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Energy consumption optimization of a continuous ice cream process

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ABSTRACT

This work investigates potential energy saves in an ice cream freezer by using a variable speed compressor and optimization's methodology for operating conditions during the process. Two configurations to control the refrigeration capacity were analyzed, the first one, modifies the pressure through the pilot control valve (conventional refrigeration system) and the second one with a variable speed compressor, both with a float expansion valve. Variable speed compressor configuration has showed the highest coefficient of performance and around of 30% less of energy consumption than the conventional one. The optimization of operating conditions in order to minimize the energy consumption is also presented. It was calculated only in France, for all ice cream and sorbet production, it is possible to save energy between 11 and 14 MWh per year by optimizing the operation of the refrigeration system through a variable speed compressor configuration.

1. Introduction

The ice cream manufacturing process consists on pumping a mix through a scraped surface heat exchanger (SSHE), usually is called "freezer". This SSHE consists in a double envelope cylinder; by the internal cylinder circulates the ice cream mix and in the envelope pass a refrigerant fluid that is constantly evaporated. The refrigerant fluid motion is carry out by a refrigeration system that usually uses a single stage compression cycle, where NH_3, R22 or another one can be used as refrigerant in order to reach the temperature range from −10 to −25 °C by using the vaporization latent heat energy [1]. The refrigeration system provides the transformation energy and depending of the process conditions and formulation, the product's draw temperature varies from −5 °C to −6 °C. This draw temperature is usually selected to freeze around 50% of the water in an ice cream mix and to get an adequate viscosity for molding and packaging [2].

Nowadays, due to higher energy prices and environmental regulations, ice cream manufacturers are not only concerned about improving the quality of the final product, but also about the reduction of the energy consumption in their production plants, in which around 60% of the energy consumption is currently used by the refrigeration systems. In the case of a traditional freezer, the overall electricity consumption is generally shared between the mix pump (5–10%), the dasher mechanical system (10–25%) and the refrigeration system compressor [3].

One of the major problems in freezer optimization is the lack of information concerning the energy consumption of ice cream freezers. It is well known that a reduction of evaporation temperature results in an increase of energy consumption for pumping, mixing and scraping the ice cream due to the higher ice content [4–6]. Similarly, the refrigeration system's cycle performance based on a vapor compression cycle also is affected with a lower evaporation temperature. All these considerations could have consequences on the product's quality.

In general, the refrigeration system capacity has to be adapted to the operating conditions, since the ice cream freezing is a continuous process. This is usually done by a float expansion valve and by operating a pilot control valve at the evaporator's outlet that limits the refrigerant flow rate through the system and consequently, reduces the refrigeration capacity [3]. In this case, the compressor keeps running continuously at its nominal speed. In this configuration, the power requirements for compression in part-load and full load operations are almost the same. Another option to control the refrigeration capacity is to use a variable speed compressor [7–9]. In theoretical terms, an electrical motor can be controlled by using variable speed drivers [10]. This concept is applied in refrigeration systems that functions with an electrical motor coupled to a compressor. By varying the compressor speed, the flow rate passing through the system is changed, modifying, the refrigeration capacity. This technology is more recent for refrigeration systems, but nowadays is available for various compressors types and a large range of refrigeration capacities. Variable speed compressor technology has already been studied in various processes like residential heat pumps and air conditioning [11], refrigeration and food storage [12], automotive air conditioning [13],

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Nomenclature

COP	coefficient of performance (–)
H	enthalpy (J kg^{-1})
$\dot{m}$	mass flow (kg s^{-1})
Q	heat flux (W)
T	temperature (°C)
W	electrical power (W)
x	mass fraction (–)
Subscripts	
comp	compressor
evap	evaporation
frigo	frigorific
ice	water ice
mix	ice cream or sorbet mix
p	product
tot	total
Others	
CFL	compressor full load
CS	compressor speed
DOM	desirability optimization methodology
DRS	dasher rotational speed
MFR	mix flow rate
RSM	response surface methodology
TR22	temperature of the R22 refrigerant
TXV	thermostatic expansion valve
VSC	variable speed compressor

chiller systems [14] or refrigeration units [15]. Those studies about variable speed compressors have several subjects as modeling [16,17], process control [15,18,19] or energy optimization [12,13,20,21].

In this sense, the objective of those investigations is to optimize the refrigeration process, mainly the energy consumption. One of the most important factors in refrigeration systems optimization is efficiency, that it is usually shown in terms of the performance coefficient (COP) [22,23], which is the ratio of the heat amount extracted from the product or the environment and the energy consumption in this extraction [24]. This COP is determined as follow:

$$\mathrm{COP} = Q_0/W \tag{1}$$

where Q_0 is the heat removed and W the energy consumption of the refrigeration system. This COP depends on the refrigeration or heat charge and the type of refrigerant fluid, represented as a measure of the energy transformed [25]. The value of Q_0 can be calculated by the next equation:

$$Q_0 = \dot{m}\Delta H_{evap} \tag{2}$$

where $\dot{m}$ is the refrigerant flow rate, ΔH_{evap} is the refrigerant fluid latent heat of evaporation in. Higher is the value of the COP, lower are the operation costs. Therefore, the COP's value is characteristic of the refrigeration's installation efficiency [26].

The COP can be optimized by using variable speed devices that have been shown to enhance the efficiency [15]. An example of energy optimization using variable speed compressors is presented by Widell and Eikevik [12]. They have moved from a conventional configuration, with a low pressure valve, to a variable speed scroll compressor in order to increase the refrigeration efficiency in industrial food storage. In addition to the refrigeration's system improvement in COP, they have assumed that € 30,000–50,000 can be saved per year (in an industrial installation) by using variable speed compressors. Alkan and Hosoz [13] investigated experimentally an automotive air conditioning system's performance with and without variable speed compressors. They have also found a significant improvement in COP when using the variable speed compressor. In general, it has been reported a significant energy saving using variable speed drivers for several applications in motor systems [27,28].

The objective of this work is to define the optimal conditions to minimize the energy consumption of the ice cream freezing process. This optimization is carried out by using a variable speed compressor and modifying the global operating conditions, taking into account the product quality constraints. Experimental measurements to compare the performance between a conventional ice cream freezer and a variable speed configuration at optimized operating conditions have been performed and are presented.

2. Materials and methods

2.1. The ice cream freezer

A pilot scale freezer (model WCB MF50) composed of a scraped surface heat exchanger (SSHE) coupled with a refrigeration system was used for the experiments. The SSHE is a double envelope cylinder. The mix flows through the inner tube and is gradually transformed into a sorbet. Refrigerant fluid flows through the outer tube in order to extract heat transformation. The heat exchange tube's inner diameter is 0.05 m and the length is 0.40 m (the cylinder total volume 7.85×10^{-4} m^3). Inside this cylinder, there is a 'solid' rotor that occupies 45% of the freezing tube volume and has two scraper blades. This equipment has a nominal output of ice cream mix from 25 to 100 kg/h and a dasher speed variation between 250 and 1000 rpm.

The refrigerant fluid is R22 (Chlorodifluoromethane) that is continuously vaporizing through the SSHE double envelope. The refrigerant flow motion is provided by an open reciprocating Bock compressor (model FK20/120K) with a variable speed motor (from 500 to 2600 rpm) and a maximal electrical consumption of 2.2 kW. A float expansion valve provides the refrigeration capacity and two configurations for the refrigeration systems were tested in order to fix the evaporating temperature in a range from −10 to −25 °C. The first one is a conventional compressor at full load (CFL, constant rotational speed of 2600 rpm), which includes a pilot control valve that manipulates the refrigerant flow rate (Fig. 1 up). The second one consists into eliminate the pilot control valve and the variable speed compressor (VSC) manipulates the refrigerant flow rate (Fig. 1 down). This second configuration includes the same compressor supplied by a frequency inverter to change speed rotation and a refrigeration circuit. The system is designed for an easy switching between the two configurations.

2.2. Sorbet mix

Sterilized U.H.T Lemon sorbet (Soft Italian style) has been used for all tests. This mix is composed of 14.6% saccharose, 8% fructose, 3% concentrated lemon juice, 0.09% dextrose, 0.5% stabilizers (Hydroxypropylmethylcellulose "HPMC", guar rubber and carob flour). The lemon sorbet mix refractometric measurements were 25.7 Brix at 20 °C. This sorbet mix was stored at 5 °C for 24 h before experiments.