Sławomir JASZCZAK, **Piotr NIKOŃCZUK**
WEST POMERANIAN UNIVERSITY OF TECHNOLOGY IN SZCZECIN, DEPARTMENT OF COMPUTER SCIENCE,
PL-71210 Szczecin, 49 Żołnierska St., Poland
WEST POMERANIAN UNIVERSITY OF TECHNOLOGY IN SZCZECIN, DEPARTMENT OF MARITIME TECHNOLOGY AND TRANSPORT,
PL-71065 Szczecin, 41 Piastów Ave., Poland

A comparative analysis of temperature control algorithms for spray booths

Abstract

Authors present a development of the temperature control system in the spray booth equipped with the two - state burner. The paper presents results of temperature control for different conditions of the external air temperature. A typical two-state algorithm isn't enough effective to minimise temperature fluctuation amplitudes inside a spray booth. Minimisation of the number of burner ignitions with acceptable fluctuation amplitudes of the temperature is possible by means of : modification of the measurement loop, modifications of the two-state algorithm. Minimisation of number of burner ignitions will increase durability of the burner and decrease consumption fuel used to start the burner. In the final part of the article selected results of real time experiments were presented and shortly analysed.

Keywords: spray booth, supervisory control system, safety.

1. Introduction

The control system of the typical spray booth consists of two separate stabilisation loops i.e. the temperature control system and the pressure control system. The control problem in spray booth is known and still developed under different point of view [10], [1], [2], [9]. Usually the structure of the control system is centralised, because one controller is used as a executive platform for control algorithms. Apart of the temperature and the pressure stabilisation, the specific air flow should be provide to get rid off toxic gases (e.g. styrene, acetone, hydrogen sulfide etc.) from the booth, typically 10000-20000 m^3/h. According to the required air flow the temperature stabilisation is a relatively difficult task. Difficulties are connected with the varying outside air temperature, which is the temperature of the inlet air and imperfections of an actuator i.e. a burner with a heat exchanger. Actuator's imperfections may be related to: a significant technological delays (a burner needs some time from the start to the full activation), inertial delays, which are related to the heat exchange process and fluctuations of the air flow according to fluctuations of the temperature of the heated air. Apart of that, a burner may work as a two state controlled device or a variable controlled device. The authors have developed temperature control algorithms, based on the two state burner, which was chosen by the end user. Such an actuator leads to a relatively poor quality of the control (relatively high fluctuations of the air temperature inside the booth), although it is exclusively stable and robust. The authors started with the classical two state algorithm and then they have introduced some modifications like calculation of the error signal based on the manipulated value i.e. the air temperature after the heat exchanger. Usually temperature control algorithms based on the process value i.e. the temperature of the booth air. Another modification was to apply the two state correction algorithm to decrease fluctuations of the booth temperature signal. It is algorithmic solution, well known as a PID two state algorithm.

2. A general description of the control system

A spray booth, presented in the Fig. 1, has to keep a stable temperature (20-25 ^{o}C), a stable pressure (5-6 Pa) and a specific air flow (4000-10000 m^3/h). A booth has two units with fans: air makeup unit (1) (supply unit) and extraction unit (5). The air makeup unit supplies a fresh air to the plenum 3 and next to the spray booth (4). The extraction unit (5) draws air and eject to the atmosphere. The air inside the booth is contaminated with overspray particles. Pulled air is purified by two stage filtering system located in the wall of the booth. The air makeup unit at the booth is equipped with heating unit (2) (one stage gas burner).

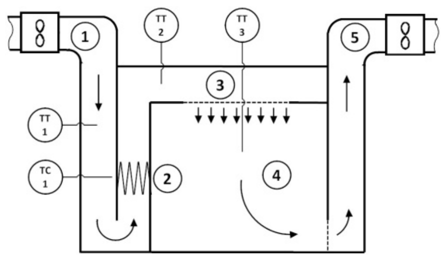


Fig. 1. A PI&D diagram of the spray booth temperature control system

A functional structure of the temperature control system is presented in the figure 2.

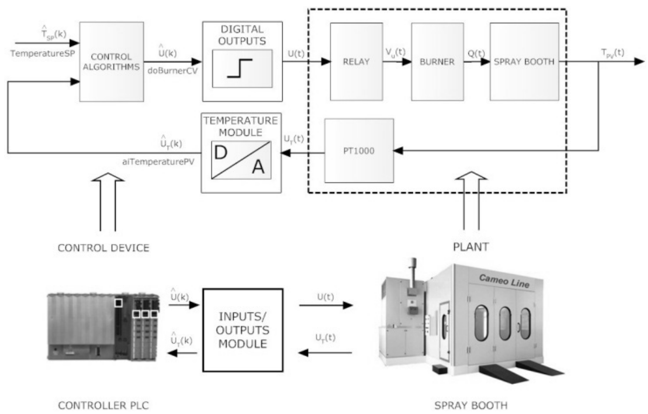


Fig. 2. A structure of the temperature control system of the spray booth

The main task of the control system is to make a temperature T_{PV} *(t)* stable and close as possible to the a set temperature $T_{SP}(t)$. A list of all physical variables in the control system is presented in the table 1.

Tab. 1. List of physical variables in the temperature control system

Signal	Variable	Alias	Description	Type
$T_{SP}(t)$	$\hat{T}_{SP}(k)$	*uiTemperatureSP*	A value corresponding to a temperature exception. Signal range <20, 25> [oC]	[INT]
$U_T(t)$	$\hat{U}_T(k)$	*aiTemperaturePV*	A value corresponding with a current temperature. Signal range <0, 30> [oC]	[INT]
U(t)	$\hat{U}(k)$	*doBurner*	A voltage value corresponding with a burner performance. A voltage value [VDC]	[BOOLEAN]

A temperature inside the spray booth T_{PV} *(t)* is measured by the temperature sensor marked as a TT3 (fig. 1) (the PT1000 element) and introduced to the control device, marked as a TC1 (fig. 1), through the a temperature module (X20CP1301(X1)) as a *aiTemperaturePV* variable. Apart of that two other temperatures are measured i.e. the temperature inside the inlet channel before the heat exchanger $T_{PZ}(t)$ marked as a TT1 and the inlet air temperature after the heat exchanger T_{MV} *(t)* marked as a TT2.

An actuator in the described system is the relay with the gas burner, which works as a two state unit. A two state control signal *U(t)* activates the burner based on the digital outputs module (X20CP1301(X3)) and the relay element. As a result of that, a two state algorithm was taken as a first algorithm for the temperature stabilization system.

3. Control algorithms analysis

As it was written above authors started the analysis of the spray booth temperature stabilization using a two state algorithm, which is widely used in the industry [3]. Two state algorithm is an effective solution in case of significant dead times and inertial delays of the plant (like in case of the refrigeration unit) and relatively large range of tolerance of the control error. In this case I/O device i.e a digital outputs module connected to a relay element determined a type of the control algorithm. It is important, that the two state algorithm is easy to implement and it does not need a significant computational power. This algorithm is often presented as a static characteristic (fig. 3).

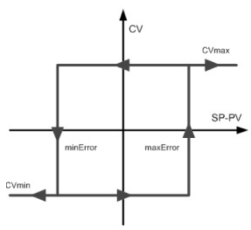


Fig. 3. A static characteristic of the two state control algorithm, where: CV_max - an amplitude of the control signal for ON state, CV_min - an amplitude of the control signal for OFF state, minError, maxError - the minimum value of error for a switch on operation and a maximum value of error for a switch off operation, respectively. In practise it is usually:minError=-maxError

As shown in the figure 3 control actions are specified based on the error signal *e(t),* given in the equation 1. This signal was calculated based on the process value $T_{PV}(t)$, marked as TT3 (fig.1).

$$e(t)=T_{SP}(t)-T_{PV}(t) \tag{1}$$

Considering relatively significant technological delays of the burner and inertial delays of the heat exchanger authors decided to calculate the error signal based on the manipulated value, precisely the temperature after the heat exchanger $T_{MV}(t)$ marked as TT2 (fig.1) instead of the temperature inside spray booth, marked as TT3 (fig.1). This simple modification, shown in the figure 4, improved the quality of the temperature control decreasing the amplitude of temperature fluctuations inside the spray booth.

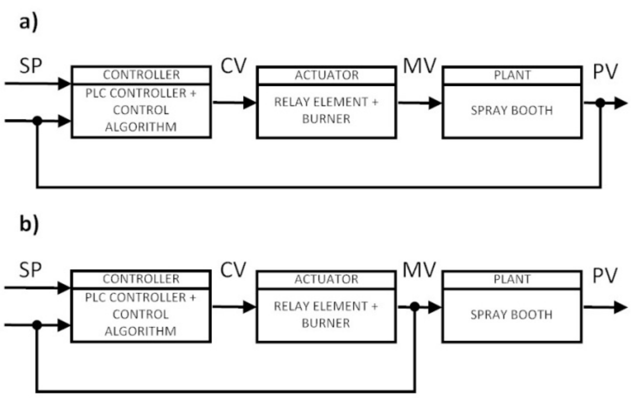


Fig. 4. Structures of a feedback loop, where : a) - a typical structure (the temperature marked as a TT3 is taken as a feedback value); b) a modified structure (the temperature marked as a TT2 is taken as a feedback value

Another method able theoretically improve the quality of the temperature stabilisation is known as a two-state PID algorithm, shown in the figure 5. The main idea of this algorithm is to use two inertial elements with a common gain *k* parameter. The output signal can be use as a adjustment signal and it is subtracting from the error signal *e(t)*. This method is effective but only in a case of using actuators without significant inertial delays.

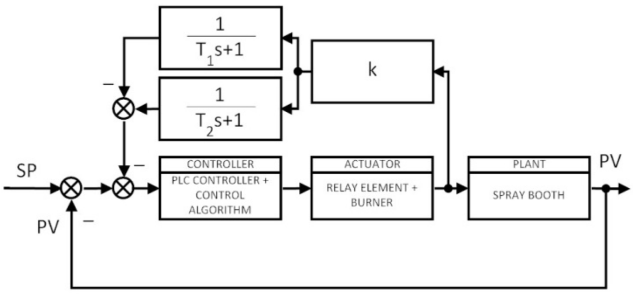


Fig. 5. A two state PID control algorithm

4. Real time experiments

Described algorithms were applied to the real plant - coating board industry in epoxy resins. In the figure 6 is shown a spray booth (a) where algorithms work. In the figure 6b a control box and a data acquisition system are shown. Operating data parameters are obtained from the PLC controller to the PC. A control software enables a data import directly to the MATLAB environment, based on the TCP/IP channel, what makes a data analysis easier.

Fig. 6. A view of the real plant : a) the spray booth b) data acquisition from the control box

Experiments were conducted for three control strategies (table 2): - a standard two state control (1) - the feedback value is taken from the temperature sensor TT3 shown in the figure 4a, - a modified two state control (2) - the feedback value is taken from the temperature sensor TT2 shown in the figure 4b, - a PID two state control (3) shown in the figure 5. The expected air temperature inside the spray booth was set up $T_{SP}(t)$ = 23 [^{o}C], an average outdoor air temperature $T_{PZ}(t)$ was equal about 5 [^{o}C]. In the figure 7 are shown results of the temperature stabilization using a standard two state algorithm with a feedback value from the temperature sensor TT3. The fluctuations amplitude of the temperature inside the spray equals 4.5 [^{o}C] (table 2).

Tab. 1. List of selected quality control indicators

A control strategy	An amplitude	A minimum value	A maximum value
1	4.4754	18.1691	27.1200
2	1.3356	21.2222	23.8934
3	4.6431	16.6522	25.9385

Much better results were obtained for the modified control system. Experiment results are shown in the figure 8. Fluctuations are lower than results from the previous experiment. The amplitude of temperature fluctuations has value less than two (table 2). The results of the experiment with the two state PID controller are shown in the figure 9. The temperature fluctuations are in a range 16-25 [^{o} C]. The following parameters were set: static gain *k*= 1, inertial constants T_1 = 100, T_2 = 200. The lower values of the air temperature inside the spray booth sound unoptimistic, but the difference between upper and lower values equals 4.6431 [^{o} C] (table 2), what is even the poorer result than in case of the standard two-state algorithm.

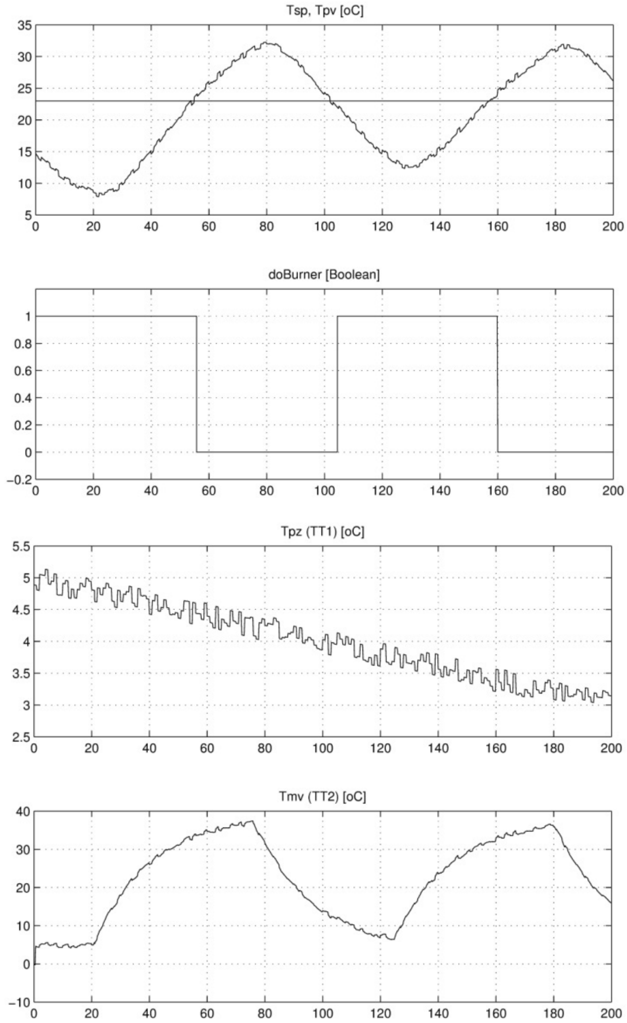
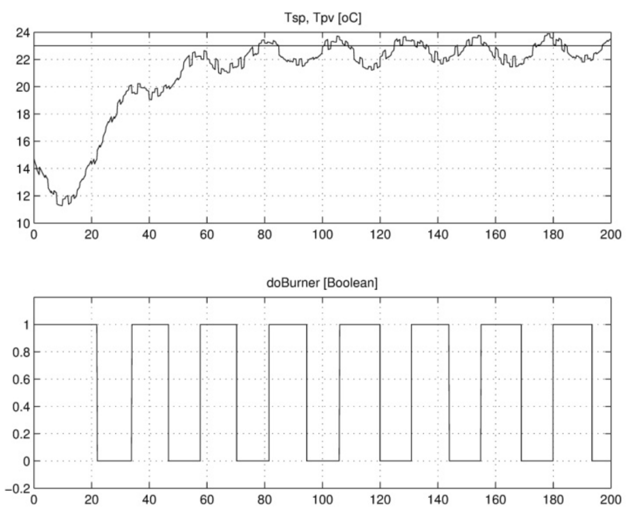


Fig. 7. A temperature stabilization with the two state algorithm and the T_{PV} based on the TT3 measurement point



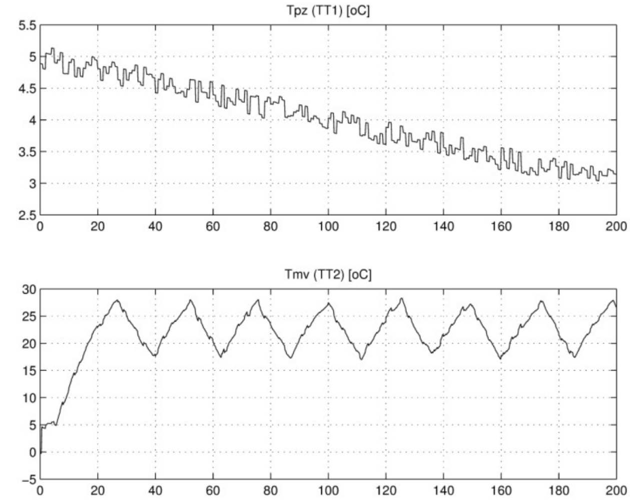


Fig. 8. A temperature stabilization with the modified two state algorithm and the T_{PV} based on the TT2 measurement point

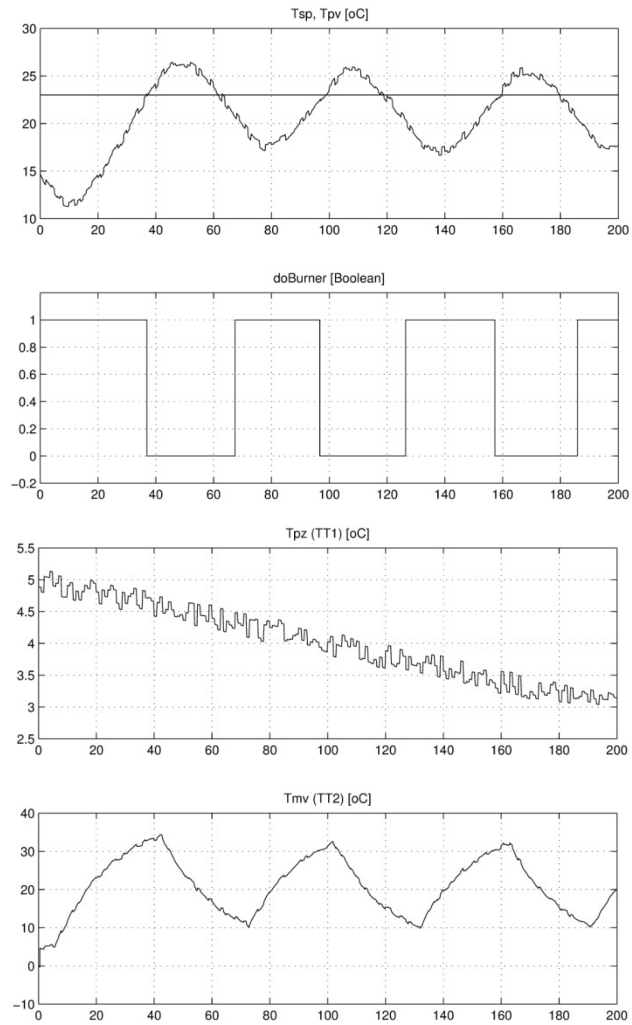


Fig. 9. A temperature stabilization with the two state PID algorithm

5. Conclusions

A standard approach uses the temperature inside a work chamber as a parameter which determines burner heat flux. The suggested method has a little different philosophy of the temperature control for the area where the air flow has high value. The temperature measurement point is located in blower duct behind the heat exchanger. Such approach introduces the duct and booth inertia as a element which makes temperature fluctuations smoother. The presented method uses a PID controller in case of nonlinearity of spray booth the another controllers can be used. For nonlinear objects are used robust control systems [4] or fuzzy logic control [7], [8]. On the dynamics of spray booth also influences the heat recovery unit. But recuperators efficiency is not invariable [5] , [6]. The authors consider next step for optimization of control system for spray booths, which bases on state space model. The model contains interdependencies between air flow, pressure and temperature. The state space model for temperature and humidity was presented at [1]. The authors at the present state do not consider the air humidity.

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Piotr NIKOŃCZUK, PhD, eng.

Graduate and employee of the West Pomeranian University of Technology in Szczecin, Faculty of Maritime Technology and Transport. In 2008 received his doctoral dissertation on the parent department. Author of over 50 publications. The subject of the research: "energy efficiency of paint spray booths," "modeling, optimization and design of process control systems" and "artificial intelligence methods".

e-mail: piotr.nikonczuk@zut.edu.pl

Slawomir JASZCZAK, PhD

Since 1994 as a assistant at the Department of Maritime Technology of the Technical University of Szczecin was leading research connected with a underwater vehicles control using artificial intelligence methods. Since 2002 as a professor assistant at the Department of Computer Science of the West Pomeranian University of Technology in Szczecin. Current scientific activity is related to the implementation of sophisticated digital control algorithms based on the PLC platform.

e-mail: sjaszczak@zut.edu.pl