Fuzzy Controller for Liquid Nitrogen Cryogenic Freezer

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Abstract: - The paper presents an automation system for a liquid nitrogen cryogenic freezer for quick freezing of meat products, using both the evaporation latent heat of liquid nitrogen and sensible heat of the nitrogen vapor. The suggested automation design solves the problem of automatic control of the conveyor speed. The dynamic model gives data using computer simulation. This equipment was designed by the principal author and is fully operational at the Thermal Engines Department, “Dunărea de Jos” University of Galați.

Key-Words: - Nitrogen, cryogenic freezer, fuzzy set, controller, meat products.

1 Introduction

Quick freezing of meat products in a cryogenic freezer consists in the use of evaporation latent heat of the liquid nitrogen, as well as of the sensible heat of the vapors, whose temperature increases up to final temperature of the frozen product. The use of cryogenic freezing with liquid nitrogen and carbon-dioxide is regarded as the “century revolution” in the food area.

The quality of the quick frozen products is superior compared to vapor compression system products. Because today's competition in the food international market concerns more the quality level than the price, quick freezing systems have continuously developed since 1960 in the USA and then in Europe.

This procedure ensures better quality of food’s taste and reduces losses due to dehydration, and longer shelf life of the processed food [1, 2]. This form of freezing is versatile and therefore it allows different high variety food production. For example, in France (1988) the frozen products consumption was 25.9 kg/year, from which 2 kg were cryogenically frozen. Therefore, needs to carry out research in this field in Romania, too. Our work is based on [3-6] and in the section 2 we give a short description of our freezing system. In section 3 we address the automatic adjusting of the freezing system and the fuzzy controller which monitories the process is described in section 4. Section 5 summarizes the present work and gives some concluding remarks.

2 Cryogenic freezing system

The cryogenic freezer is shown in **Error! Reference source not found.**, and has the following features: hourly freezing capacity: 110-120 kg; dimensions: 5220 x 750 x 1450 mm; weight: 500 kg; the temperature of frozen product: -18 ^{0}C; the length of conveyer band: 4.2 m; speed of the band: 0.44 m/min; freezing time: ≈ 10 min. Based on the tests carried out on a pork product with a constant thickness (25 mm), one found out that the thermal core temperature of the product ($t_C \leq -18^0$C) was achieved depending on the exhausted nitrogen vapors temperature, for constant freezer capacity and sprayed liquid nitrogen flow-rate can influence the operating condition of the cryogenic freezer in stationary regime are: outside air temperature, fat contents of the product, the distance among products on the band, the blockage of a forced air circulation fan and product thickness.

If the exhausted nitrogen vapors temperature increases, the nitrogen consumption decreases. For a vapors temperature of -30 °C, a -18 °C temperature in the core of product is easily achieved. One considered that the exhausted low temperature nitrogen vapors can be used for cooling a temporary food-bank used for product storage prior shipping.

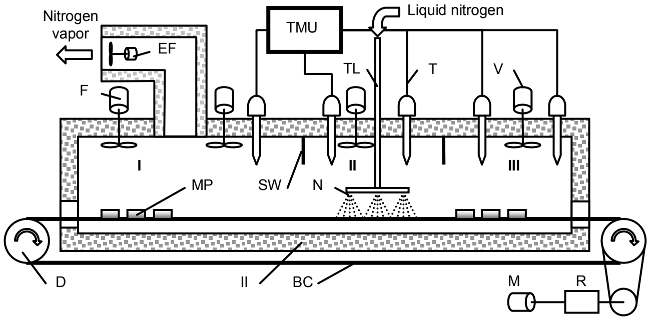

Fig.1. Cryogenic freezer.
M - electric motor; MP - meat product; BC - belt conveyor; R - worm reducer; F - fan; EF - vapor exhaust fan; N - nozzle; SW - separating wall; TL - nitrogen transfer line; D - drum; TMU - temperature measuring unit; T -thermo resistance; I - pre-cooling area; II - freezing area; III - sub-cooling area

The band speed automatic adjusting system has to operate for a temperature interval of -40 to -20 °C, with a - 30 °C reference temperature.

3 Automatic adjusting of the freezing system

The main objective for automatic adjusting system is to assure minimum errors for output parameters, without operator intervention. The goal of the adjusting system is achieved if the disturbances are maintained within the previously known limits. The objective, structure and operation mode of the adjusting system are presented in the next paragraphs. The regulated target is the cryogenic freezer described in the previous paragraph. The technological purpose is cooling of the product pieces at -18 ^{0}C average temperature, with a small temperature variation inside the product, a maximum productivity and a minimum consumption of cooling agent. Some conditions can be contradictory, so, it is useful to analyze the model of the regulated object, in order to decide the performance limits and required compromises. **Error! Reference source not found.**, schematically shows the following parameters of our experimental device:1. Products thermal core temperature when leaving the tunnel; 2. Products surface temperature when leaving the tunnel;
3. Cooling agent outlet vapor temperature; 4. Productivity; 5. Average temperature of the cooling-room; 6. Band speed; 7. Initial temperature of the cooling agent; 8.Cooling agent flow-rate; 9. Product density on the conveyor band; 10. Size of the product; Initial temperature of product; 11. Initial temperature of the product; 12. Average exterior temperature.

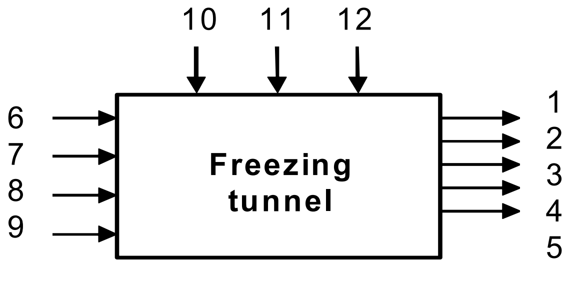

Fig. 2. System's parameters flowchart

The sizes 1, 2, 3, 4 are process controlled conditions. The average temperature in the cooling-room is an intermediate parameter of the model, and 6, 7, 8, 9 are the input parameters. Of them, the cooling agent initial temperature was definitively fixed when the liquid nitrogen was chosen for the cooling process. The product size (10) represents a perturbation parameter, hard to modify (it is technologically given), but easy to measure, in order to choose the average operating point of the tunnel [7, 8]. The product density on the band is also a technological given (the distance between pieces of the product is 10 mm). Therefore, only the liquid nitrogen flow-rate and the band speed can be selected as the execution parameters for the system. The last two parameters are disturbances, the most important being the product's temperature.

From technological considerations, some of the presented parameters have a small variation range. The productivity represents the multiplication between the speed of the band and the density of product on the band; its value is limited by the flow-rate of liquid nitrogen, if we assume a constant product temperature. The nitrogen flow-rate has an optimum value (in stationary regime) imposed by the tunnel parameters and by the main disturbances, meaning, that for certain product dimensions and for an initial temperature, there is a limit value above where the productivity does not increase [9, 10]. Because the productivity and the efficiency are main parameters for the equipment, it is important to choose an operating point for which the agent flow-rate is close to the optimal one, and the band speed provides the specified outlet product parameters. Product size and inlet temperature are major disturbances, but average exterior temperature is not.

Therefore, in order to achieve its goal, the adjusting system can operate under the following conditions:

- there is a static operation point, chosen considering the efficiency and productivity, that depends on the product dimensions and initial temperature;
- the nitrogen flow-rate and speed of the band are the execution parameters;
- the output parameters are the core product temperature, the product surface temperature when leaving the tunnel, and the temperature of the exhausted nitrogen vapors.

- the quality sizes for adjusting control are: the average temperature of the product output from tunnel and the difference between inside and surface temperature of the product.
- The parameters t_1, t_2 are the average output temperature of the product, respectively the output temperature of nitrogen vapor. All these parameters have small variations around the static operating point therefore one can consider a linear behavior of the system. Transfer functions are:

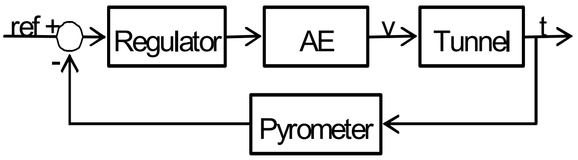

Fig. 4. Speed adjusting flow chart

$$H_1(s) = \frac{K_1}{T_1 s + 1} \tag{1}$$

$$H_2(s) = \frac{K_2 \cdot \exp(-T_{m2} s)}{T_2 s + 1} \tag{2}$$

$$H_3(s) = \frac{K_3 \cdot \exp(-T_{m3} s)}{T_3 s + 1} \tag{3}$$

$$H_4(s) = \frac{K_4 \cdot \exp(-T_{m4} s)}{T_4 s + 1} \tag{4}$$

The time constants are about a few minutes (T_1 = 3…4 min, T_2 = 4…8 min T_3 = 3…4 min). The delay T_{m2} is relatively small (below 10 sec) while T_{m3}, T_{m4} are between 20…40 sec. Model identification is done each time by the product density on the conveyor band and the inlet temperature. Nevertheless, the variations of these parameters are relatively small. Considering that the nitrogen flow-rate influences on both measurable parameters by means of the delay time, and also the difficulty of regulating this flow-rate we choose as the sole execution parameter the speed of the band. The adjusting scheme is presented in Fig. 4 where the controlled parameter is the required product surface temperature when leaving the tunnel, computed (when starting the tunnel) from the required average temperature and the estimated temperature gradient. AE is the motor automation and the pyrometer is the transducer for measuring the external temperature of the product.

Regulator speed control transfer function is:

$$H_R(s) = K_P\left(1 + \frac{1}{T_1 s}\right) \tag{5}$$

The size of the integration time constant is also a few minutes, in order to compensate the main time constant of the H1 function. The temperature regulator is a standard one, used for slow processes, but we can also use a numerical one, with the possibility of recording the stationary regime values, characteristic for each perturbation range; in order to measure the surface temperature of the product when leaving the freezing tunnel, the pyrometer is placed above the conveyor belt, closed to it, aimed to the product surface, as shown in Fig. 5. The time constant of the pyrometer is very small and we may neglect it.

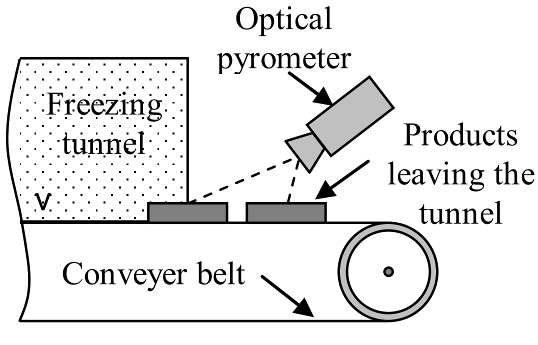

Fig. 5. Products' surface temperature measurement

4 Fuzzy controller for freezing system monitoring

As we mentioned in the previous section, the controller is responsible for production scheduling by maintaining the temperature profile constant through the tunnel length at a given conveyor speed, e.g. production throughput. We model the controller's job by considering the following production plan:

a) We consider that our system shown in Fig.…has to deal with n types of parts, e.g. fish, slices of meat, etc.

b) The processing time of each part is denoted as t_i and is also the time necessary for one part to travel

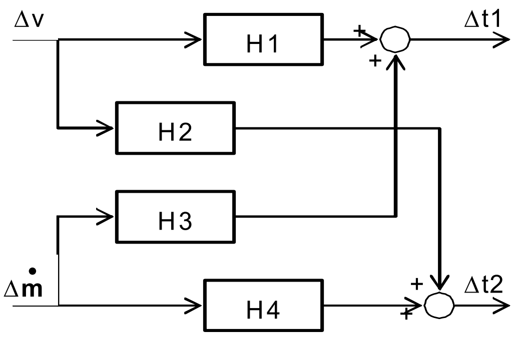

Fig. 3. The simplified dynamic model

through the tunnel freezer, equal to ll/v, where ll is the length of the freezer area and v is the speed of the conveyor (see Fig.1). The throughput rate r_i for part I can be computed using the following relation:

$$r_i = \frac{N_{t_i}}{t_i} = \frac{N_{t_i}}{ll} \cdot v \qquad (6)$$

Where $t_i = \frac{ll}{v_i}$, with v_i the speed of the conveyor for part i, i=1, …, n. We assume that each part type is characterized by a certain speed of the conveyor, e.g. is characterized by a certain residence time in the tunnel freezer and parts are sorted on slot of types before processing.

We model our system as a discrete event system, e.g. we consider that our system is driven by events. The main events we meet in the system are the following ones:

1. Set the next part to be processed
2. Set the speed of the conveyor according to the part type to be processed

If more than one of part type exists, then we shall sort the parts on types (e.g. the sort of meat, the dimensions of meat slices, etc) and then the system chooses the first one according to the following decision factors:

a) The vulnerability of the part types
b) The number of part types
c) The market demand
d) The processing time t_i, i = 1, …, n.

We can easily see that these events form a criteria decision problem similar to Multi – Attributive Decision Making (MADM) problem [11]. From all the criteria, we shall determine the solution which ensures the best throughput for the system. To solve this problem, we address a modified version of Yager's formulation, where a fuzzy representation for criteria and a crisp representation for criteria significance are used [12].

In order to calculate the control action, we adopt the following strategy:

1. Determine the error and the error's rate of variation;
2. Translate the error values into fuzzy variables;
3. Use the rule of inference for determining the decision rules;
4. Find the deterministic input of the controller used for controlling the freezing system.

We use the following fuzzy primary terms for the measured values of error and its variation: VL = very low; L = low; SL= slightly low; Z = zero; SH = slightly high; H = high; VH = very high. These linguistic values are represented by functions with four discrete values in the interval [0, 1] associated with 15 discrete values of the scaled variables in the interval [-1, 1].

As we well know, the Yager method involves the implication c→ s_c, where c is the criteria vector and s_c is the significance of criteria under consideration. In order to apply the Yager's method we shall list the criteria, e.g. criteria's priority, in Table 1 and the significance of criteria, e.g. the preference scale, is given in Table 2.

Table1. Criteria and their priorities score

Criteria	Priority score
Vulnerability of type parts	1.0
The number of part types	0.8
The market demand	0.6
The processing type	0.7

Table 2. The significance of the criteria from Table 1

Attribute	Numerical equivalent
Very low (VL)	-1.0
Low (L)	-0.8
Slightly low (SL)	-0.5
Zero (Z)	0
Slightly high (SH)	0.5
High (H)	0.8
Very high (VH)	1.0

Using these values, the fuzzy decision algorithm used in this work is fairly described as follows:

1. Calculate the membership grades that represent the degree of importance of each criterion C_i, i = 1,…, n.
2. Generate the fuzzy set C_i.
3. Determine the membership grades in the fuzzy set and arrange them into an upside-down tree structure, T_j, j = 1, …, m.
4. Determine the decision fuzzy set D_k, $j \leq k \leq i$ by the intersection of the sets C_i and T_j: $D_k = (C_i, \min T_j)$, i = 1,…, n; j = 1, …, m.
5. Determine the alternative C^* with the most significant grade of membership in the fuzzy set:

C^*: $\mu(C^*) = \max_i \mu(C_i)$, i = 1, …, n.

6. The composition rule determines the output value through the inference process of the fuzzy rules, including the backup alternative: $\mu_{result} = \min_k [D_k, C^*]$, $i \leq k \leq j$, I = 1, …, n; j = 1, …, m.
7. After the inference process is completed, the center of mass de-fuzzification method is applied, in order to determine a numerical value from the fuzzy controller for the production (freezing) system.

In order to test our approach, we consider a set of production orders, each of them characterized by the number of parts of different type, by the due date and by the assigned priority. An initial set of orders was randomly generated. In the production process demand rates are updated up to the necessary set of orders under production. We used for implementing the fuzzy controller the MCHC11F1 microcontroller. The simulation performed in our laboratory using the device described earlier is shown in Table 3.

Table 3. The match operations with the laboratory experimental device (operations e.g. type of meat), time expressed in seconds

Match	Type of meat/time [s]
1.	pork (2 cm thickness) / 11
2.	pork (4 cm thickness) / 16
3.	pork (6 cm thickness) / 21
4.	pork (8 cm thickness) / 30
5.	pork (10 cm thickness) / 40
6.	fish: tuna (2 cm thickness) / 10
7.	fish: tuna (4 cm thickness) / 12
8.	fish: tuna (6 cm thickness) / 16

5 Conclusion

Our automation design partially solves the problem of conveyor band speed adjusting. To fully solve the problem we need to use the cooling agent outlet vapor temperature as a control input. Time constants can be found out during testing [13, 14]. The simplified dynamic fuzzy model of the controller allows performing easily various computer simulations and further investigations could improve the present model. Some aspects regarding experimental work in our laboratory are shown in the pictures below.

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