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MASTER DEGREE THESIS

Mathematical Modeling and Control System Simulation of the Batch Canned Food Sterilization Processes

By

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CERTIFICATION

I, Associate Professor Jia Shi, hereby certify that I have read this manuscript and recommend for acceptance by the Xiamen University a dissertation entitled "Mathematical Modeling and Control System Simulation of the Batch Canned Food Sterilization Processes" in fulfillment of degree of Master of Engineering at Xiamen University, People's Republic of China.

Signed………………

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ORIGINAL STATEMENT

The research described in this thesis Masters of Engineering was conducted under the supervision of Associate Professor Jia Shi at the Department of Chemical and Biochemical Engineering, Xiamen University. I hereby declare that the work submitted is my own and that appropriate credit has been given where reference has been made to the work of others. I also confirm that it has not been previously or concurrently submitted for any other degree, diploma or any other qualifications at Xiamen University, P.R China or other institutions.

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ABSTRACT

Abstract: Batch process is one of the most important industrial processes due to its advantages in various aspects of production and has thus been largely applied in many industries including the bioproducts, fine chemical and food industries. Moreover, the progress in both the application and control of batch processes in the food industry has been significant. Steam retort canned food sterilization is an important production process in the food processing industry and is considered to be the most common process in modern industrial sterilization. The process has multi-variant, nonlinear characteristics and is also an energy consuming production process, hence the significance of doing extensive research on its modeling, simulation and control so as to be able to assure the safety and quality of thermally processed canned foods and improve the efficiency and controllability of the process. The details of the work that was done are presented in this thesis as follows:

In the first place, a mathematical model of both the retort and the can systems is presented the model, which is a dynamic model of sterilization process, is built based on the principles of mass and energy conservation, and it composed of these two subsystems which are connected by mass and heat transfer. In the situation where the dynamics of valves is not negligible and the automatic control valves are regulated by a controller (which regulates steam and water valves) during the heating stage and (which regulates air and vent valves) during the cooling stage, the main actuators of the process are also modeled.

Secondly, in order to study the control problems correlated with tracking pressure and temperature profiles in a batch retort and improve the performance in different stages of the sterilization process, control strategies have been presented by employing a simple proportional integral and derivative (PID) controller, which is the most common control technique in the industry. A PID controller scheme is further developed for temperature and pressure control, the output from the controller drive two final control elements by using split range control logic. The proposed scheme was implemented on MATLAB/SIMLINK platform and the simulation results show the effectiveness and better performance of the control configuration for pressure and temperature control. Finally, the shortcomings are discussed and analyzed on the basis of the dynamic model.

Keywords: sterilization process, control strategy, batch steam retort, PID controller, split rang PID control

摘要

摘要: 批次生产（加工）是现代工业的一种重要生产方式，在产品制造（加工）方面具有许多突出的优点。目前，该生产方式广泛应用于生物产品加工、精细化工以及食品工业。特别是在食品加工行业，批次生产过程的应用以及相关控制技术已经取得了显著的进展。在食品加工行业中，罐头食品的高压灭菌过程既是一道关键的生产工序，同时也是一个典型的批次生产过程。该生产过程既具有多变量和非线性特点，同时也是一个高能耗的生产过程，因此针对该类过程的建模，仿真以及控制技术的研究，对于保证生产过程的安全、产品的质量以及过程的能效以及可控性都具有十分重要的意义。针对于该过程，本论文进行的主要研究工作如下：

首先，基于物质很能量守恒原理，本论文对罐头食品高压灭菌过程全系统进行了数学建模，所获得的过程动态模型由灭菌锅和罐头两个子系统组成，子系统之间通过热量传递关联。同时，考虑到实际生产系统中必须通过调节阀门来实现升温和降温过程的自动控制，因此对于生产过程中的主要执行机构也同时进行了数学建模。

其次，针对于高压灭菌过程不同生产阶段的温度和压力期望轨迹跟踪控制问题，本论文首先研究并仿真了工业过程中常用的 PID 控制策略。在此基础上进一步提出了采用分程控制策略的 PID 控制方案，并在 MATLAB/SIMULINK 构建的仿真平台上对该控制方案进行了仿真。仿真结果表明，对于压力和温度控制来说，这是一种更有效的控制方案。最后，论文还对该控制方案的优缺点进行了讨论和分析。

关键词：蒸汽灭菌过程，控制策略，蒸汽灭菌锅，PID 控制器，分程 PID 控制

LIST OF ABBREVIATIONS

GA	Genetic Algorithm
CRT	Constant Retort Temperature
ILC	Iterative Learning Control
IMC	Internal Model Control
MIMO	Multiple input multiple output
PI	Proportional Integral
PID	Proportional Integral and Derivative controller
RHC	Receding Horizon Control
MPC	Model Predictive Control
PSO	Particle Swarm Optimization
VRT	Variable Retort Temperature

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Chapter 1 Introduction

1.1 Introduction

Batch process is one of the most important processes in many industries due to its advantages in various aspects of production, and has been largely applied to bioproducts, fine chemicals and food industries. With the demand for quality, batch processes are getting diversified and receiving increasing attention from researchers. Continuous innovation and improvement of processing procedure and its facilities made food processing, and thermal processing in particular, to be confronted with global competitiveness. Moreover, with time, batch mode has become more mature and has acquired a significant role in modern industry and, as it can be seen from the literature in Food Science, thermal processing is very extensive. Most of the references reviewed focused on the study of the processes with microbiological and biochemical aspects.

Sterilization of food processes in industry is an important production process and it is a typical multi-stage batch production process. Currently, there are many popular sterilization methods such as dry heat sterilization, sterilization by radiation, microwave sterilization and filtration sterilization. In these methods of sterilization, high temperature high pressure steam sterilization method is the simplest one because of its good sterilization effect, its sterilization time is short, is simple and easy in operation, it occupies a very important position in production etc. It is a widely used method of sterilization in modern food, pharmaceutical and fermentation industries, and determines the cost of production and product quality throughout the production process. However, the most actual operations of the sterilization process in an industrial production still depend on experience of the worker. Manual operation often results in product quality fluctuations, serious energy overconsumption, low production efficiency, safety risks, and lack of ease of optimization of the entire production process and management. Thus, there is an urgent need to subject such a sterilization process into mathematical modeling, model simulation, and system design and optimization to study different kinds of control in order to achieve automatic control for the running applications' processes to make the production process safer and more rapid. One of the purposes of this thesis is to simulate the actual production of retort canned processes by establishment of a complete sterilization processes dynamic model, based on material and energy balance principles.

From the conservation principle of material and energy balance, mathematical models of retort and can systems were established and linked, and interrelated by heat transfer, both of which constituted a complete mathematical model of a high temperature, high pressure steam sterilization system. Based on this sterilization system model, a simulation and control platform for heating, venting and cooling stages and simulation of overall sterilization process was developed, the model's parameter values for each heat transfer coefficient determined including coefficients of evaporation and condensation, once again, to the simulation platform based on the key variables for process were carried out using Split Range PID controller design and control of the sterilization process.

1.2 Literature review

The food industries are facing critical changes in response to consumers nowadays, which in addition to safety and health awareness, demand an ever larger diversity of food products with high quality standards. On the other hand, these industries are in a permanent quest for new markets and population sectors not accessible before, which immediately translates into the search for more efficient processes, in order to gain market share[1].Even though the literature in thermal processing and Food Science is very comprehensive, yet most of the references deal with the process from the microbiological prospective[2].

Most processes in industry can be divided into two types: batch mode and continuous mode. Nowadays, important processes are executed in batch mode. These run intermittently, have much flexibility in response to market requirements and produce low volume and high value products which are the fundamental reasons of using such operations[3].In the case of liquid or particulate products, the former mode of operation is preferred while the latter is more common in the case of prepackaged solid products. In general, it could be said that although continuous operation is widely and increasingly used at present, batch production has an important place whenever high quality specifications and/or plant flexibility are developing parallel to a growing market complexity where demand requires a wider product spectrum.[4].

In pharmaceuticals, polymer technology, biotechnology and food industry, batch operations function as the heart of process transformation and dominate over continuous. Moreover, drying, fermentation, evaporation, and sterilization, which are important operations in the food industry, usually execute in batches[5]therefore, thermal sterilization in steam retorts it has a significant effect in resent research and as first reasons of choosing this process is that it can be used in almost all industrial of the bioproducts sector and it classify as high energy consumption process. The another reason is that from a control point of view, nonlinearity behavior and uncertainty is a complex dynamic characteristic of sterilization process which make this operation a challenging problem.[6]. In addition to these properties, sterilization is multi-stages operation and all this is influenced by a complex phenomenon of mass and energy transfer in sterilization process. The energy efficiency has significant effect in the whole production cost of industry[7].Process variables at different stage of production interact to determine the production efficiency and product quality [6].

As a limiting stage in the production cycle sterilization goal is, inactivation through the heat of possible spore, microorganism or enzymes present in foodstuffs or bioproducts. This can be done while the prepackaged products put in the retort and steam flowing through it. The degree of inactivation as measured by the microbiological lethality is a crucial for determining the temperature and processing time inside the product furthermore, undesirable degradation of nutrients can be caused by thermal sterilization[8]. Study the thermal sterilization of conduction-heated by using different optimal temperature time profiles, taken in consideration the different objectives functions including process time, nutrient retention and energy consumption was proposed by[9, 10]. Later on implementation of the optimal profiles through controller which is capable of providing optimal performance by eliminate the offsets and overshoot which can cause over processing and quality problems[6].

The economic importance and the capability to be applied in various aspects of industry make thermal sterilization more interest [11-13].Mainly, thermal sterilization is focused on safety and quality of the final product, energy consumption and total process time. Thermal sterilization requirements which can be determine by using analytical method of numerical method and based on these procedures can by design dialogue software be used to simplify an engineering [14].

Thus, the main objectives of thermal sterilization process controllers relies into inactivation of microorganisms present in the foodstuff, minimizing the operation time and preserving as much as possible product quality, because of these reason, the sterilization process can be divided in three stages that use different control strategies: Venting, heating and cooling. The first stage is venting which can be carried out manually, so the controllers can be designed to control the remain stages of the process heating (where one of the main objective is to maintain sterilization temperature at a certain value by manipulating the entrance of steam in the retort), and cooling (where avoid pressure drop is important)[15].

1.2.1 Control techniques of canned food sterilization

Nowadays a PID controller is most commonly used control strategy in an industrial sterilization process. For instance, in [16] the process was developed and controlled based on a proportional integral (PI) controller. A study of using linearization system approach to improve the quality control or reduce the cost was presented by implement Q-PID or Q-PI techniques according to [17]. Whereas a PID type controller parameters estimated using (IMC) was stated by [6, 18].It was found that during heating stage, PID controller has good performance as long as the plant be able to operate as closely as possible of the constant heating temperature around the tuning region; unfortunately, controller over and over have to repeat its action to operate in other conditions, for instance, when the amount and type cans has been changed which is difficult to carryout.

Online correction of the lethality value is an advanced control strategy that can be used for control of thermal sterilization of canned food and assuring safety, process efficiency as that reported by[19]. Nonlinear heat equation associated to control constraints is a good example of study optimal control problems were stated by.[20], and the large scale continuous optimization is the expression that can be used to describe approximation of optimal control and sequential quadratic programming can be used solving this optimal, but such kind of algorithms has mathematical complexities, And that why using other algorithms like optimal receding horizon controller (RHC) can give good results and better investigation and study of model uncertainty[21].

From control standpoint high gain PI controller has a good performance during the complete sterilization cycle when put into consideration at least locally the plant is a first order [16] this correct in case of energy gained from the steam can be quickly eliminated [4]. Thus, in the case of temperature and pressure control during the sterilization cycle, the dynamic information of the plant is required and can be provided by the model that relevant for purposes of controller design. And on basis of the dynamic model the experimental performance and limitations of these control strategies can be analyzed. Moreover, use to study the effect of nonlinearity of the dynamic model