Sławomir JASZCZAK, **Piotr NIKOŃCZUK**
Westpomeranian University of Technology in Szczecin, Department of Computer Science,
PL-71210 Szczecin, ul. Żołnierska 49, Poland
Westpomeranian University of Technology in Szczecin, Department of Maritime Technology and Transport,
PL-71065 Szczecin, Al. Piastów 41, Poland
DOI 10.1000/182

A MODEL OF THE REFINISHING SPRAY BOOTH AS A PLANT OF AUTOMATIC CONTROL

Abstract

Authors present a spray booth dynamic model and a short analysis of technological factors, which may have an influence for dynamic of controlled parameters. The main idea is to find robust control algorithms (mainly for the temperature control), which make a process stable in any working point. The paper presents a preliminary concept of the temperature and pressure control system dedicated for spray booths. A selected set of results of the temperature stabilization is shown in the paper.

Keywords: spray booth, control algorithms, temperature control, overpressure control

1. Introduction

The air temperature control is a part of the most developed control systems for spray booths [6]. The other controlled parameters are overpressure and air balance.

The spray booth control system should support stabilization of two parameters: temperature and air overpressure despite of:

- influence of outer disturbances (intake air temperature and humidity, etc.);
- continuous changes of the dynamic model' parameters;
- technological constraints of burners and fans power (nonlinearity of the model – saturations, dead zones, hysteresis, etc.);
- changes of the set point values.

Generally a spray booth operates in two modes i.e. spraying and coating, which are related to various temperature set points. From technological point of view a stable temperature has significant influence on a quality of a ready-made coating. The temperature and overpressure should be controlled independently. The overpressure inside the booth eliminates pollutants (e.g. dust) coming from outside the chamber. Unfortunately a pressure stabilization process disturbs a temperature control are mutually dependant. An exchange of air causes some changes in the temperature distribution.

2. A plant description

A typical spray booth operates in two basic modes: coating and drying. Additionally, the short ventilation mode occurs immediately before and after the completion of the basic modes.

During the coating mode (Fig.1a), the air in the spray booth is constantly exchanged with air supply and exhaust ducts. The air is drawn through the open damper 1 and pre-treated through a preliminary filter 3. Then if necessary, the air is heated by a burner 4 to a temperature of (usually) 20 – 21 Celsius degree, and pumped into the working area through the ceiling filters 5. The air contaminated by overspray is extracted from the chamber through a *paint stop* filter 6 installed in the floor and an extraction duct.

During the drying mode (Fig.1b) the extraction fan is off. The air in the spray booth is recirculated. It is realized by closing damper 1 and opening a recirculation damper 2. The damper 1 is not completely closed and delivers of about 10% of the fresh air in the recirculation flow. The air temperature in the drying mode is usually maintained within the range of 40 to 60 Celsius degree.

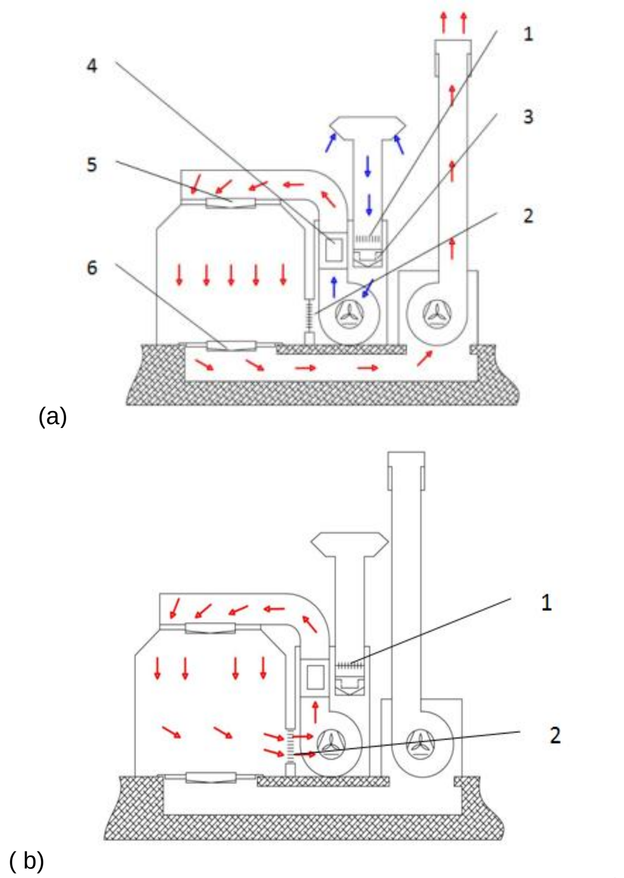

Fig. 1. Typical spray booth in painting mode (a) and drying mode (b), 1 – damper of the suction duct, 2- recirculation damper, 3 – preliminary filter, 4 – burner, 5 – ceiling filter, 6- paint stop filter.

During coating mode inside a spray booth there is a slight overpressure. This prevents the ingress of dust and other contaminants by the door or by small leaks in the spray booth structure.

3. A transfer function of the spray booth

For the temperature control a linear model of the spray booth has transfer function of second order inertial plant:

$$G_T(s) = \frac{T(s)}{Q_1(s)} = \frac{K_B K_S}{(1+sT_B)(1+sT_s)} \qquad (1)$$

where:
$G_T(s)$ – temperature control transfer function,
K_B, T_B – the dynamic parameters of the burner model,
K_s, T_s – the dynamic parameters of the spray booth's inertial construction model.

The temperature control transfer function parameters depend on burner power, volume of exchanged air and burner' heat exchanger efficiency. The spray booth construction parameters of inertial transfer function is associated with thermal properties of all ducting elements. A mathematical model of the spray booth is additionally complicated by the static characteristic of the burner.

The heat flux generated by the burner is limited to the range of burner nominal power. Heat flux from the burner is not the only one parameter that has an impact to a temperature control dynamic in spray booth. The temperature dynamic also depends on the volume and temperature of intake air. In paint spray booths the air volume is adjusted by dampers or by fan performance. The fan performance is controlled by frequency inverters. For refinishing spray booths the air volume is typically in the range of 20 000 – 30 000 m^3/h. It requires a high power of heat source. The power of burners is in the range of 200-300 kW. The specific heat capacity of the air and the burner power performance give the possibility to determine the minimal temperature of intake air to assure the set temperature inside the painting chamber. Is possible to minimize the burner power consumption using heat recovery installations, but should be taken into consideration decrease of heat recovery efficiency in in case of overspray sediments [5].

The next, most often controlled parameter of the spray booth is overpressure. The overpressure linear model can be also represented by transfer function of second order inertial plant:

$$G_0(s) = \frac{K_F K_A}{(1+sT_F)(1+sT_A)} \qquad (2)$$

where:
$G_T(s)$ – overpressure control transfer function,
K_F, T_F – the dynamic parameters of the fan,
K_A, T_A – the dynamic parameters of air flow ducting.

The fan performance has main influence for the overpressure control dynamic. The next important parameter for overpressure dynamic is a dynamic of the air flow ducting. The parameters of air flow ducting transfer function are constantly changing that is mainly caused by filters contamination.

There are high interactions between overpressure and temperature dynamics.

4. A structure of the control system

An architecture of the control system is shown in a figure 2. It contains following levels: an I/O devices level (sensors: temperature sensor, a pressure sensor, etc.), actuators (a burner, inlet and outlet fans controlled by two separate inverters, AD and DA transducers), a direct control level DDC (Direct Digital Control) (a PLC controller), a supervisory control level SC (Supervisory Control - a PC computer).

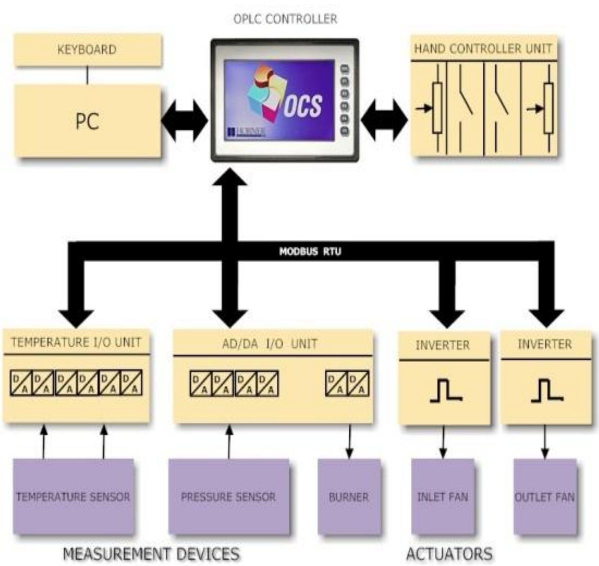

Fig. 3 A general diagram of the spray booth' digital control system.

A PLC controller is a hardware platform for algorithms and the human machine interface (HMI). Communication between a spray booth sensors and actuators and a PLC controller is realized by the Modbus RTU protocol with RS-485 standard. Taking into account dynamical features of the spray booth as a plant of temperature control the PLC controller with a touch panel was used as a control unit.

The standard control system of temperature is equipped with one temperature sensor installed inside painting chamber, but the control circuit dedicated for research experiment is equipped with 6 temperature sensors located in different measurement points: outside the building, inside the intake duct, inside extraction duct and 3 temperature sensors inside the painting chamber. Measurement data from six points will help to identify dynamics of temperature control dependant of temperature values in different points. Similar situation is for control loop of overpressure. Overpressure control system is equipped with one pressure sensor installed inside a chamber. The fans performance is adjusted by frequency inverters. The inverters feedback is a set of parameters: frequency, power consumption, power factor etc. All this data allows to create an accurate simulation model of the spray booth. It has been used at numerical experiments of adequate control strategy.

A presented architecture of the control system enables an easy hardware reconfiguration and testing various control algorithms, what is important in case of non-linear plant such as a spray booth. At this stage of the development basic control algorithms, widely used in an industry i.e. PID algorithms, were tested. Authors assumed 25 degrees Celsius as a set point temperature (TemperatureSP) for a coating mode and 60 degrees Celsius for a drying mode. A control system was tested for two different temperatures outside of the spray booth i.e. 21 and 18 degrees Celsius.

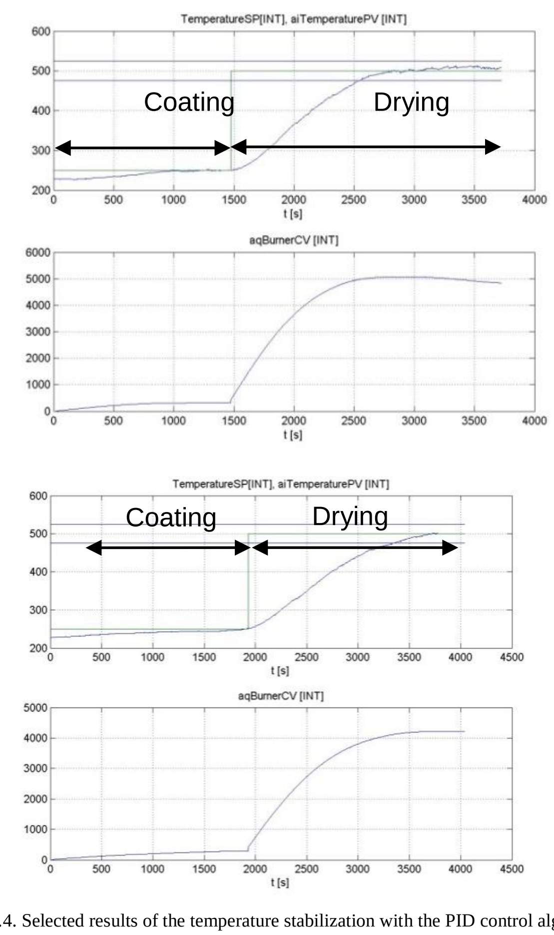

Fig.4. Selected results of the temperature stabilization with the PID control algorithm type ISA.

In the figure 4 a selected characteristic of the controlled signal i.e. a temperature inside of the spray booth (aiTemperaturePV) and a control signal i.e. a burner power (aqBurner) in the temperature stabilization system with the PID control algorithm type ISA is shown. Important is that a controlled system is stable and control quality is acceptable in both operating modes i.e. coating and drying. This means that a control system has a sufficient robustness in case of changing one of the most important disturbance i.e. an intake air temperature for the spray booth.

The dynamics of controlled parameters are constantly varying. For a good control performance the control system tracks dynamics of the spray booth and tune settings of controllers. There are many strategies of controllers tuning [1,2,3,4,6,7]. The temperature control dynamic also depends on working mode. During drying mode the air is recirculated, and its temperature control dynamic is completely different from spraying mode when fresh air is used.

In case of different dynamics of temperature control in different working modes of the spray booth, the PID or another temperature controller should have a possibility of working in two modes synchronous with spray booth mode. The controller settings for each mode should be adequate to dynamic.

4. Conclusions

Presented model of spray booth' dynamic includes a gas or oil burner with heat exchanger. On the market there are also alternative methods of air heating. Taking into consideration a dynamic model of spray booth with other heating method, the dynamic of the heat source should be updated adequate to its construction. The dynamic model also depends on the air exchange ducts organization. The air flow organization inside a paint booth has also influence on temperature sensors localization. In a standard solutions there is a vertical airflow shown in Figure 1, the temperature sensor is usually installed in the middle of ceiling filter's grating. For other air flow distribution solutions the sensors localization should be changed.

More and more often refinishing spray booths are equipped with heat recovery units – cross recuperators. This kind of installation decrease costs of spray booth operation by reducing air heating energy consumption as well connected costs. A recuperator completely changes the thermal dynamic of spray booth as well in short and long time operation. The overspray sediments created on recuperator lamellas are thermal insulators and causes continuous decrease of heat exchange efficiency [5]. Heat exchange efficiency has also an impact on the paint spray booth thermal dynamic. Growing overspray sediments also causes decrease of recuperator channels cross-section. It results in an air flow resistance increasing and finally leads to complete clogging up of recuperator channel. In order to ensure safe and reliable operation of paint spray booth, the control circuits of recuperator contamination status should be taken into consideration. The easiest way of recuperator's clogging status is measurement of pressure difference between air inlet and outlet of recuperator's hot air ducting.

In case to ensure the high quality of finishing or refinishing and a painter comfort the automatic control system should be extended of air humidity control. The air humidity is also interdependent with temperature.

5. References

[1] Bohn C., Atherton D.P., An Analysis Package Comparing PID Anti-Windup Strategies, IEEE Control Systems, 1995, 34-40.

[2] Jaszczak S., Szybkie prototypowanie cyfrowych algorytmów sterowania z wykorzystaniem programu Simulink., Metody Informatyki Stosowanej, 2010, No. 2.

[3] Jaszczak S., Lenartowicz P., Praktyczne aspekty metody strojenia algorytmów PID i PID-podobnych opartej na eksperymencie przekaźnikowym. Pomiary Automatyka Kontrola, 2013 nr 07, s. 608-610.

[4] Nikończuk P., Królikowski T., *Ewolucyjne metody projektowania regulatorów odpornych*, Pomiary Automatyka Kontrola, nr 4/2010, vol. 56, str. 297-30

[5] Nikończuk P., Preliminary analysis of heat recovery efficiency decrease in paint spray booths, Transactions of the Institute of Metal Finishing 2014 VOL 92 NO 5, 235-237

[6] Ogonowski Z., Drying control system for spray booth with optimization of fuel consumption, Applied Energy 88 (2011) 158

[7] Pivonka P., Comparative analysis of fuzzy PI/PD/PID controller based on classical PID controller approach. Fuzzy Systems, pages 541 – 546, 2002.

PhD Eng. Piotr NIKOŃCZUK

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

PhD Sławomir JASZCZAK

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 Westpomeranian 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@wi.zut.edu.pl

Received: 00.00.2014 Paper reviewed Accepted: 05.01.2015