DEVELOPMENT OF A PHOTOVOLTAIC ICE-MAKING MACHINE

Summary

Photovoltaic-powered machines are suitable for use in locations without reliable electricity supply infrastructure. This work deals with an ice-making machine driven by photovoltaic (PV) electric energy, intended for use at isolated communities, such the ones in the northern brazilian rainforest region. A prototype was developed based on a commercially available (AC-powered) refrigerated cabinet, whose refrigeration system was modified to be powered by a photovoltaic electric system. The refrigeration system was modeled in order to aid to analyze the equipment performance. The simulation model was validated with data measured with the original AC-powered configuration and then used in a sensitivity analysis of the machine performance for some design parameters. Experimental results for the PV prototype are presented and discussed. The results allowed to identify improvements to the original design of the machine.

Key-words: ice-making; photovoltaic; refrigerating system simulation.

1. Introduction

The development of refrigeration was one of the greatest advances of modern civilization, allowing to store and to distribute products that need conservation at low temperature. Modern refrigeration machines are mostly electrically driven, therefore the availability of large-scale refrigeration becomes difficult in remote locations without reliable electricity supply infrastructure.

This is what happens, for example, in riverside communities located in the Amazon Region in northern Brazil. The population of these areas is heavily dependent on fishing, both for food and as an economic activity, and the difficulty of obtaining ice for fish conservation becomes a serious problem (Lima et al., 2012). In this way, photovoltaic-driven ice-making machines are suitable equipments to improve the sustainability of the fishing productive chain, due to:

- the production of ice at the site guarantees a substantial improvement in the quality of preserved foods;
- the use of free solar energy source can reduce costs and avoid the burning of fossil fuels in the food production chain; and
- the use of ice as a thermal energy storage avoids the use of chemical accumulators of electrical energy (batteries), which in general presents a strong negative environmental impact in its life cycle (Driemeier and Zilles, 2010).

To this end, a PV ice-making prototype system has been designed and tested. The photovoltaic generation systems has an output of 1,100 Wp working on 310 V. The photovoltaic system supplies electric power in DC mode, which is converted to AC power by an electronic inverter in the control unit that supplies 3-phase 220 V AC power to the compressor. The ice-making machine is composed of a condensing unit and a refrigerated cabinet where a 3-shelves plate-type evaporator and the trays for the production of ice bars are placed. The production of ice bars in batch was chosen because of the ease operation and maintenance, and low cost of the equipment (Almeida et al., 2010). The frequency inverter is also required to control the induction motor rotational speed. As the intensity of the power supply varies throughout the day, it is not possible to keep the electric motor at constant speed, and its control is therefore necessary within the acceptable range for the proper operation of the compressor. The electric motor can only be driven when the minimum speed of 1,260 rpm can be achieved. Below the minimum speed, the energy produced by the modules was discarded by Joule effect using resistors.

In order to improve the design of the ice machine, a mathematical model was developed to simulate and analyze its operation. The mathematical model will help in analyzing the behavior of the coupling of the cooling system with the photovoltaic generation throughout the day and in different climatic conditions, allowing to propose changes in order to increase ice production and efficiency.

2. System modeling

2.1. Refrigerated cabinet

In order to estimate the heat load, in addition to the heat required in the ice-making process, the cabinet was mathematically modeled employing the electric analogy of the heat transfer, which included conduction through the cabinet walls and the internal and external convection.

2.2. Refrigerating system

To simulate the operation of the refrigeration cycle, the method of Gonçalves et al. (2009) was employed, which uses a lumped approach in steady-state condition. Conservation of energy equations (1^{st} law analysis) were derived for each of the components of the system (compressor, condenser, expansion device and evaporator) using an enthalpic approach. The compressor was modeled using the volumetric and isentropic efficiencies. The system of equations describing the refrigerating system behavior was solved using the EES - Engineering Equation Solver software that also provides the refrigerant properties.

2.3. Validation of the models

To validate the refrigerated cabinet model, the global thermal conductance (UA) of the cabinet was measured by the reverse method (Melo et al., 2000). In this procedure the temperature inside the cabinet was kept stable and above the external temperature by the use of electrical resistance heater. External and internal temperatures as well as the power supplied to the heater were measured over a period of 30 minutes, allowing to determine the global thermal conductance. A value of 2.30 W/K was obtained for the UA factor.

To serve as a baseline case and also to generate data to validate the refrigeration system model, the ice-making machine was tested in its original configuration. For a typical load of 36 kg of water in a 10 h test, the machine took approximately 3 h to lower the temperature from 20 °C to 0 °C and from this moment on the temperature remained constant (indicating that ice was forming) for more than 5 h. After this period, with the completion of solidification the temperature dropped again reaching -1.5 °C. Evaporating temperature reached -25 °C and the refrigerating power (capacity) was around 1,850 W with a COP value around 2.0.

3. Results and discussion

The PV-driven prototype was tested under similar conditions (load of 36 kg of water in a 10 h test). In this case the machine took only 2 h to reach 0 °C, mostly because water temperature at the beginning of the test was 2.6 °C lower than in the reference test, and also because the ambient temperature was approximately 10 °C lower, which reduced the external heat load. It was not possible to solidify all the water mass: in the 10 h period 31.64 kg of ice was produced, with 4.36 kg of water left. Evaporating temperature was lower, reaching -29.9 °C, the refrigerating power stabilized around a lower level of 1,500 W during most of the operation cycle, enabling a COP value also lower, around 1.67 (17% lower).

Figure 1 shows the behavior of the system pressures at both modes of operation. In the standard operation, condensing (p_{cond}) and evaporating (p_{evap}) pressures behaves typically for this kind of system. In the PV-driven operation, due to the need for a minimum solar irradiance level for the compressor drive, the compressor was activated only at about 7:50 and was shut down at 16:30. This explains why the system was not able to solidify all the water charge.

Figure 2 shows the irradiance level measured, the power delivered to the compressor ($\dot{W}_{comp}$) and the power dissipated by Joule effect ($\dot{Q}_{res}$) for the PV-driven prototype. It was verified that the compressor had its peak of power supply between 09:00 and 15:00 approximately, that is, during 6 hours it operated with full use of the refrigerating capacity of the ice-making machine, showing that the available solar energy was enough to provide the power required for the compressor. From 07:50 to 9:00 and from 15:00 to 16:30 the machine operated below the full capacity. Beyond these periods, the system was shut down and the available power was entirely dissipated.

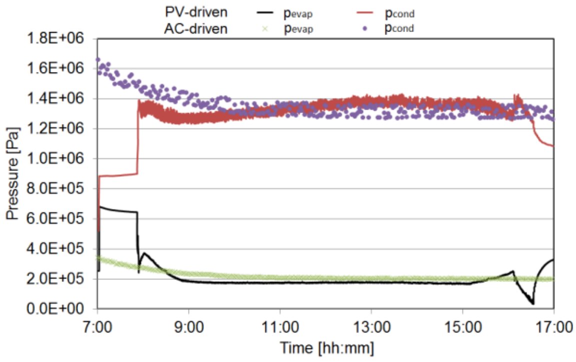

Fig. 1: system pressures, AC vs. PV operation

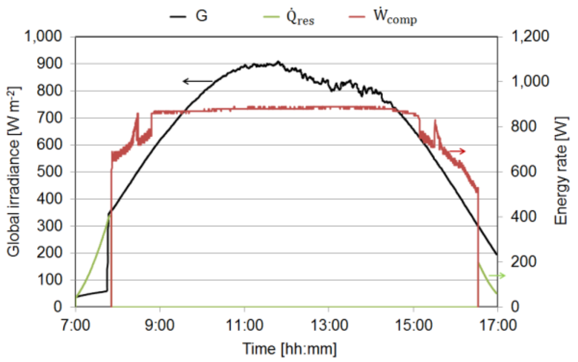

Fig. 2: irradiance and power levels, PV operation

When compared to the operation in standard mode, the PV-driven prototype produced a smaller amount of ice. It is important to note that this decrease was associated mostly to the reduction of solar incidence and not to a reduction in machine performance. During the period in which the irradiance was high, the performance of the refrigeration system was similar. This suggests that the photovoltaic generation system can be improved in capacity to increase the ice production at lower values of solar irradiance.

Results showed that the external thermal load to the cabinet had a significant influence. Hence, the design of the cabinet could be improved in order to enable a more efficient operation. Another interesting development would be the study of the most suitable format for the ice-forming recipients to accelerate the solidification process. Lastly, it is also important to note that some improvements can be introduced to the refrigeration machine to improve the performance, especially to the expansion device.

4. References

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