HEAT-AND-POWER PROCESSES OPTIMIZATION BY MEANS OF MODEL-BASED SIMULATION

Dmitry Antropov
JSC, Etalon MCS", Kazan, Russia

Rosica Ivanova, Renat Sadykov
Kazan State Architectural Building University, Kazan, Russia

Sergey Yeryomin, Rauf Kafiatullin
PO "Kazenergo", Kazan, Russia

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Abstract: A firmware was developed for simulation of heat-mass transfer processes in power equipment such as steam or water boilers and dryers. Hardware of this pilot plant is based on modern microprocessors control devices. Software rests on specially developed mathematical models. The functions and structure of the model of fully automated boiler and dryer control system (B-DCS) are described in detail. One of the variants of implementation of B-DCS on the example of the dryer unit for drying bioactive products is considered. The analysis of the optimality criterion problem and selection of the optimal control structure are reviewed using Pontryagin's maximum principle. The objective of optimization is to reduce expenditures of operational process.

1 INTRODUCTION

The depletion of the resources of extensive development of economy makes critical the issues of the development of intensive process technologies and their introduction in the industry. In the rapidly developing technologies these challenges can be competitively met only by methods of computerized mathematical modelling which reduces the amount and time of R&D required and enhances its quality. The realization of these advantages in the computerized automated design and control systems, scientific research requires the unity of mathematical, algorithmic, informational and software support for various processes and tasks in power engineering, chemical technology and biotechnology. This unity should be based on the generalizing mathematical models (MM) covering the basic aspects of the development of the intensive process technologies. However, in common practice highly specialized MMs of empirical character down to regressive ones are in use owing to the fact that the conventional, more universal MMs do not adequately incorporate such features of the intensive process tecnologies as multi component structure and lability of the process agents, low process observability and reproducibility, intensity and coherency of various features of the happening phenomena, interference of process technology stages.

We have designed a model of a fully automated boiler and dryer control system (B-DCS) based on the microprocessor data acquisition and control devices designated for training of the students.

The B-DCS model allows to familiarize with the processes taking place in the boiler and drying units in the absence of processing system. It allows to solve problems of mathematical modelling adequacy of the basic processes in a boiler or a dryer. The capacity of the B-DCS processing unit permits to realize complicated optimization algorithms and to analyze their efficiency.

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2 FUNCTIONS OF THE B-DCS

The intelligent laboratory-scale plant implements the following functions of the automatic control and supervision:

Boiler automated control:

- Boiler control in an automatic mode using the set algorithm (check readiness for start-up, ventilation, kindling, initial heating, output of operating conditions, shut down;
- Boiler regulation using basic process parameters (load, fuel - air ratio, chamber pressure, etc.);
- Implementation of the process protection and interlocking;
- Diagnosis of the boiler process equipment condition;

Automated control of the boiler-house auxiliaries consists of:

- Control of the deaeration unit, network, and intake pumps;
- Water level control in the additional feed tank;
- Regulation of the temperature schedule and heating system hydraulic mode;
- Energy transmitter logs (gas, steam, heat) and automatic regulation of thermal energy output for customers.

Dryer automated control and remote supervision:

Includes the following process control objects: dryer; charging device; unloading mechanism; receiver; condenser; hotwell.

Controlled parameters:

- dryer top pressure; pressures upstream of a receiver.
- dryer lower part temperature; inlet and outlet air temperatures;
- inlet and outlet product temperatures ;
- air consumption in a dryer;

3 STRUCTURE OF THE B-DCS

The B-DCS model includes the following basic levels (fig. 1):

- emulation of sensing transducers and actuators level
- processing unit level
- human interface (HI) level.

Field level - the level of the sensing transducers and actuators. In the laboratory-scale plant the role of sensing transducers is played by PC with program emulation of a real object. Input-output (I/O) modules are set on PC. The program simulates functioning of field sensing transducers, emulating their current output signals. Emulation programs software can be based on the SCADA-system with the proper scripts which are carrying out process imitation or on special software based on the virtual devices technology. Current signals are transferred to the next level - on an input of the control unit.

4 MATHEMATICAL MODELLING AND OPTIMIZATION OF THE BIOPRODUCTS DRYING PROCESS

Let's consider one of the variants of implementation

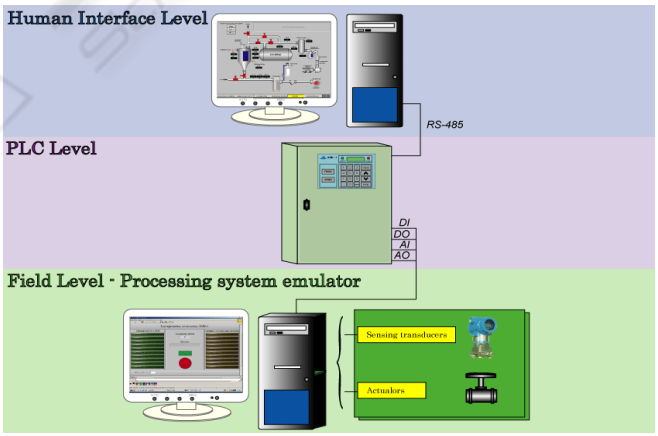

Figure 1: Structure of the B-DCS.

of the above mentioned B-DCS on the example of the model of the dryer unit for drying bioactive products. The creation and application of computerized generalizing MMs and the development of intensive drying process for bioactive products exemplified by highly purified α - amino acids.

The desiccation of highly purified α- forms of irreplaceable amino acids as follows: Thr (threonin), Trp (tryptophan), Leu (.Leucin), Ile (iso-leucin) involves removal of the mixture of ethanol (in which they are practically insoluble) and water with solubility of 0.02-0.09 kg/kg at 20^0 C. The residence time in vacuum dryer is up to 72 hours.

In view of the pressing requirement for the development of commercial technology for intensive desiccation of pure amino acids 25 types of dryers were analyzed on the computer in an effort to find the method of adequate intensive drying technology: vacuum application, active hydrodynamic regimes.

A complex pilot plant was fabricated [1,2] for the selection of appropriate drying process and the following processes were tested : desiccation in pseudo-liquified and densely purged beds , desiccation by pressure reduction (DPR), vacuum oscillating desiccation - repeated alternation of heating by hot gas and vacuum cooling, impulse desiccation by depressurization of drying chamber (DDC)- a new method proposed.

It was experimentally established that free moisture is basically removed from the bioproducts being investigated and they tend to agglomerate. The agglomeration mechanism is related to the change in the liquid phase composition upon desiccation: the crystals partially dissolve in the mixture upon rapid increase of water proportion (more volatile spirit is removed faster) and subsequently start to stick to each other. So as to loosen and break the agglomerates the impulse depressurization was effectively employed causing breaking normal stresses dependent on the duration and depth of terminal pressure drop, size, inner structure and temperature of agglomerates.

The proposed method alowed to meet the requirements for the dispersive structure of amino acids and to reduce τ_c to 0.5 hour or less. The unit incorporates the dryer, heating agent feeding line, depressurization system and receiver.

5 DRYING PROCESS DESCRIPTION

The installation scheme is represented in fig. 2 (screen shot of the engineer's interface). The raw material goes through the charging device of the drying apparatus and then enters the drying chamber. In the drying chamber the product is exsiccated by hot air. The product is unloaded pneumatically in the loading tank. In the drying chamber vacuum creation is possible with the help of pumping system consisting of the pump, the condenser and the hotwell .The drying process can be carried out in various ways. In emulation system in the capacity of control and regulating blocks the most widespread drying regimes are used.

Regime 1 – Drying in filtering and pseudo-liquefied layers.

Regime 2 – Drying by pressure decline.

Regime 3 – Drying by the combined pressure drop and vacuum.

This method integrates the following regimes of drying:

- Preheating;
- Depressurization;
- Pumping out;
- Layer tossing up;
- Clearing the filter.

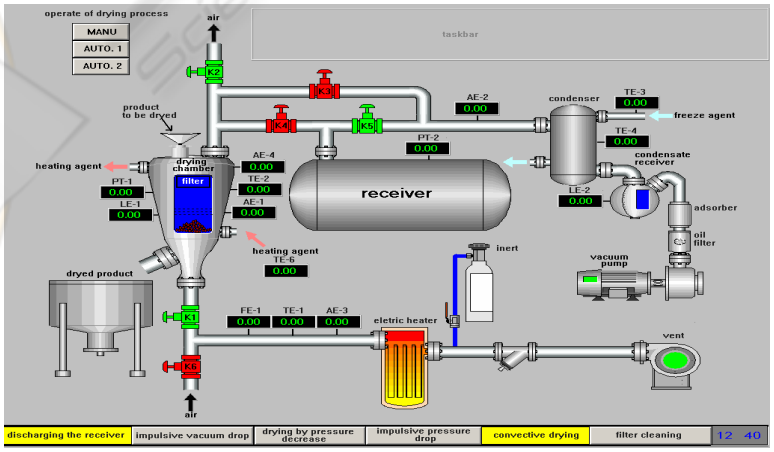

Figure 2: HI of the dryer unit.

In the course of mathematical modelling the pressure drop hydrodynamic calculations were made, based on the model of stationary adiabatic flow from a larger vessel via a confuser without friction. The equation [2] in the explicit form was obtained for Pc. The depressurization stage as vacuum dehydration process was divided into two parts. The duration of air evacuation $(\tau_{ов})$ was calculated from the formula [3]:

$$\tau_{ов} = \frac{V}{\kappa} \int_{P_к(\vec{x}_0,\tau_0)}^{P_к} \frac{dP}{PQ(P)} \qquad (1)$$

where V - free volume of drying chamber; *k* - polytrope index; *P, $P_н$* – pressures: current and vapour saturation of multi component liquid phase; *Q (P)* efficient pumping speed of vapour/air mixture calculated by constant volume method [7]; $\vec{x}$ - vector of liquid phase composition*; T* - material temperature; index "0" - adopted for initial values.

The analysis of internal heat mass transfer at the stage of vapour pumping showed that it is described by non linear differential equations of filtration and heat transfer [1, 2]:

$$\begin{aligned} \rho_c \frac{\partial U}{\partial \tau} &= \frac{\partial}{\partial z}\left(K_p \frac{\partial P}{\partial z} \right), \\ \rho_c c \frac{\partial T}{\partial \tau} &= \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z} \right) + \rho_c r \frac{\partial U}{\partial \tau}, \end{aligned} \qquad (2)$$

where $K_p = K/\eta\mu$ - molar filtration coefficient; *K* – permeability of capillar porous solid ; η - kinematic viscosity coefficient of vapour/air mixture being removed; μ - apparent molecular mass of vapour/air mixture being removed ; ρ_C - dry material density; r - heat of vapour formation; *c* – specific heat; λ - heat transfer coefficient; *U* – humidity of material; τ - time; *z* – spatial coordinate (or material layer plane orthogonal towards axis *z*).

It was determined that heat transfer had no influence on the process and, thus, vacuum desiccation process has local invariants - functions $U(T), \vec{x}(T)$ and $P(T)$ which do not depend on τ. The availability of invariants radically reduces the required scope of experimental research relating to combined heat and dehydrating influence of desiccation process on the preparations and facilitates kinematic calculations of desiccation process. The measurements showed that at the layer height H = 0.03 - 0.02 m the temperature of pressure reduction desiccation was the same throughout the whole product. In view of this the local invariants play a balancing role and are calculated via integration of the following system of ordinary differential equations (SODE) [3]:

$$\begin{cases} \dfrac{dU}{dT} = UI, \\ \dfrac{d\vec{x}}{dT} = (\vec{y} - \vec{x})\, I, \end{cases} \qquad I = c/rU\,, \qquad (3)$$

whilst dehydration kinetics - by integration of equation as follows:

$$\frac{dU}{dT} = \frac{\left(\dfrac{V}{cM}\right)\left[\langle \vec{\mu}, \vec{\beta} \rangle - \rho R\right] \cdot \dfrac{q(\tau)}{RT} + \rho Q(P)}{\vec{\mu} M + V \dfrac{r}{c} \cdot \dfrac{\left[\langle \vec{\mu}, \vec{\beta} \rangle - \rho R\right]}{RT} + \dfrac{V}{U} \cdot \dfrac{\langle \vec{\mu}, \vec{\alpha} \rangle}{RT}}, \qquad (4)$$

where $\langle \cdot, \cdot \rangle$ - scalar product of vectors; *M* – mass of dry material; *R* – universal gas constant; vectors $\vec{\alpha}$ и $\vec{\beta}$ are determined only by the conditions of vapour/liquid equilibrium [3], $\vec{x}$, $\vec{y}$ - vectors of composition of liquid phase and removed vapours, to be determined from the equation of vapour/liquid equilibrium. The equation (4) is solved together with the equations of material and power balance of vapour pumping stage (DPR):

$$\begin{cases} U\ d\vec{x} = (\vec{y} - \vec{x})\, d\mathrm{U}, & \text{(a)} \\ \mu \mathrm{M} \dfrac{dU}{d\tau} + \rho\, Q(P) + V \dfrac{d\rho}{d\tau} = 0, & \text{(в)} \\ cM \dfrac{dT}{d\tau} - rM \dfrac{dU}{d\tau} = q(\tau), & \text{(c)} \end{cases} \qquad (5)$$

(a - liquid phase material balance) (в - vapour material balance) (c - damp product power balance) as ordinary differential equations system of summarizing order n + 2.

Thus, a non trivial property of distillation material balance was revealed (first equation of the system (5)) to accumulate the error upon numerical integration [3]. In system (5)

ρ - vapour density, M – dry product mass in the dryer, $q(\tau)$ - heat supply rate. The system thermodynamic parameters are determined by the additivity rule:

$$c = c_c + U\langle \vec{c}, \vec{x} \rangle, \quad (6)$$
$$r = \langle \vec{r}, \vec{y} \rangle,$$

where c_c – specific heat of the dry product, $\vec{c}$ and $\vec{r}$ - molar specific heat evaporation heat of the components.

The analysis of heat mass transfer in the pseudo liquified bed was performed within the external task of mass exchange particle - heating agent for the binary liquid mixture ethanol-water on the basis of equations set (ES) of Stephan - Maxwell multi component diffusion. The total mass exchange intensity was set empirically by function $\varphi_в(U,T)$ - relative air humidity at the outlet from the layer, determined by methods of structural risk minimization [5]. For heating stage kinetics ES was derived:

$$\begin{cases} \frac{dU}{d\tau} = \frac{G}{MRT_a\mu_y}\left[\varphi_a\mu_2 P_2(T_a) - \varphi_b\mu P_H(\bar{x},T)\cdot\frac{P_a - \varphi_a P_2(T_a)}{P_a - \varphi_b P_H(\bar{x},T)}\right], \\ \frac{dT}{d\tau} = \frac{r}{c}\cdot\frac{dU}{d\tau} + G\,c_p(T_{т.н.} - T), \\ \frac{d\bar{x}}{d\tau} = \frac{\bar{y}_y - \bar{x}}{U}\cdot\frac{dU}{d\tau}, \end{cases} \quad (7)$$

where the composition of the vapours removed (index *y*) from the amino acids $\vec{y}_y$ is calculated with consideration of water vapours heating by gas, index 2 refers to water, ρ_g – gas density at normal volume flow rate G, c_p – gas specific heat at constant pressure.

The stage models are included into the calculation sequentially , are interrelated by marginal conditions and , in the aggregate, form a common DDC process model adequate to the experimental data obtained [2].

The hardware and operating modes of the bioproducts drying shop have been optimized to reported expenses in accordance with the approaches [6]. The task of the pressure drop system design is delineated and solved by decomposition. The optimum operating modes of the unit are defined by formulation and solution of the task of optimum control with criterion functional:

$$I = \frac{1}{M}\int_0^{\tau_c}\left\{E_i + E_{pi} + ZG\left[E_{ai} + (T_{ha} - T_{at})E_{hi}\right]\right\}d\tau, \quad (8)$$

where E_i (\$/s) – expenses irrespective of the mode, E_{pi} – cost of 1 second of vacuum pump operation, E_{ai} – cost of 1 m^3 of sterile air, E_{ha} - cost of heating of 1 m^3 of air per 1 K, index i designates i variant of hardware, $Z(\tau)$ – regime function equal to 0 at depressurization stages and to 1 at heating stages. Allowable equations

$$\psi(\tau) = [M, G(\tau), T_{ha}(\tau), Z(\tau)] \quad (9)$$

are limited by certain conditions ensuring product quality. The analysis of the task with the application of maximum principle of Pontryagin revealed the structure of optimum control:

$$\psi_{opm}(\tau) = [M_{\max}, G_{\max}, T_{ha\max}, Z_{opm}(\tau)] \quad (10)$$

where $M_{\max}$, $G_{\max}$ and $T_{ha\max}$ - maximum allowable values of parameters. It was revealed that the increased rate of depressurization system results in reduction of reported expenses on DDC bioproducts. Optimum $Z_{opm}(\tau)$ and τ_c highly depend on the composition of the removed mixture (τ_c for spirit is 4.4 times lower than τ_c for water). The regime optimization reduced the reported expenses and τ_c by 40 %. In comparison with vacuum-desiccators τ_c is reduced by order of 1 ÷ 2.

6 SIMULATION RESULTS

Some tests were made with irreplaceble amino acid – Leucin. Figure 3 shows the results of the design data and simulation experiments for main parameters U - liquid specific mole contention **x** – alcohol mole fraction , T – temperature of the material.

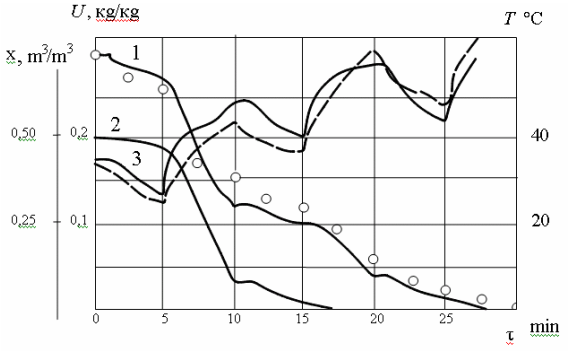

Figure 3: Design and experimental data comparison of Leucin drying. G = 0,007 m^3/s, T_{rp} = 95 °C, H = 0,005 m, τ_v = 5 min. Firm lines – design: 1 – U, 2 – $\mathbf{x}_v$, 3 – T; — — — – T, experiment, o – U, experiment.

7 CONCLUSIONS

In this paper we have presented a task-level system which can be used for the following purposes:
1. Students familiarization with heat-mass transfer processes in power equipment.
2. Development and identification of new mathematical models of above-mentioned processes.
3. Optimization of the real equipment selection and its operation modes.
On the example of the model of the dryer unit theoretical base for optimization of bioactive products drying technology have been developed. The analysis of the problem with the application of the Pontryagin's maximum principle has revealed optimal control structure. At the expense of the mode optimization the costs and time of a α-amino acids drying (τ_d) are reduced by more than 40 %. In comparison with the vacuum-shelf dryers τ_d of the bioactive products is reduced by 1 - 2 orders.

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