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Hard candy cooling: Optimization of operating policies considering product quality

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ABSTRACT

To guarantee acceptable hard candy quality during the cooling stage, the distribution of the product's temperature throughout the cooling tunnel must be controlled. Hence, the product's quality depends on the operating conditions of the cooling process and the air conditioning system. In this paper, hard candy quality, operating policies and production planning are integrated in an NLP optimization mathematical model to obtain optimal operating polices under different operating modes, minimizing the annual cost. The resulting model is applied in different case studies in which the production of one, and then six products, is analyzed considering different levels of production, demand and conveyor belt capacities. The study also considers different operating conditions for the air conditioning system under three possible operating modes during the year.

1. Introduction

The cooling stage during the production process of hard candies is one of the most critical unit operations because many quality problems, such as deformation, fragility and aggregation, may appear at this stage. Fig. 1 schematically shows the required unit operations for the hard candy production process. As illustrated in Fig. 1, the cooling tunnel has two air ducts (entrance and exit) and is composed of three conveyor belts (CBs), which are mechanically driven by an engine connected to an adjustable frequency drive (AFD) to vary the residence time of the candies. While the candies are moving along the tunnel, they come into contact with cooling air (CA), which flows parallel to the belts.

Air cooling velocity is regulated by manipulating the operating speed range of the fan. In contrast, the air cooling temperature is set up in a heat exchanger (HE) using auxiliary utilities (cooling/heating), as shown in Fig. 1. The operating conditions of the heat exchanger depend on the air temperature and the optimal value of the cooling temperature.

The heat exchanger feed is formed by mixing (or not) two available streams into a mixer (M1): the cold water stream (CW) from the cooling tower and the hot water stream (HW), which is also used at the tempering stage to temper a stretch of the stainless steel belt. The proportions of the mixture will depend on the model restrictions and the seasonal conditions, which will change the input variables of the cooling tower and, therefore, the temperature of the cold water stream.

As shown in Fig. 1, an alternative air recycling stream at the exit duct is also included in the air conditioning system, which increases the available degrees of freedom to conveniently adjust the operating variables (fluxes and temperatures) and to also reduce the operating costs.

From the point of view of product quality, the size of the hard candy, production level, the dimensions of the cooling tunnel, the temperature and velocity of cooling air, and residence time of the candies inside the tunnel play critical roles in the cooling efficiency. For example, a high air velocity may lead to a non-uniform temperature profile, which increases the product's fragility and causes the production of misshapen candies and their consequent rejection, resulting in significant financial losses. In contrast, higher candy temperatures at the end of the tunnel and incorrect residence times lead, respectively, to deformation and the candy aggregation. Therefore, the operational mode of the cooling tunnel is crucial for the final candy's quality.

Higher product quality is definitely obtained when the tunnel is operated in such a manner that the difference in temperature between the center and the surface of the candy is minimized (the more uniform transient temperature behavior), ensuring an appropriate temperature for the wrapping stage (28–40 °C).

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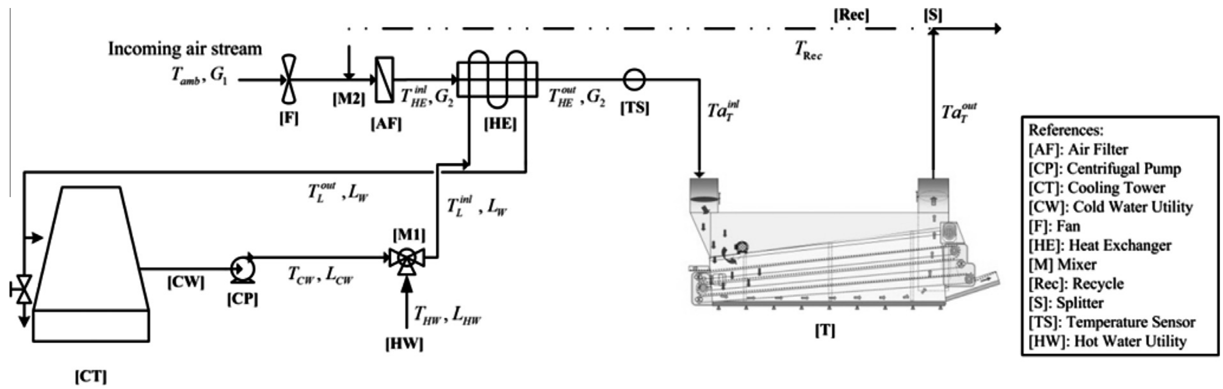

Fig. 1. Flow sheet of the air conditioning system coupled with the cooling tunnel.

Temperatures higher than 40 °C lead to stickiness or deformation problems (non-conforming products). In contrast, temperatures lower than 40 °C lead to higher residence times, requiring an "infinite" length cooling tunnel. Finally, the thermo-physical properties of the products and their composition also influence the product's quality (Reinheimer et al., 2010).

The aim of this work is to present an optimization model to solve a dynamic optimization problem for the revamping of a hard candy production line and taking into account a measure of the product's quality. The dynamic optimization model is based on a previous work in which the operating conditions of the cooling tunnel were optimized to minimize hard candy temperature differences, which are, in turn, associated with quality problems (Reinheimer et al., 2012). The model proposed in that article is now properly extended to include a quality model, which explicitly penalizes product rejection in the economic objective function. The model is also extended to determine the operating schedule of the cooling tunnel to manufacture six different types of hard candy products (of different flavors) as a function of the product demand throughout a time horizon of 1 year. Thus, the trade-offs associated with product quality, temperature difference profiles, production level, and production and reprocessing costs are simultaneously optimized. The annual production has been divided into three distinct seasons: defined as winter ($k = w$), summer ($k = s$) and mid-season ($k = m$). Therefore, three different scenarios or operating modes have been investigated in relation to the seasonal operating cost. The model can be used for operation planning and for the optimization of the operating conditions when a revision of the existing line (production increment) must be satisfied. Candy size and composition, ambient air properties, heat transfer area, and operating costs are the main input data for the optimization model. In this case, the heat transfer area of the heat exchanger, the air duct section in the cooling tunnel, and the capacity of the cooling tower are fixed because the equipment already exists.

The resulting model is implemented in GAMS (General Algebraic Modeling System) and solved using CONOPT, a local optimization algorithm based on the reduced gradient method.

2. Assumptions and mathematical model

2.1. Assumptions

The main assumptions of the model can be summarized as follows:

- Candies are considered homogeneous and isotropic spheres.
- Model 1-D. Temporal variations of the temperature in the radial direction are considered.
- Choi and Okos' models (1986) were used for the estimation of thermo-physical properties, such as density, thermal capacity, and thermal conductivity.
- Variations in thermo-physical properties with temperature are neglected for the temperature range considered in this work.
- There is no moisture loss. Due to the low water content of hard candy (2.5%), water loss during the cooling of candies is insignificant. Accordingly, moisture intake from the air is also negligible because air humidity is monitored, and profiles can be considered constant between the values at the tunnel entrance and exit.
- Changes in air humidity are small enough to produce a negligible effect on the thermo-physical properties of the air. The properties of air flow are calculated as the average temperature of the cooling air flow stream.
- The convective heat transfer coefficient is computed as the area averaged value of the local heat transfer coefficient (Becker and Fricke, 2004).

2.2. Mathematical model

The complete mathematical model includes the heat transfer model (energy balance of the unsteady heat transfer process), including the corresponding boundary conditions, the air conditioning model, and the equations necessary to compute the enthalpies and physical properties of the air, which are described in detail in Reinheimer et al. (2012).

In this section, the main constraints that were coupled into the previous model and that are related to the proposed cost model for flavored hard candy products are presented. The actual model is based on the following two indexes: k and i which are used, respectively, to refer to the season ($k = w,s,m$) and type of hard candy product (i = 1–6).

Seasonal capacity, production, and operating cost are calculated to achieve annual production capacity constraints. Different seasonal production plans can be obtained according to the operating modes selected for the proposed objective function (minimizing the annual operating costs).

As mentioned earlier, the maximum temperature difference between the center and the surface of pieces of hard candies is associated with fragility problems during the wrapping stage. As can be observed from previous results (Reinheimer et al., 2012), the risk of product fragility is high at the beginning of the cooling process because the temperature difference reaches its maximum value and then decreases slowly.

Hence, a quality variation constraint, defined as the product rejection rate, φ, is included in the optimization model. The type of function was adopted considering historical data for the product rejection rate due to fragility problems, which are closely related to