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A model of the refinishing spray booth as a plant of automatic control

Abstract

The authors present a spray booth dynamic model and a short analysis of technological factors, which may influence the dynamics of the controlled parameters. The main idea is to find robust control algorithms (mainly for temperature control), which make the process stable in any operating 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 given in the paper.

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

1. Introduction

The air temperature control is a part of 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 the 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, the pressure stabilization process disturbs the temperature control, they are mutually dependant. The exchange of air causes some changes in the temperature distribution.

2. Plant description

A typical spray booth operates in two basic modes: coating and drying. Additionally, a 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 an open damper 1 and pre-treated through a preliminary filter 3. Then, if necessary, the air is heated by a burner 4 to the temperature of (usually) $20 - 21$ Celsius degree, and pumped into the working area through ceiling filters 5. The air contaminated by overspray is extracted from the chamber through a paint stop filter 6 installed in the floor and the 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 the damper 1 and opening the recirculation damper 2. The damper 1 is not completely closed and delivers 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 degrees.

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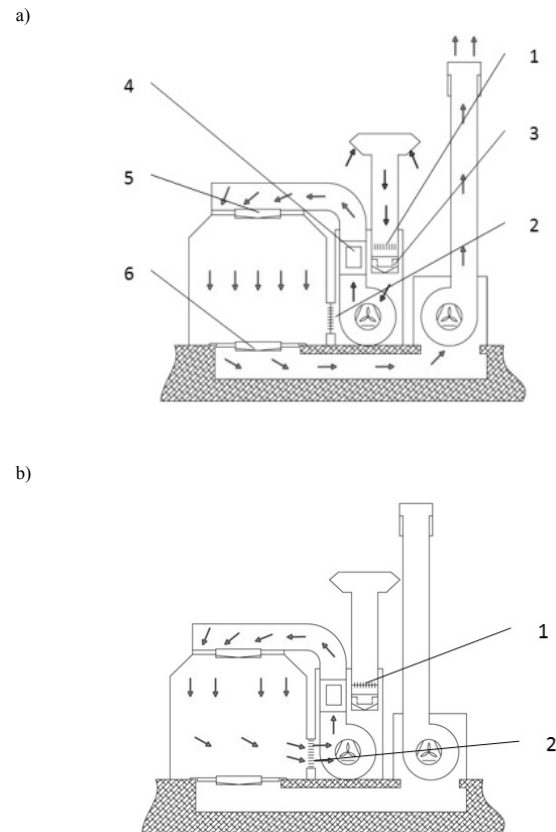
a)

b)

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

3. The transfer function of the spray booth

For the temperature control, the linear model of the spray booth has the transfer function of a 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 – dynamic parameters of the burner model,
K_s, T_s – dynamic parameters of the spray booth inertial construction model.

The temperature control transfer function parameters depend on the burner power, the volume of the exchanged air and the burner heat exchanger efficiency. The spray booth construction parameters of the inertial transfer function are associated with thermal properties of all ducting elements. The 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 the burner nominal power. The heat flux from the burner is not the only one parameter that has an impact on the temperature control dynamics in the spray booth. The temperature dynamics also depends on the volume and temperature of the 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 the 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 minimum temperature of the intake air to ensure the set temperature inside the painting chamber. Is possible to minimize the burner power consumption using heat recovery installations, but decrease in the heat recovery efficiency in the case of overspray sediments should be taken into consideration [5].

The next, most often controlled parameter of the spray booth is overpressure. The overpressure linear model can be also represented by the transfer function of a 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 – dynamic parameters of the fan,
K_A, T_A – dynamic parameters of air flow ducting.

The overpressure control dynamics is mainly influenced by the fan performance. The next important parameter affecting the overpressure dynamic is the dynamics of the air flow ducting. The parameters of the air flow ducting transfer function are constantly changing that is mainly caused by contamination of the filters.

There are high interactions between the overpressure and the temperature dynamics.

4. The control system structure

The architecture of the control system is shown in Fig. 2. It contains the following levels: the 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), the direct control level DDC (Direct Digital Control) (a PLC controller), the supervisory control level SC (Supervisory Control - a PC computer).
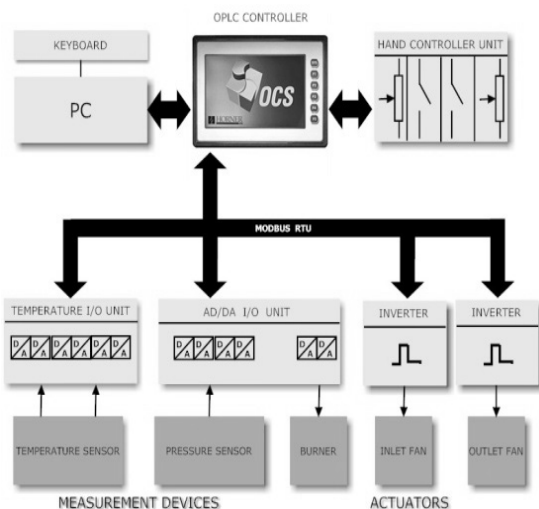

Fig. 3. General diagram of the spray booth digital control system

A PLC controller is a hardware platform for algorithms and the human machine interface (HMI). Communication between spray booth sensors and actuators and the 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 the painting chamber, but the control circuit dedicated for research experiment was equipped with 6 temperature sensors located in different measurement points: outside the building, inside the intake duct, inside the extraction duct and 3 temperature sensors inside the painting chamber. The measurement data from six points help to identify the dynamics of temperature control dependant on the temperature values in different points. A similar situation is for the control loop of overpressure. The overpressure control system is equipped with one pressure sensor installed inside the chamber. The performance of the fans is adjusted by frequency inverters. The feedback of the inverters is a set of parameters: frequency, power consumption, power factor etc. All this data allows creating the accurate simulation model of the spray booth. This model was used in numerical experiments of the adequate control strategy.

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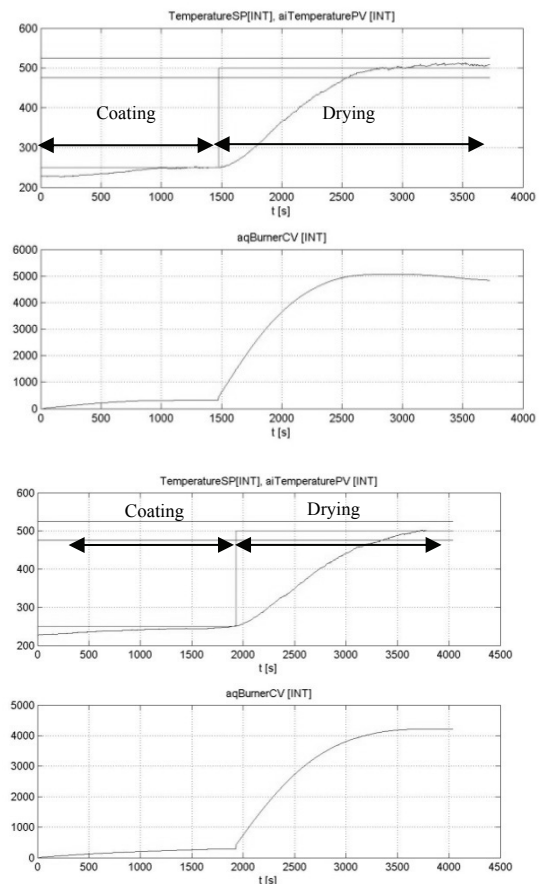

Fig. 4. Selected results of temperature stabilization with the PID control algorithm of type ISA

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

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

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

5. Conclusions

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

More and more often refinishing spray booths are equipped with heat recovery units – cross recuperators. This kind of installation decreases the cost of spray booth operation by reducing air heating energy consumption. A recuperator completely changes the thermal dynamics of the spray booth as well short and long time operation. Overspray sediment created on recuperator lamellas is a thermal insulator and causes continuous decrease in the heat exchange efficiency [5]. The heat exchange efficiency has also an impact on the paint spray booth thermal dynamics. Growing overspray sediment also causes decrease in the cross-section of recuperator channels. It results in the air flow resistance increase and finally leads to complete clogging up the recuperator channel. In order to ensure safe and reliable operation of the paint spray booth, the status of recuperator contamination should be taken into consideration.

To ensure the high quality of finishing or refinishing and the painter comfort, the air humidity control should be additionally performed by the automatic control system. The air humidity is also interdependent with temperature.

6. References

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