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More efficient mushroom canning through pinch and exergy analysis

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ABSTRACT

Conventional production of canned mushrooms involves multiple processing steps as vacuum hydration, blanching, sterilization, etc. that are intensive in energy and water usage. We analyzed the current mushroom processing technique plus three alternative scenarios via pinch and exergy analysis. The product yield, utility use, exergy loss, and water use are used as sustainability indicators. Whilst rearrangement of the production process could maximally save up to 28% of the heat input and up to 25% of the water usage, the most important improvement is obtained by re-using blanch water, which improves the overall yield of the preservation and canning process by 9%, also saving water and exergy use in the production.

1. Introduction

The production of canned food products is energy intensive, since these foods need to be blanched, sterilized and cooled. Canning mushroom involves vacuum hydration of the highly porous mushrooms, blanching and sterilization that are energy and water intensive. It is therefore useful to investigate alternative process schemes that may reduce the use of energy and water.

Pinch technology summarizes the distributed use of a resource such as heat in a complex process in one simple diagram. The insights resulting from this can be used for designing a new process system, or for modification of an existing process (Feng and Zhu, 1997). The analysis determines a pinch point based on the minimum driving force (with heat, the minimum temperature difference, ΔT_{min}) that is needed to achieve a certain rate of transfer between streams. The minimum amounts of the external utilities in a production system, are estimated with the help of a quality-quantity diagram (in case of heat, temperature–enthalpy) known as the composite curve.

While the simplicity is the greatest strength of pinch technology, in general, it deals with one process resource at a time, such as heat, mass, water etc., and cannot deal with several resources at the same time (Apaiah et al., 2006; Aspelund et al., 2007). For example, heat pinch only uses temperature as quality parameter neglecting other parameters such as changes in pressure and composition of the streams, which often are quite important in food production.

Exergy analysis can do this. The monitoring of the use of resources through heat and mass balances, based on the first law of thermodynamics, has been used for several years to reduce both the use of energy and resulting environmental emissions. Feng and Zhu (1997) called this approach “at the best incomplete and at the worst wholly incorrect” as this does not consider that resources have different qualities at different stages.

The quality of a resource can be expressed in terms of its ability to be used, or in terms of its capacity to do work, by exchange with the environment. As an example, the quality of heat depends on its temperature: the higher the temperature it has, the more can be done with it. If a high-quality heat source is used to heat another stream, the temperature is reduced, and its quality is decreased. Energy sources such as electricity, and chemical energy have a higher ability to do work than the energy contained in other sources such as the exhaust heat that is emitted through a chimney (Jankowiak et al., 2014). Likewise, also material streams and other resources can be assigned an exergetic content, which also give a quality to these streams. Unlike pinch technology, exergy analysis does not identify solutions but can be used to compare the exergetic efficiency of alternative scenarios (Zisopoulos et al., 2015).

The evaluation of the process efficiency by using pinch or exergy analysis is relatively novel in the domain of food processing, but well established in other fields, such as the chemical industry, and mechanical and energy engineering. In this work, both techniques are used to evaluate the efficiency of the use of resources. We

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typically see that the techniques complement each other well.

First, we analyze the current canned mushroom production system, via a detailed analysis of the mass flows, plus the exergy flows during the production of canned mushrooms. Each unit operation is evaluated both in terms of their energy and exergy efficiencies. We then propose three different alternative routes for canned mushroom production. The yield value of each alternatives is used to calculate the amount of raw mushroom that has to be processed to get the same amount of final product. The minimum heating and cooling requirements to process raw mushroom for each of the alternatives are evaluated using pinch technology. Similarly, water and exergy need of the alternatives are also calculated. The production scenarios are compared based on their product yield, water consumption and exergy losses to find a more sustainable alternative for production of canned mushroom.

2. Materials and methods

The data of the current production of canned mushroom used in this study was obtained from Lutèce, located in Horst, The Netherlands. For process simulation experiment, white button mushrooms (*Agaricus bisporus*) with a cap diameter of 4–5 cm were used for all the production simulation experiments. The mushrooms were received within 2 h of their harvest. The blanch water was obtained from Lutèce. The brine solution contained 2% sodium chloride and 0.5% citric acid (pH 3) (Vivar-Quintana et al., 1999).

2.1. Process simulation experiments

Mushrooms were vacuum impregnated with water at room temperature after their receipt. The mushrooms were first evacuated in a vacuum chamber below 100 mbar. The mushrooms were then hydrated by supplying tap water into the chamber and releasing the pressure. The mushrooms stayed immersed for 5 min for sufficient hydration. The vacuum hydrated mushrooms were then blanched at 90 °C for 15 min by submerging them in a temperature controlled water bath. After blanching, the mushrooms were cooled to room temperature in cold tap water. The mushrooms were sliced and filled in a 300 ml cylindrical glass jars with 2.8 cm diameter and 12 cm height. A brine solution was added to achieve a 1:1 vol ratio of sliced mushroom and brine water. Finally, sterilization was carried out at 126 °C for 15 min. The canned mushrooms were allowed to stand for one day before their drained weight was measured. The contents of the cans were drained in a sieve for 2 min. After draining, the remaining weight was measured, and expressed in the yield of canned mushrooms as

$$\%yield = Y_b \times Y_c \tag{1}$$

in which Y_b is the weight ratio of blanched mushroom to the fresh mushroom and Y_c is weight ratio of canned to the blanched mushroom.

2.2. Pinch analysis

Pinch analysis on heat was carried out following the procedure described in literature (Feng and Zhu, 1997; Foo, 2009; Ian, 2010). All streams were divided into two types: hot streams that should be cooled down, and cold streams that should be heated to a certain temperature, based on the change of enthalpy required in these streams. The minimum temperature difference for heat transfer (ΔT_{min}) was selected to be 10 °C to ensure an adequate driving force for heat transfer. A Grand Composite Curve (GCC) was constructed in a temperature–enthalpy (T-H) diagram, which was used to estimate the minimum heating and cooling utilities needed to produce the canned mushroom in the current situation and under the various proposed methods.

2.3. Exergy analysis

The total exergy of a stream is the sum of its chemical and physical exergy. The chemical exergy is the exergy that is involved in creating the chemical components from a standardized environment, while the physical exergy includes the exergy that is needed to bring those substances to their temperature, pressure and mechanical conditions, starting with those in the standardized environment. In our standardized environment, we adhered to the definitions by Szargut (1989), choosing a temperature and pressure of 25 °C and 1 bar, respectively.

The chemical exergies were calculated as:

$$B_{Chem} = \Phi \sum (b_{o,i} x_i) \tag{2}$$

in which $b_{o,i}$ is the specific chemical exergy (MJ/kg) of components, x_i is the mass fraction of the components and Φ is the size (flow rate) of the stream. The values of $b_{o,i}$ are adopted following Szargut (1989).

The thermal exergy is calculated following Bösch et al. (2012) with

$$B_T = \Phi\, Cp \left[(T - T_0) - T_0 \ln\left(\frac{T}{T_0}\right) \right] \tag{3}$$

in which B_T is defined as the exergy due to a different temperature than that of the standardized environment, Cp is the specific heat capacity, T is the temperature of the stream, and T_0 is the temperature of the standardized environment (25 °C). The pressure exergy (of for example steam) was calculated as:

$$B_P = \Phi \frac{RT_0}{M_W} ln\left(\frac{P}{P_0}\right) \tag{4}$$

in which R is the universal gas constant, P is the pressure of a stream, P_0 is the pressure of standardized environment (1 atmospheric pressure) and M_W is the molecular weight of substance.

In principle, the exergy change involved in mixing the chemical compounds needs to be incorporated, however, in systems consisting of mostly biopolymers, its value is very low compared to that of other contributions, and we may safely neglect it in our calculations. Only in the brine solution the exergy of mixing is significant, and there was calculated as:

$$B_M = N_{tot} R T_0 \sum (x_i ln(a_i)) \tag{5}$$

with N_{tot} the total number of moles in the stream calculated from the molecular weight and a_i the activity of component i, which is calculated by finding the activity coefficient using the extended Debye-Hückel relation (Davies et al., 1952) as described earlier (Paudel et al., 2015).

2.4. Sustainability indicators

The unit operations involved in the current production of canned mushroom were evaluated with thermodynamic law efficiencies; the so called first law efficiency (FLE) and the second law efficiency (SLE) as follows.

$$FLE = \frac{theoretical\ energy\ need}{actual\ energy\ input} \tag{6}$$

The FLE values of unit operations calculated in the current