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WIND-ELECTRIC ICE MAKING FOR VILLAGES IN THE DEVELOPING WORLD

by

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Abstract

For many villages in the developing world, renewable energy sources are the most economical means of providing power. There is a significant need for ice to preserve fish and produce for shipment to market. Since fishing villages are near coastlines with fairly reliable wind resources, wind-powered ice machines would capitalize on a good match between ice demand and energy supply. To date little work has been done on the use of wind turbines for ice making applications. This paper presents the results of a wind-electric ice making research project conducted by the University of Colorado, the National Renewable Energy Laboratory and Bergey Windpower Co. Several potential problems related to intermittent and variable frequency operation were determined prior to testing. Initial tests were conducted using a dynamometer to evaluate the significance of these potential problems under simulated conditions and to define basic performance expectations for ice makers in the 1.2 tons/day size range. Field testing will be completed soon to determine long-term performance of one ice maker.

Introduction

In many remote communities throughout the developing world there is a great need for ice to preserve fish and perishable produce. The small number of refrigerated trucks available to transport fish to market reduces competition and puts the fishermen at the mercy of the truck drivers, who charge high prices and keep erratic schedules. In some villages, fishermen and farmers limit their harvest to subsistence levels because there is no method of preserving excess yields. In other locations where a fish market has developed, up to 50% of the catch is lost due to ineffective preservation and storage methods (Malvestuto, 1982 and Pariser, 1979). In both of these cases, significant market development could result with reliable preservation.

Providing reliable refrigeration from renewable power sources would encourage sustainable development in these communities. It would also help curb undernutrition and malnutrition since fish are high in protein and reducing fish loss would reduce protein loss (Schreitmuller, 1982). Furthermore, well preserved fresh fish have higher nutritive value than fish that have been preserved through other means, such as smoking, drying, or salting (Sutinen, 1975).

Since many of these communities are not electrified, renewable energy is often the most cost-effective option for providing power. The most immediate need for ice is in fishing villages, which are often along coastlines. Coastal areas often have a reliable wind resource, providing a good match between the need for ice and the availability of wind to make it. In wind energy systems where excess energy is generated, incorporation of an ice maker could also provide another means of storage. In this case the excess renewable energy is stored less expensively than in battery banks.

Flake ice was chosen over block or cube ice for this project for several reasons. Block and cube ice are formed via a batch process, which may require a defrost cycle, a more complex control strategy and uninterrupted power. Flake ice is made and harvested continuously and can therefore better withstand the intermittent nature of the wind. With no defrost cycle, all the energy consumed is used to make ice, leading to a more efficient process. Flake ice also provides the best preservation of fish and produce because it completely surrounds the product.

System Configurations

Ice makers can be incorporated into wind energy systems in two ways. Figure 1 shows an ice maker attached to a mini-grid or storage system through the inverter. In this case, the ice maker is powered by constant frequency alternating current, usually at 50 or 60 hz. All known off-the-shelf ice makers are designed to operate under these conditions. Figure 2 illustrates a second configuration in which the ice maker is directly coupled to a variable-speed wind turbine through a controller. This configuration is based on the experience gained from previously developed variable frequency wind-electric water pumping systems which are currently operating successfully at more than 25 sites (Bergey, 1994). Directly coupled wind-electric ice making has the advantages of simplicity, lower cost, and more efficient operation since it does not include an inverter or rectifier. The ice maker is powered by variable frequency alternating current and operates over a range of frequencies from 30 hz to 90 hz, depending on the wind speed. Since commercially available ice makers are not designed to operate at variable frequencies, this configuration raises some interesting electrical and refrigeration cycle issues. To understand the problems that could arise from this type of operation it is worthwhile to briefly examine the typical vapor compression refrigeration cycle.

Ice Making Fundamentals and the Refrigeration Cycle

A typical refrigeration cycle is shown in Figure 3b. The corresponding pressure-enthalpy diagram in Figure 3a describes the thermodynamic characteristics of the process. There are four primary components in a refrigeration system: a compressor, a condenser, an expansion valve, and an evaporator. Ice is formed in or on the evaporator, depending on the specific design. Under normal circumstances, refrigerant leaving the evaporator is a vapor since most refrigeration cycle compressors can be damaged if incompressible liquid refrigerant is pumped through them. In hermetic compressors, which are typically used in ice makers, the refrigerant circulated through the system is dissolved in the oil used to lubricate the compressor. Under normal constant speed operation, proper mass flow rates and temperatures must be maintained to assure that the oil and refrigerant separate sufficiently to perform their respective functions.

Anticipated Problems

After consulting with various refrigeration experts and ice making manufacturers, a list of potential problems related to wind-powered ice making was compiled. Problem issues fall into two categories: intermittent power issues and variable frequency issues. The first category of problems listed below are likely to occur when power is lost due to no wind in the directly coupled system or loss of power to the mini-grid for some reason.

1) Some ice makers have switches which would have to be manually reset each time power is lost or there is no wind. It probably would not be difficult to omit these switches from the circuit, if desired.

2) Some ice makers have start-up and shut-down control sequences that could damage the compressor if power were lost and these cycles were not allowed to perform their intended function.

3) The cutter bar or auger which removes the ice from the freezing surface could freeze to that surface after power is lost if the refrigerant left sitting in the evaporator is very cold from high-speed or long-term operation. If there is insufficient time to allow this ice to melt, the auger motor, cutter bar or speed reducer could be damaged when the unit is restarted.

4) Many ice makers have crankcase heaters that help the refrigerant and oil separate for proper lubrication of the compressor. Increased compressor wear could result in cold climates since the crankcase heater would not run continuously. In warm climates this is not an issue.

The category of problems associated with running ice makers at variable speeds are listed below. These problems apply only to directly coupled systems.

1) With a variable frequency power source, the dynamic stability of the expansion valve in the typical refrigeration system is questionable. The response time of the controls on a typical thermostatic expansion valve is an order of magnitude longer than the typical variation in frequency the system is likely to encounter with a wind energy source. This difference in response times could damage the compressor, since there is a greater chance of pumping liquid through the compressor and damaging the valves. In the refrigeration industry there have been problems with conventional thermostatic expansion valves in some variable speed applications. To study this potential problem, two ice makers were tested--one with a conventional refrigeration cycle and one with a low pressure receiver and liquid overfeed system to guarantee that no liquid refrigerant enters the compressor.

2) Low refrigerant flow at low speeds could compromise compressor lubrication. If the mass flow rate is too low and the necessary temperature conditions are not met, the refrigerant velocity in the condenser and evaporator may become too low and dissolved oil may not be carried back to the compressor to lubricate it.

3) The control system could be affected by variable electrical characteristics. As the frequency of the incoming power fluctuates between 30 and 90 hz, the corresponding voltage

and current fluctuate. It is possible that the voltage or current could drop to a level where the control circuitry will not operate.

Experimental Set Up and Data Acquisition System

Since the mini-grid configuration poses only intermittent power issues and the directly coupled system poses both intermittent and variable speed issues, the directly coupled system was tested. Two ice makers were tested--one with a conventional configuration that included a thermostatic expansion valve and another with a low-pressure receiver and liquid overfeed system to ensure that the compressor receives only vapor.

One ice maker employed for this test was a 1.1 metric tons/24 hours (1.2 ton/day) Scotsman FM2400WE-3A, which has two ice making units electrically connected so that each can be turned on separately. Although the units can be run separately, they share the same connection to a three-phase power source. When only one unit is running ice production is reduced by half and the Scotsman produces 0.66 metric tons/day (0.6 tons/day). This ice maker works by submerging the cylindrical evaporator in water and scraping off newly formed ice from the inside surface using a helical auger. As the ice is pushed to the top of the evaporator by the auger, it is pressed to remove excess water before being released into the bin below.

The second ice maker, a North Star Coldisc D12, uses a low-pressure receiver and liquid overfeed system. It produces 1.0 metric ton/day (1.1 tons/day). This ice maker uses an approximately 38 cm (15 in.) diameter rotating disk through which cold refrigerant passes. Ice forms as water sprays on the disk's surface and is scraped off by stationary blades when the disk rotates.

Each ice maker was instrumented to measure several performance parameters. A Campbell Scientific CR21X data logger was used to record all of the data. Thermocouples measured temperatures for: the ambient air, inlet water, evaporator, condenser, compressor, ice product and compressor motor. Magtrol power analyzers measured AC voltage, current, and power on each of three phases from which the system voltage, current and power were determined. Frequency measurement and system control were provided by a Bergey Windpower Co. (BWC) pump control unit (PCU-10) designed for BWC's wind-electric water pumping systems. A modified version of the PCU-10 will be used as the controller in commercial wind-electric ice making applications. The amount of ice produced was measured using a flow meter to monitor the amount of water that flows into the ice maker and is converted to ice. Two Maximum anemometers are measuring wind speed during field testing.

The following test protocol was observed for each ice maker. A baseline case was established by connecting the ice maker to a conventional grid at 60 hz, establishing equilibrium and testing all parameters mentioned above except wind speed. The ice maker was then connected to a BWC EXCEL 10-kW permanent magnet alternator. A 75-hp dynamometer drove the permanent magnet alternator at a variety of speeds to simulate the wind. The stability and performance of the ice maker were then tested over the complete frequency range the ice maker is likely to experience when powered by a wind turbine (i.e.

from 30 to 90 hz). The dynamometer was operated at 60 cycles per second initially, then stepped down to 50 hz, up to 70 hz, down to 40 hz, up to 80 hz, down to 30 hz and up to 90 hz to gradually verify the range over which the ice maker could be operated. All parameters except frequency and flow rate were measured and recorded at a 5-second scan rate during this test. The frequency and flow rate were measured every second and averaged and stored every 5 seconds. Wind speed was not recorded for this test.

The ice maker's stability and performance were tested under conditions similar to real wind in a ramp-up test. In this test, the dynamometer was brought to 40 hz, held there for 10 seconds; then ramped up to 70 hz and held there for 10 seconds; then ramped down to 40 hz and held for 10 seconds. This process was repeated for approximately 10 minutes while all parameters, except wind speed, were measured and stored on a 1-second scan rate. A cut-in/cut-out test was performed to monitor system behavior when the wind is fluctuating above and below the minimum speed required to start the ice maker. The PCU-10 was set at a cut-in frequency of 38 hz and a cut-out frequency of 32 hz. The dynamometer was then ramped up and down between 30 and 45 hz every 5 minutes while all parameters, except for wind, were measured at a 1-second scan and storage rate. The final test, which was underway at the writing of this paper, involves connecting the ice maker to a complete BWC EXCEL system.

Experimental results

In addition to determining system performance, refrigeration cycle stability and system electrical characteristics were evaluated. Of the potential problems identified prior to experimentation, only a few were found to be significant. The most important problem involved the large start-up currents and corresponding voltage drops that occurred when either ice maker was turned on. Induction motors generally require six to eight times the running current at start-up as the motors accelerate up to synchronous speed. This problem was not encountered in the wind-electric water pumping systems since the centrifugal pumps used start up under no-load conditions. Reciprocating compressors, however, are fully loaded at start-up and consequently have large start-up torques. Future work will explore ways to reduce these start-up currents. Some options include using soft-start electronics, modifying the alternator windings, adding capacitors and modifying the control sequence of the ice makers to stagger start-up of the different motors. In the last instance each motor would be allowed to come on only when sufficient frequency and voltage have been reached to withstand the additional start-up current and voltage drop.

Due to the problems caused by these high start-up currents, test results are limited at this point to the Scotsman ice maker with only one, 0.6 lbs/day unit operating. Figure 4 shows the response of power and ice production to step changes in frequency. As expected, the ice maker consumed more power and produced more ice as the motors turned faster at a higher frequency. This information is also displayed as power and production curves in Figure 5. The curve fits to the data are second order polynomials. The large scatter in the ice production data is an artifact of measuring production via the intermittent water flow into the ice maker. Data was gathered at six frequencies: 40, 50, 60, 70, 80, and 90 hz. Vertical bands within each of these frequency clusters occur because the dynamometer delivered power at frequencies close to, but not exactly at, the desired frequency and the data logger recorded only whole values of frequency. Once field test results have been obtained, the expected ice production for a given site can be calculated using a modified version of Figure 5 and the annual wind speed distribution. This modified production curve will have wind speed along the abscissa instead of frequency.

As shown in Figure 5, the power the wind turbine supplies to the ice maker never exceeds 3 kW, even though the turbine is rated at 10 kW. At this point, an oversized generator is needed to handle the ice maker's large start-up currents. Once this start-up problem has been solved more of the wind turbine's capacity can be utilized and a better match between the ice maker size and wind turbine size can be achieved.

As Figure 6 shows, frequency varies linearly with voltage. This indicates that the ratio of the voltage to frequency is constant at 2.5 over the whole frequency range of this test. A constant voltage-to-frequency ratio is important because it indicates that the motors in the ice maker are operating in ranges that will not damage them. In fact, a constant voltage-to-frequency ratio is more important to the motor than the specific voltage or frequency at which it operates. This ratio appears to be low compared to other direct-drive systems, such as the wind-electric water pumping application, which has ratios in the range of 3 to 4 (Bergey, 1990).

Figure 7 displays the results of the ramp-up test conducted to determine the transient response of the system to rapid changes in frequency. The two temperatures plotted help describe the stability of the refrigeration cycle. While the temperatures vary with the frequency, they stay within an acceptable range, indicating that the system remains stable throughout the test. This stability indicates that the thermostatic expansion valve did not cause any of the anticipated problems. Therefore, the choice of ice makers which can be incorporated into wind-electric ice making systems is not limited to low-pressure receiver/liquid overfeed systems, but includes a much wider range of machines.

The efficiency of refrigeration cycles is measured by a coefficient of performance (COP), defined as the desired output or useful refrigeration divided by the required input or net work. In the case of an ice maker, this translates to the thermal energy needed to make a given amount of ice divided by the electrical energy consumed. Figure 8 shows the Scotsman's COP over the frequency range tested. The fact that the unit is not operating as efficiently at high frequencies is not necessarily bad since the goal in these applications is to make ice over a wide range of wind speeds and resulting frequencies, not to maximize system efficiency.

The anticipated freezing of the cutter bar to the evaporator surface after power is lost following high-speed or long-term operation did occur. The auger froze in place after the ice maker had been operating for 2 to 3 hours and was cycled on and off frequently. The ice, however, melted, and the auger and motor did not appear to be damaged. Modification of the existing PCU-10 to add a cycle delay sequence should solve this problem.

It appears that the control system on the ice maker does not operate at the low voltages the system experiences at low frequencies since the ice maker stopped or cut-out between 31-38 hz prior to the PCU-10 cut-out at 30 hz. Setting the cut-in and cut-out frequencies higher should ensure that the on/off control for the ice maker is determined by the PCU-10 and that the ice maker shuts off when expected. Possible additional wear on the compressor due to low refrigerant flow at low speed was not evaluated, but will be part of the field test program.

Planned Follow-on Tests

Future work will involve additional testing of the North Star unit and modification and testing of the Scotsman control software. Methods to reduce the large start-up currents need to be explored and implemented. Field testing is underway which will define performance under real wind conditions. Long-term testing is needed to determine if variable speed operation significantly reduces compressor life. Additional study of the containers available to store and transport ice and fish is also needed in order to evaluate local materials with appropriate thermal properties.

Conclusions and Recommendations

The results of this project have demonstrated that conventional ice making equipment can operate when directly coupled to a variable frequency wind turbine. Continued research is needed to address the problems caused by large start-up currents and to provide field test results and long-term performance data. Wind-electric ice making holds great promise in meeting an important need in remote third world villages.

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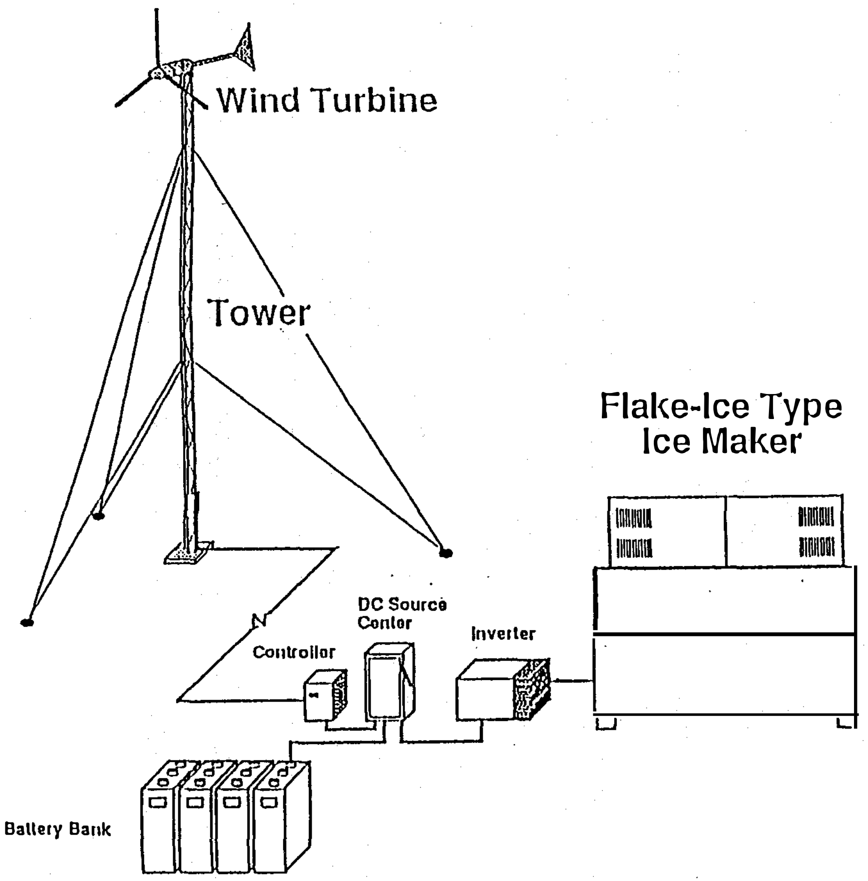

FIGURE 1. MINI-GRID, CONSTANT FREQUENCY WIND-ELECTRIC ICE MAKING SYSTEM

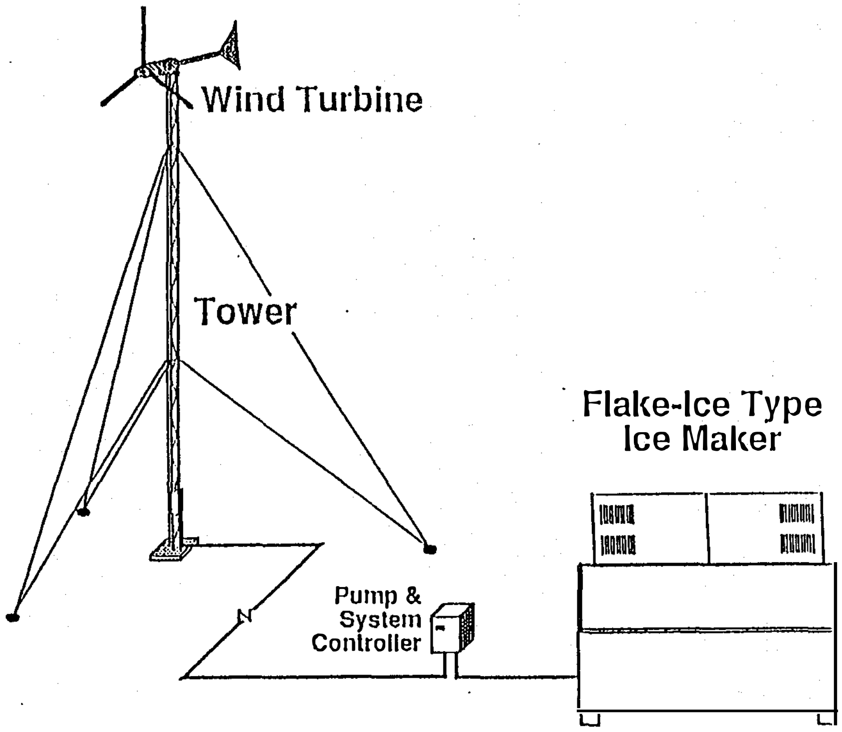

FIGURE 2. DIRECTLY COUPLED, VARIABLE FREQUENCY WIND-ELECTRIC ICE MAKING SYSTEM

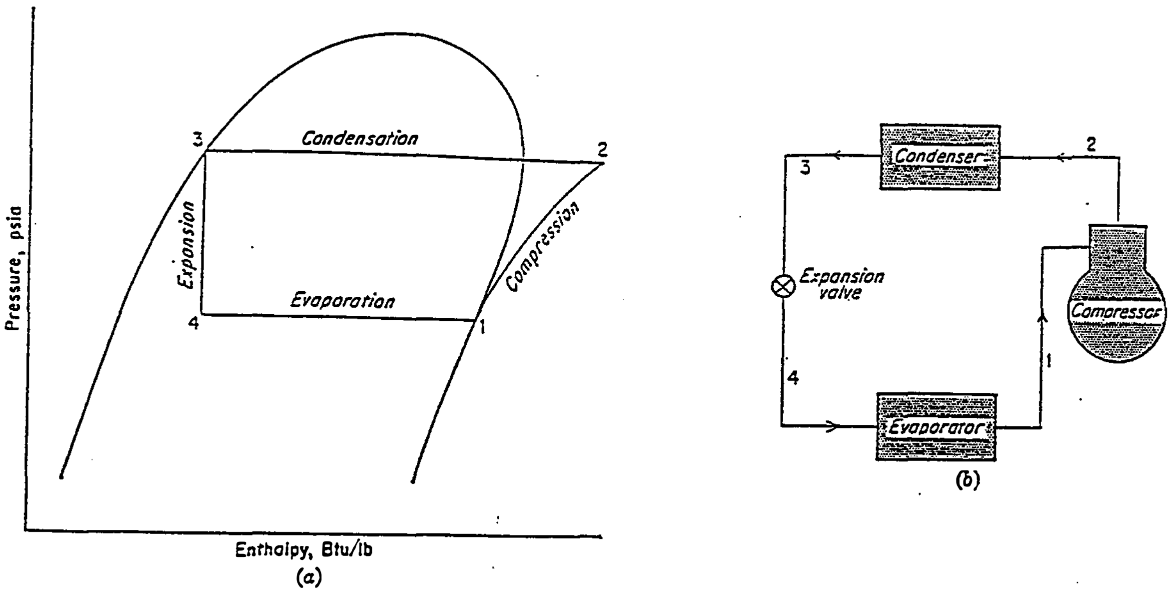

FIGURE 3. (a) THE STANDARD VAPOR-COMPRESSION CYCLE ON THE PRESSURE-ENTHALPY DIAGRAM
(b) FLOW DIAGRAM OF THE STANDARD VAPOR-COMPRESSION SYSTEM

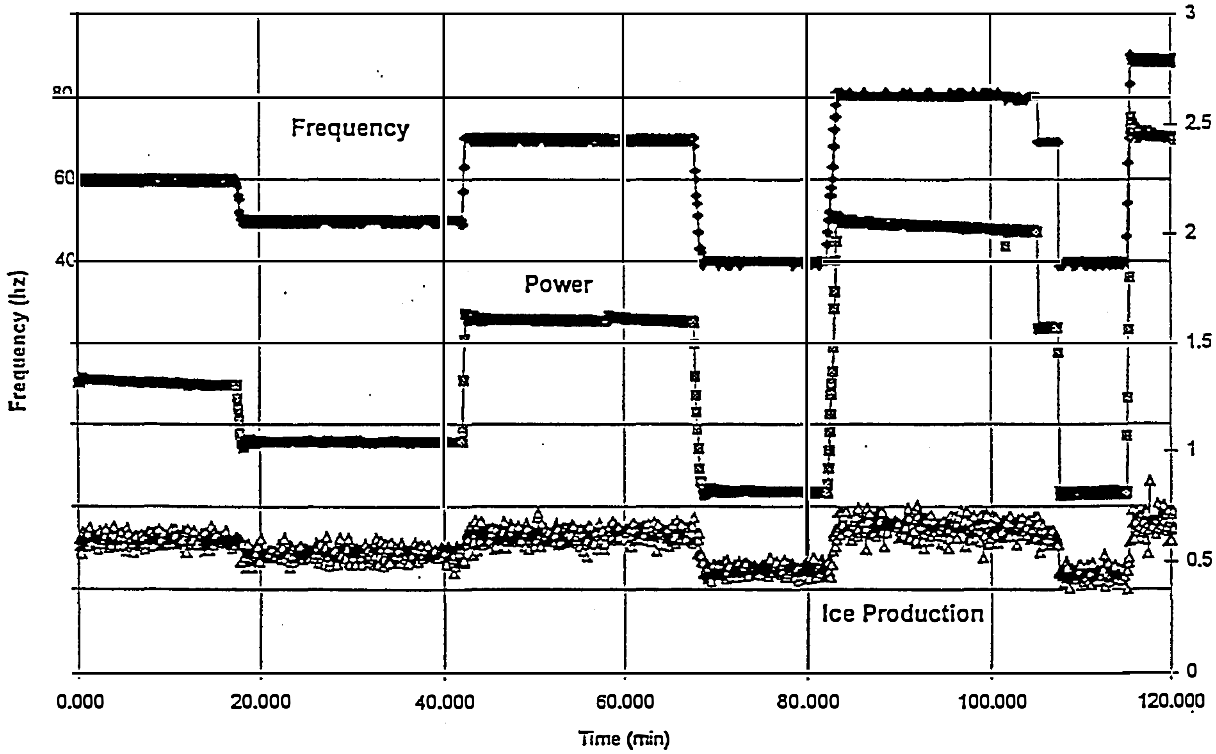

FIGURE 4. SYSTEM RESPONSE TO STEP CHANGES IN FREQUENCY

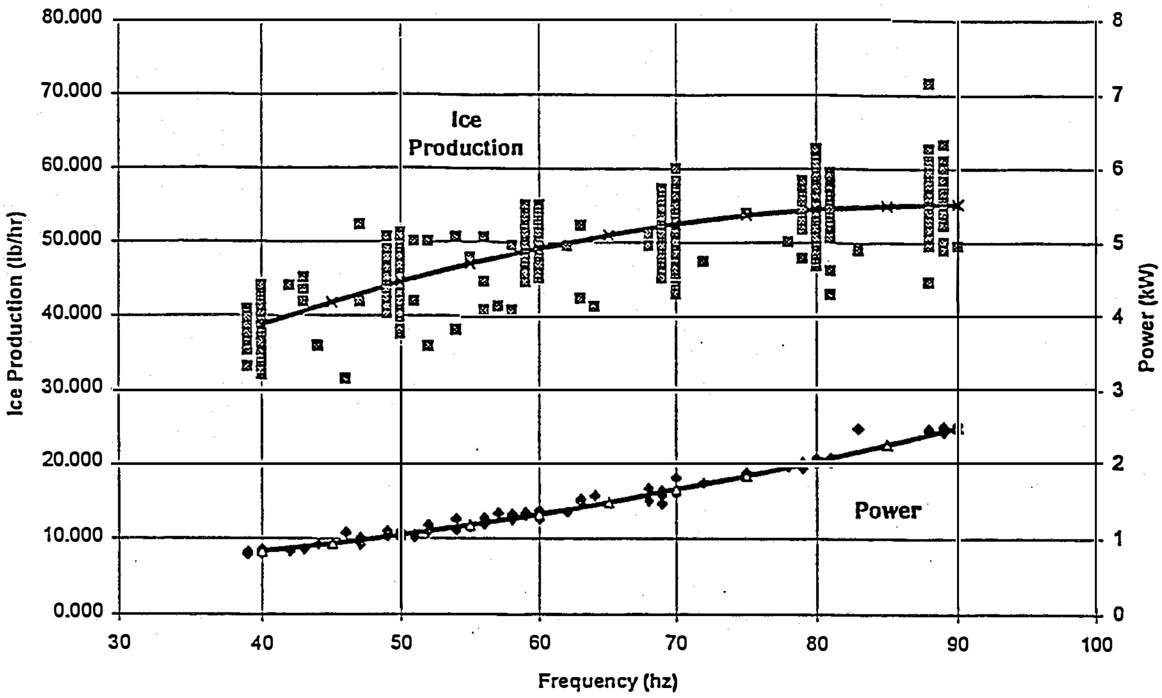

FIGURE 5. ICE MAKER PERFORMANCE

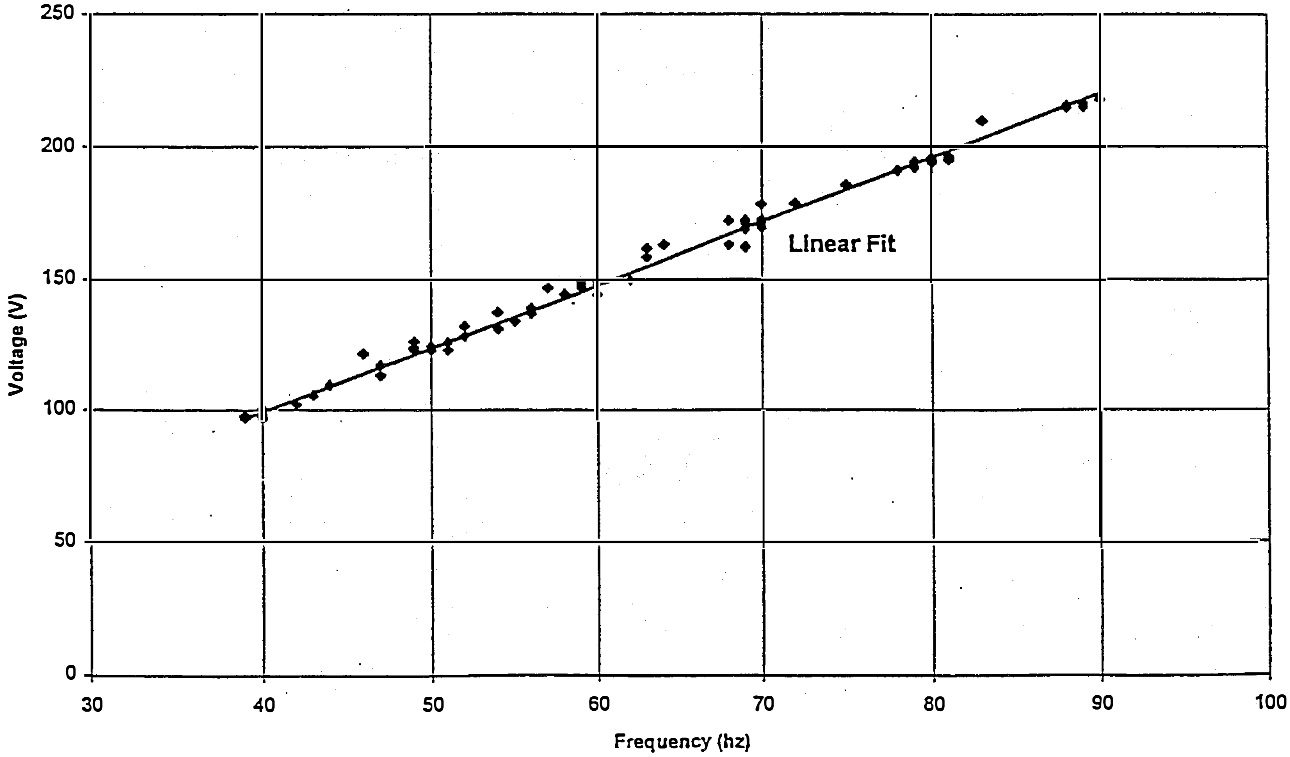

FIGURE 6. VOLTAGE-FREQUENCY CHARACTERISTIC

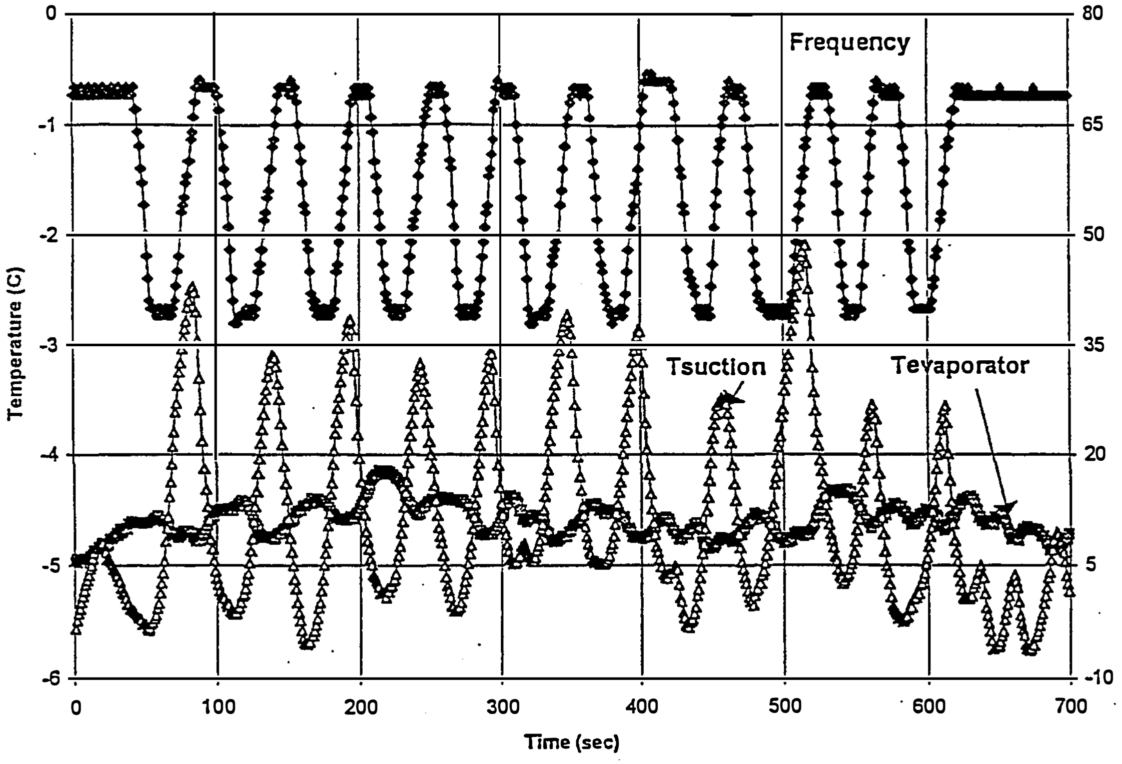

FIGURE 7. TRANSIENT EVAPORATOR RESPONSE

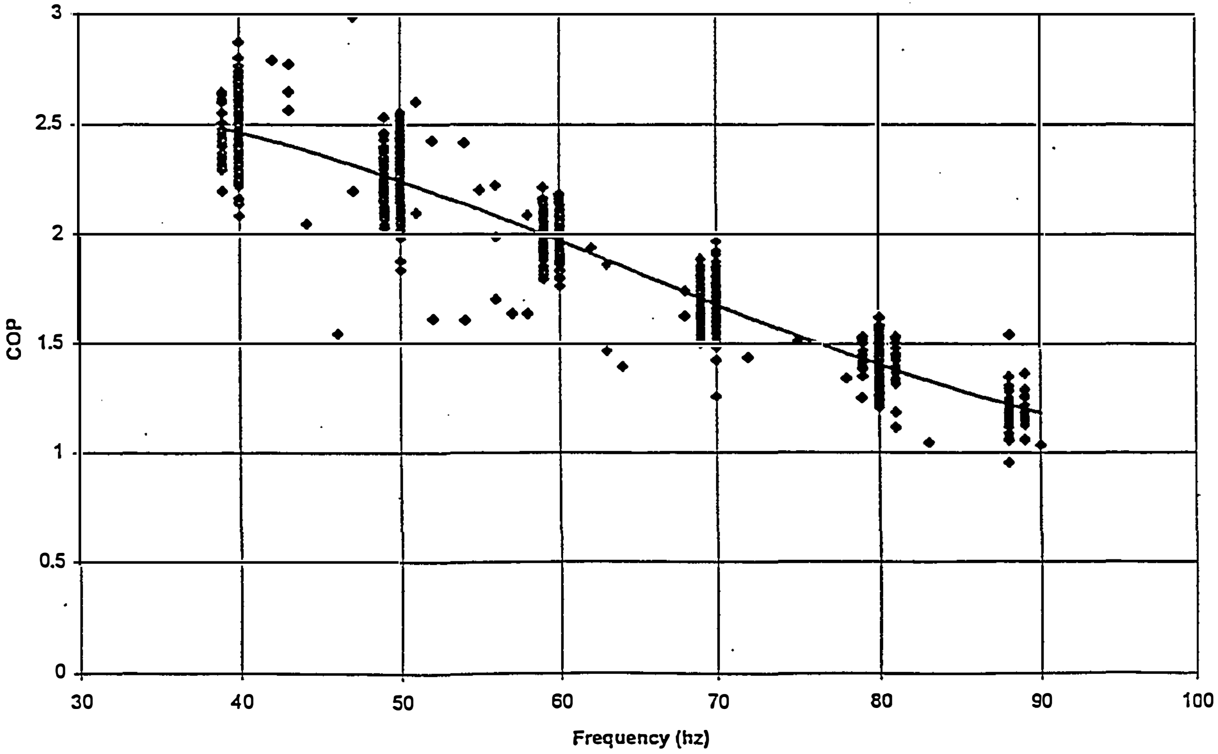

FIGURE 8. COEFFICIENT OF PERFORMANCE