessel. A phase comparator will measure the phase shift between the motor current and piston position. Optimum performance of the compressor occurs over a narrow range of phase relationships between current and piston position. Therefore, as changing operating conditions affect the stiffness of the gas spring, the output frequency can be adjusted to maintain phase relationship. The control of the system is accomplished with an inexpensive 8 or 16 bit microcontroller. The control does not use a great deal of digital filtering or sophisticated control algorithms, so any midrange microcontroller will have sufficient processing power to do the job.

Heat management/removal

By the nature of the work of a compressor, a large portion of the input energy turns into heat. Most of the compression heat leaves the compressor through the discharge process. However, part of the heat is conducted out through the structure. If not properly managed, this can cause the compressor's temperature to rise, lowering its efficiency and, in extreme situations, damaging its components.
There are few ways to transfer and remove heat from the compressor system. Oil, aside from serving as lubricant, is used in some cases as a medium to transfer heat to the shell directly or through a heat exchanger. Liquid refrigerant leaving the condenser is sometimes redirected back into the pressure vessel to do the same. Another method is to use the incoming refrigerant gas to flow through the compressor structure and remove its heat. In some types of compressors, the motor and compressor body is mounted in direct contact with the pressure vessel. In this way the heat is conducted directly to the ambient air.

Design Solution

In light of the goal to achieve as small a compressor as possible, considering the mechanical spring limits, we selected an opposed configuration with an operating frequency of 95 Hz that makes use of a gas bearings system. The inlet valves are mounted on the two faces of the opposed pistons and the discharge valves are mounted radially from the workspace through the cylinder wall. Heat management is realized with the axial flow configuration and with a compressor body in direct contact with the pressure vessel.
The Driver/Controller is a variable frequency square wave using reconstruction technique with stroke modulation capability.

Motor Design for CPU Compressor

The motor is a moving permanent magnet type, where the magnets are attached to a structure that is coupled to the piston and move in an air gap formed by two sets of steel lamination structures and a coil carrying an oscillating current [9,10].
Due to the limitations of the mechanical springs, the frequency and stroke were set. To achieve the power required while maintaining the target dimensions, the design called for rare earth NdFeB permanent magnets. In the compressor assembly, there are two identical motors.

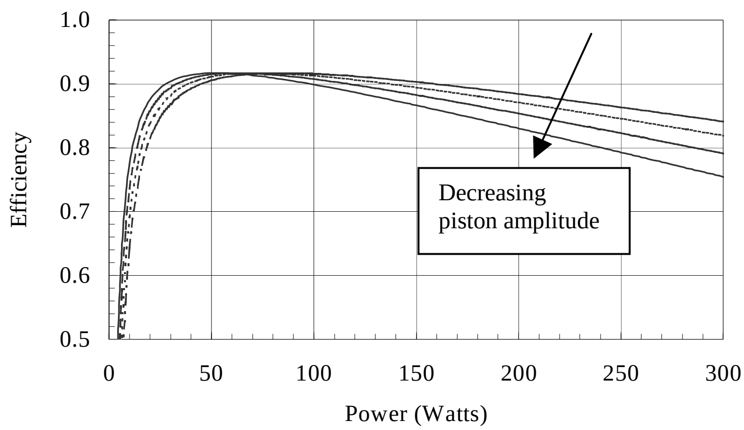

Figure 4. Linear motor efficiency at different piston amplitudes (5.5 mm, 6.0 mm, 6.5 mm, 7.0 mm)

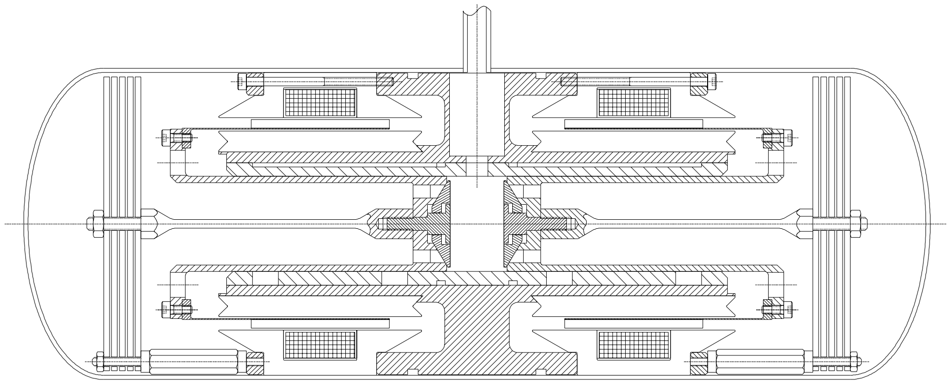

Figure 5. Compressor Schematic.

Performance Tests and Observations

Figure 6 is a summary of a series of performance tests conducted on a calorimeter while varying the suction and discharge pressure.
The tests were conducted using a non-condensing/evaporating calorimeter. In this way the cycle was performed mainly at the superheated state with a small amount of vapor being condensed in a side branch for temperature control at the mixing chamber. Suction pressure and temperature were controlled using variable valves and monitored through a variety of gauges, sensors and transducer. Input power was measured through an electrical power meter and cooling power was measured through the use of a Coriolis mass flow meter. Discharge pressure was adjusted through the total system's refrigerant charge.

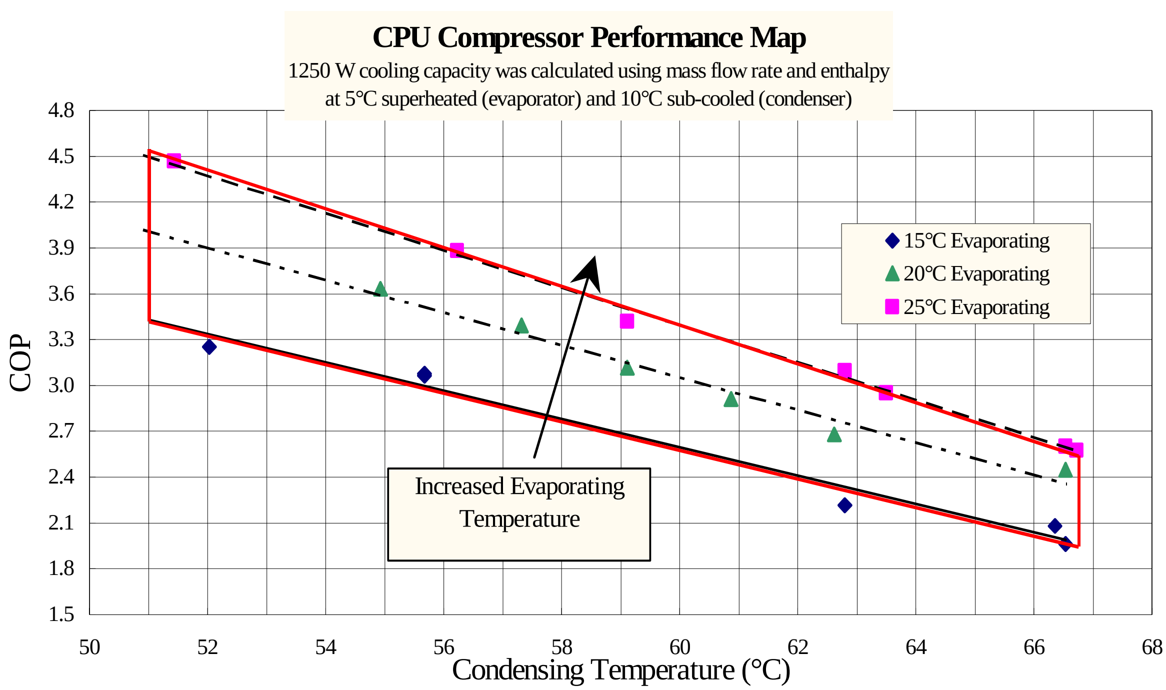

Figure 6. Compressor Performance Map

The CPU compressor performed within 10% of the design parameters. An early failure of the discharge valve was analyzed and corrected. The suction inertia valves proved to be working very well once we manage to gain a good surface fit. Heat removal from the casing was done with an external fan. Capacity modulation was done to nearly zero capacity. Balancing the spring-mass pairs resulted in nearly imperceptible residual compressor vibration levels. Noise measurements were not carried at this stage and will have to be addressed in the future.

With initial study suggesting manufacturing cost comparable to conventional technology, we consider the CPU compressor design as a viable solution for its intended application.

As a continuation to this program, a smaller unit intended for the cooling of a single processor unit was studied. In this study, a compressor small enough to fit onto the Mother Board of a desktop computer was suggested and a design prepared. Such a compressor would have a cooling capacity in the range of 150 W – 200 W and would fit into an envelope of 38 mm in diameter and 150 mm long.

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