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Design of an Innovative Plant for Fast Freezing of Potato Dumplings

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Abstract

The design of an innovative plant for fast freezing of potato dumplings at temperatures much lower than traditional freezing plants is presented in this study. The designed plant is constituted by two separate loops: the first loop, where the cooling energy is obtained at low temperature, is based on a reversed Brayton cycle while the second loop, where the dumplings are frozen, is a forced-air freezer room. Optimal plant parameters, such as temperature and velocity of the freezing medium (air), to obtain the required fast freezing time of dumplings are evaluated. Depending on the requested freezing time and on the mass per hour of dumplings to be processed, the suitable plant solution can be identified and finely designed.

The proposed solution overcomes limits of traditional freezing plants, such as ones operated by vapour compression cycles, which cannot reach such low temperatures without exceeding in complexity and number of stages. For this reason, the plant is proved to be a viable, cost-effective alternative to traditional freezing plants used in food industries.

Introduction

Fresh food when processed and/or harvested continues to undergo chemical changes that involve spoilage and deterioration of the product. This food deterioration is due to enzymes and bacteria that cause the loss of texture and nutrients, the colour change, and the taste change. Freezing for short or long term period is a valuable technique of food conservation to extent food shelf life and to reduce food waste. The recommended temperature to storage frozen foods is -18°C (Biglia et al., 2018) as this is the temperature at which enzymes and bacteria stop growing.

Water represents a high percent of weight of most foods, even over 90% in fruits and vegetables. Part of this water is bound with chemical substances while the remain one is unbound and held within the cell walls. When the temperature of the food drops below freezing point, the unbound fraction of water freezes and expands. The ice crystals cause the cell walls rupture and, consequently, nutrients will be released during food thawing and food texture will be also much softer than it was before freezing. The cell wall damage can be controlled by freezing the food as quickly as possible since quick freezing process allows small ice crystals to be formed. Indeed, slow freezing produces only large ice crystals.

Freezing time can be defined as the time taken for the temperature of the food core to be reduced to -18°C. The time of the freezing process depends on: (1) physical and chemical properties of the food; (2) velocity of the medium used to freeze the food, typically purified air, and (3) temperature of the medium (Biglia et al., 2016; Pham, 2014; ASHRAE, 2010). Freezing plants adopted in food industry are usually operated by vapour compressor thermodynamic cycles. These plants allow the medium (air) temperature to be reduced at [-40, -20] °C. The low temperature air is usually circulated in closed freezer rooms with a velocity between [1, 5] $m \cdot s^{-1}$. These freezers are named air blast freezers (Dempsey and Bansal, 2012). Specific air blast freezers have been developed for small and/or thin foods (e.g. slices of fruit, fish fillets, etc.) where air is injected directly on the external surface of the food at very high velocity, more than 20 $m \cdot s^{-1}$. This technology, known as impingement (Salvadori and Mascheroni, 2002), significantly reduces the freezing time as the heat transfer coefficient between medium and food is high (> 50 $W \cdot m^{-2} K^{-1}$). Alternatively, a liquid medium (e.g. $CaCl_2$ solutions, CO_2, N_2, etc.) may be used in food freezing (Galetto et al., 2010). An advantage of liquid medium is the enhanced heat transfer coefficient that is 10 to 20 times higher than the one obtained with gaseous medium used in air blast freezers.

Low temperatures for food freezing can also be achieved by means of a reversed Brayton cycle (Biglia et al., 2017; Foster et al., 2011). In this work, an innovative plant configuration for potato dumplings freezing at very low temperatures (< -70 °C) is presented. The designed plant is constituted by two separate loops: the first loop, where the cooling energy is obtained at low temperature, is based on a reversed Brayton cycle while the second loop where, the dumplings are frozen, is a forced-air freezer room. Optimal plant parameters, such as temperature and velocity of the freezing medium (air), to obtain the required fast freezing time of the dumplings are evaluated. Depending on the requested freezing time and on the mass per hour of dumplings to be processed, the suitable plant solution can be identified and finely designed. The proposed solution overcomes limits of traditional freezing plants, such as ones operated by vapour compression cycles, which cannot reach such low temperatures without exceeding in complexity and number of stages. For this reason, the plant is proved to be a viable, cost-effective alternative to traditional freezing plants used in food industries.

Food freezing plant

The proposed food freezing plant can be outlined into two sub-systems: (1) a freezer room where food is frozen by means of refrigerated air, and (2) a reversed Brayton cycle, which produces cooling energy at very low temperature. A heat exchanger, installed in the freezer room, connects the two systems.

Freezer room

The final quality of frozen foods is related to the resulting freezing time τ, which, for a specific food product, can be obtained by finding the proper trade-off between temperature T_m and velocity v_m of the medium. Therefore, the design of a freezing room is not a trivial task.

Given the mass of fresh food G that has to be frozen per unit of time, the cooling capacity Q of the freezing room can be easily computed as

$$Q = G \cdot \Delta E \quad (1)$$

where ΔE is the energy that has to be removed from the food during freezing process (Biglia et a., 2016; ASHRAE 2010). The parameter ΔE depends on several food product data: 1) temperature at the beginning and at the end of the freezing process, 2) chemical composition and 3) shape. The higher the ΔE is the higher the freezing time τ will be.

The freezing time τ can be evaluated as reported by authors Biglia et al. (2016); according to the type of food, the size of the batch lot M [kg] can be defined as

$$M = G \cdot \tau \quad (2)$$

Considering the case of batch processes, an important parameter resides in the mass M of the batch that can be frozen in the insulated room as a function of medium temperature T_m and velocity v_m and of the plant cooling capacity Q. With this aim, a chart of the batch lot size has been defined for potato dumplings, in which iso-mass curves has been calculated as a function of food production rate G, of freezing time τ and of cooling capacity Q. Therefore, the proper size of the lot to be frozen by batch can be obtained. In potato dumpling, moisture and ash fractions content have been evaluated experimentally as they deeply affects the freezing time τ.

Reversed Brayton cycle

The main components of the reversed Brayton cycle are turbo-machineries and heat exchangers. The scheme of the cycle, showing components links, is reported in Figure 1.

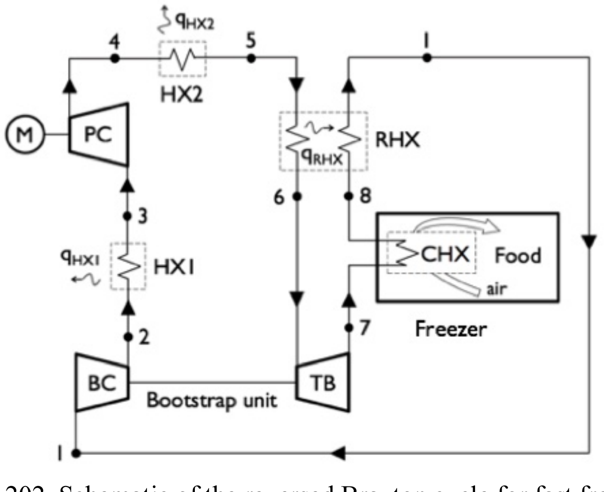

Figure 202. Schematic of the reversed Brayton cycle for fast freezing.

The refrigerant gas enters the bootstrap compressor (BC) at state 1, where the pressure is minimum, and is compressed to state 2. The gas is then cooled to state 3 in the heat exchanger (HX1) and next, the gas is compressed in the motor-compressor (PC) to the maximum pressure and temperature of the cycle (state 4). Once compressed and before entering the turbine, the gas is sequentially cooled in HX2 (state 5) and in a regenerative heat exchanger (RHX), state 6. In the subsequent expansion through the turbine, the gas achieves the lowest temperature of the cycle at state 7. The mechanical work produced by the turbine through the expansion is supplied to the bootstrap compressor by installing the two components on the same shaft. The gas exiting the turbine, before re-entering the compressor BC, passes through the cold heat exchanger (CHX) installed in the freezer room, state 8, and through the RHX, state 1. In the CHX, the gas cools the air in the batch freezer by absorbing heat released by the food during the freezing process. The refrigerant gas always remains in the gaseous state at each state of the cycle. Dry air has been selected as refrigerant gas of the cycle.

The coefficient of performance (CoP) of the reversed Brayton cycle can be defined as

$$\mathrm{CoP} = \frac{h_8(T_8\,, p_8) - h_7(T_7\,,p_7)}{\left(h_4(T_4, p_4) - h_3(T_3\,,p_3)\right)\eta^{-1}} \tag{3}$$

which is the ratio of the gas enthalpy difference in the CHX and in the PC, taking into account the electric motor efficiency η.

The heat released by the refrigerant gas in HX1 and HX2 can be recovered to enhance the performance of the reversed Brayton cycle. Indeed, thermal processes are typically required in the food industry for cooking, heating (Biglia et al., 2015; Comba et al., 2011, 2010), blanching, debacterisation (Biglia et al., 2017), etc.

A numerical model of the proposed reversed Brayton cycle has been developed to evaluate its energy performance. The steady state form of the energy rate balance was used to develop the thermodynamic model of the cycle's components. More in detail, steady-state conditions were considered and heat losses across the cycle's components were neglected. The model was implemented by using Matlab® environment and the thermodynamic properties of the dried air were evaluated by using REFPROP database.

Results and Discussion

Freezer room

Moisture fraction content and ash in potato dumplings have been measured experimentally. Potato dumplings, after being characterised in terms of shape and weight, have been put into the oven at 105 °C for 24 hours to remove humidity (Figure 2). Then, dried potato dumplings have been put into the muffle at 450 °C for 6 hours to obtain ash content.

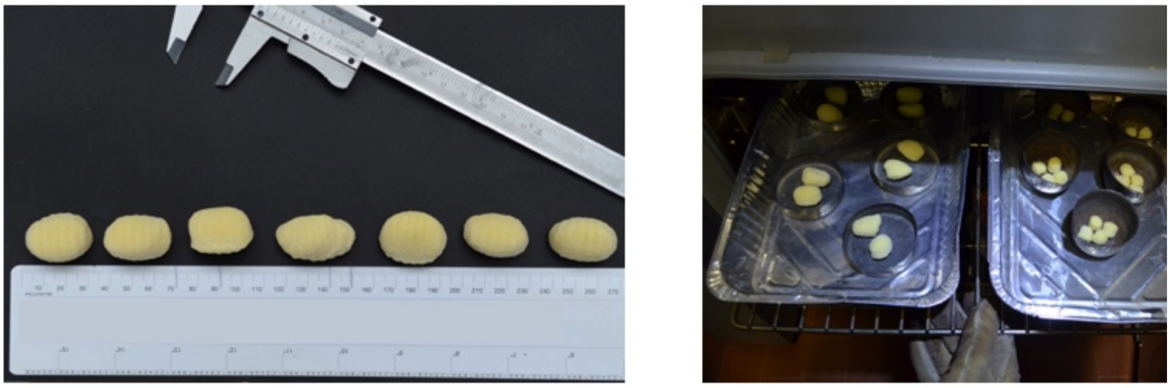

Figure 2. Potato dumplings experimental tests.

Results of potato dumplings characterisation have been reported in Table 1 together with data obtained from the label attached on the food packaging label. Latent heat of potato dumplings has been found on literature (ASHRAE, 2010).

Table 90. Composition of potato dumpling and geometrical data.

Potato dumplings	
Moisture fraction content [%]	0.495
Protein fraction content [%]	0.137
Fat fraction content [%]	0.067
Carbohydrate fraction content [%]	0.278
Fiber fraction content [%]	0.054
Ash fraction content [%]	0.023
Initial food temperature [°C]	15.0
Initial freezing temperature [°C]	-1.0
Final food temperature [°C]	-25.0
Latent heat [kJ/kg]	228
Ellipsoid shape*	
a [cm]	2.9
b [cm]	2.0
c [cm]	1.6

*Potato dumplings shape has been modelled as an ellipsoid

Figure 3 shows two charts that have been developed to properly size the cooling capacity Q of the freezer room. In particular, the chart in Figure 3a reports the freezing time as a function of the air temperature and of the air velocity that flows in the freezer room. The chart in Figure 3b reports the cooling capacity Q of the freezer room as a function of the freezing time and of the food production rate G.

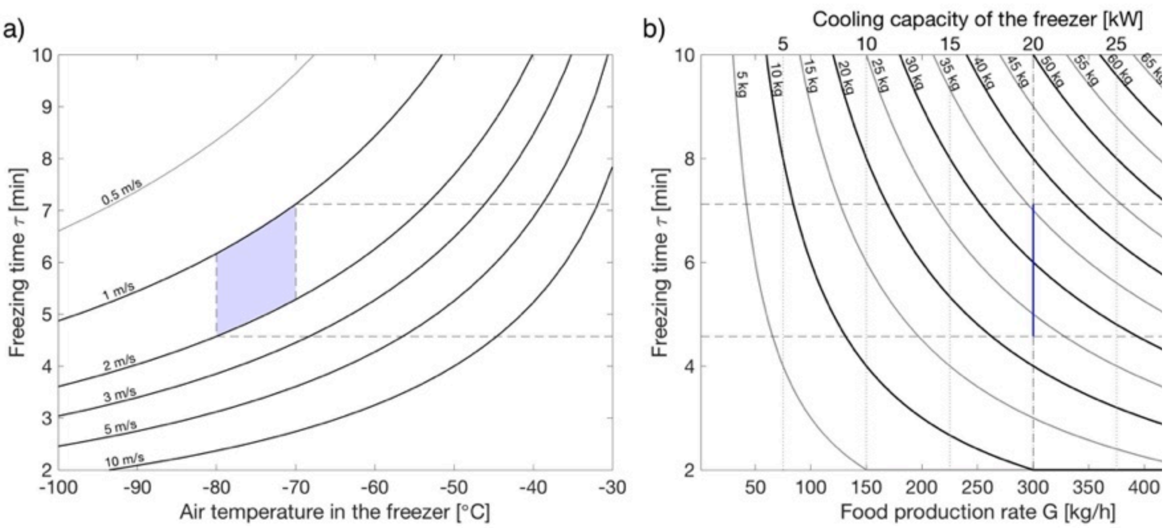

Figure 3. Potato dumplings freezing time τ as a function of medium temperature T_m and velocity v_m (a), and as a function of food production rate G and freezer cooling capacity Q (b).

For example, the blue area indicated in Figure 3a is representative of some combinations of design parameters (air temperature and velocity) that assure a certain freezing time of the food potato dumplings. The freezing time is linked to the cooling capacity and food production rate in second chart (Figure 3b).

In particular, the time τ required to process the potato dumplings from an initial temperature of 15 °C to a final temperature of -25 °C, was evaluated with an air temperature T_m and velocity v_m and varying within the ranges [-80, -70] °C and [1, 2] m/s respectively. The resulting freezing time for potato dumplings, with the operative ranges reported above, results to be in the range [4, 7] minutes. It should be noticed that, for low air velocity values, a reduction in the air temperature involves a significative decrease in the freezing time.

The second chart can be used to size the freezing room in terms of capacity and batch lot. With the aim of freezing 300 kg/h of potato dumpling (blue line in Figure 3b), ensuring the freezing time reported in Figure 3a, the suitable cooling capacity of the room resulted to be equal to 20 kW. Once the range of freezing time τ (highlighted by horizontal dashed lines in Figure 3a and 3b), obtained by the proper trade-off between values of T_m and v_m, has been determined, the most adequate batch lot size, in term of mass of potato dumplings, can be obtained (iso-mass curves in Figure 3b). Processing the potato dumplings in the freezing room with air temperature in the range [-80, -70] °C and air velocity in the range [1, 2] m/s, the size of the batch lot M resulted to be in the range [22, 35] kg. According to the results of Figure 3, trolley and freezer room to host potato dumplings were selected and designed respectively (Figure 4).

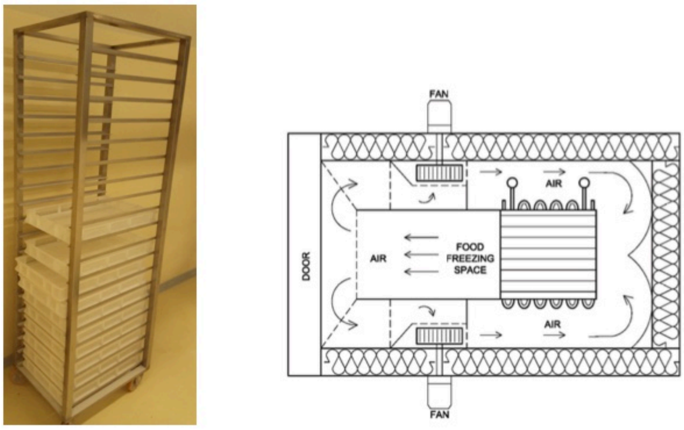

Figure 4. Trolley to host potato dumplings (a) and section of the designed freezer room (b).

Reversed Brayton cycle

The energy performance of the reversed Brayton cycle has been studied by means of a performance analysis. The results of the performance analysis, considering the main thermodynamic parameters influencing the cycle performance, are shown in Figure 5. Given a fixed cooling capacity of the freezer room, 20 kW as shown in Section 3.1, the temperature difference of the dry air in the CHX (Figure 5a) affects the mass flow rate of the cycle and, consequently, the size of the cycle's components. The maximum pressure of the cycle (Figure 5a), the TB isentropic efficiency and RHX effectiveness (Figure 5b), given a fixed temperature at the inlet of the freezer room, affect the TB expansion ratio and, consequently, the mechanical work produced in the bootstrap unit and the required mechanical work (electric motor) to drive the primary compressor.

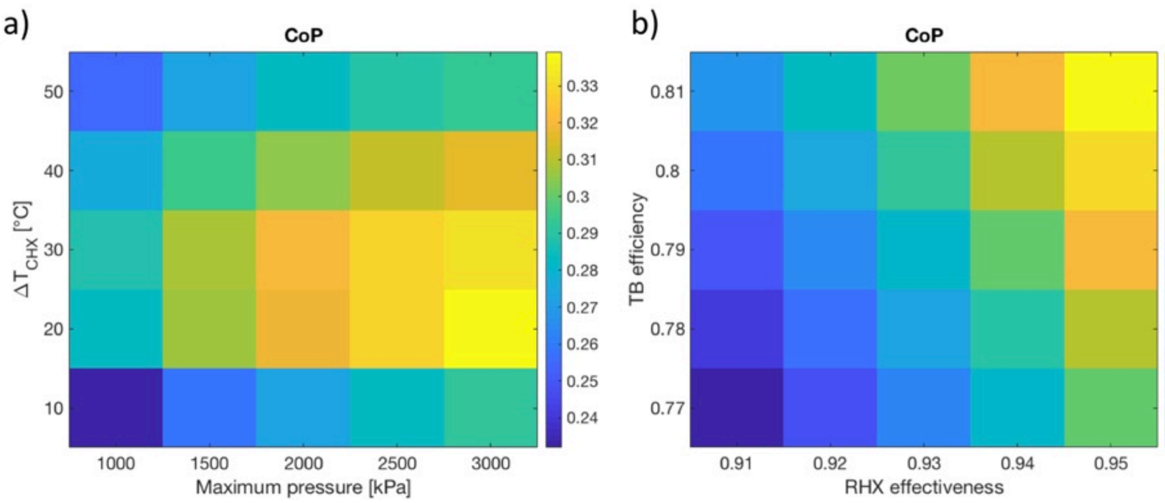

Figure 5. Reversed Brayton cycle performance: Effect of the maximum pressure and temperature difference in CHX (a) and effect of the RHX effectiveness and TB isentropic efficiency (b).

According to the performance analysis results and to real datasheet of the reversed Brayton cycle components, the thermodynamic states (temperature and pressure) of each cycle node of the best operating conditions of the reversed Brayton cycle is reported in Figure 6.

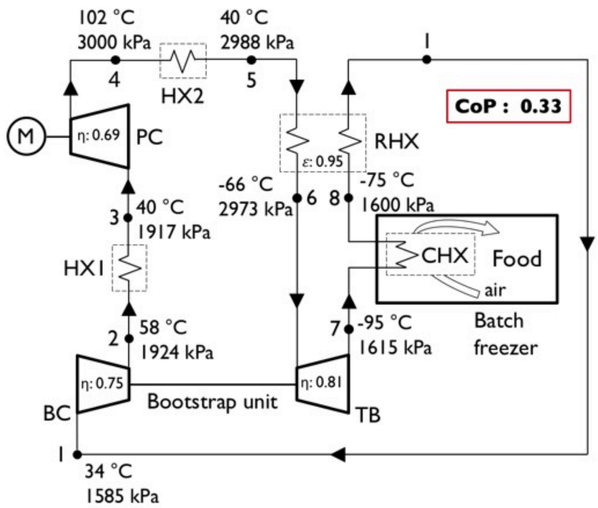

Figure 6. Results of the performance analysis of the reversed Brayton cycle.

The resulting values of the dry air mass flow rate, mechanical power of the turbo machineries and of the heat exchangers, and coefficient of performance are reported in Table 2.

Table 2. Specifications of the reversed Brayton cycle for food freezing.

Parameter	
Dry air mass flow rate [kg/h]	3176
Turbine mechanical power [kW]	23
Bootstrap compressor mechanical power [kW]	21
Primary compressor mechanical power [kW]	60
Cooling capacity in the freezer room [kW]	20
Capacity of heat exchanger, HX1 [kW]	16
Capacity of heat exchanger, HX2 [kW]	59
Coefficient of performance	0.33
Global coefficient of performance	1.58

The maximum and minimum temperature of the cycle account for 102 °C and -95 °C respectively. It should be noted that, 16 kW of heat (HX1) can be recovered from the cycle at low temperature (< 60 °C) while 59 kW of heat (HX2) can be recovered at medium-low temperature (< 100 °C). This amount of heat could be used for space heating and/or food processing, allowing a global coefficient of performance equal to 1.58 to be achieved. The mechanical power of the turbine is larger than the mechanical power of the bootstrap compressor to balance mechanical losses of the bootstrap unit. Mechanical power of the primary compressor takes into account the electric motor efficiency. The coefficient of performance, without heat recovery, was found to be 0.33.

Considering an electricity cost of 18 c€/kWh, a running cost of 55 c€ per kWh of cooling energy has been estimated for the proposed innovative freezing plant.

Conclusions

The design of an innovative food freezing plant has been presented. The innovative freezing plant is based on a reversed Brayton cycle where the cooling energy is produced and a freezing room where the potato dumplings are frozen. The proposed freezing plant is able to run at very low temperatures (< -70 °C) which guarantee fast food freezing into the freezing room. In addition to the 20 kW of cooling capacity at low temperatures in the freezer room, the reversed Brayton cycle allows 75 kW of heat to be recovered at medium-low temperatures in the heat exchangers HX1 and HX2.

The CoP of the reversed Brayton cycle, without heat recovery, resulted to be 0.33 with a running cost of 55 c€ per kWh of cooling energy. The global CoP, including heat recovery, was found to be 1.58. The freezer room allows a production of 300 kg/h of frozen potato dumpling with a batch lot of 25/35 kg.

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