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Temperature control algorithms for a refinishing spray booth

Abstract

In the paper, a comparative analysis of control algorithms in the temperature control system for spray booths is presented. Additionally, basic technological limits which may have some influence on the quality of control are described. From technological point of view, a typical spray booth operates in two modes i.e. coating and drying, which are related to different temperature work points. In practice, it is the main reason of changes in plant dynamics, precisely changes in dynamical parameters of the spray booth. The authors analyzed other technological factors which might disturb the temperature inside the booth and finally make a painted covering worse or even useless. The main idea was to find robust control algorithms, mainly for temperature control, which make the process stable in any working point. In the final part of the paper, selected real time experiments are presented to show typical working modes of the spray booth and to proof the robustness of the developed and implemented control algorithm.

Keywords: spray booth, control algorithms, temperature control.

1. Introduction

The air temperature control is a part of most developed control systems for spray booths [8]. The other problem, not described in this paper, is airflow control [5].

The spray booth control system developed by the authors supports stabilization of temperature and overpressure signals despite of:

- influence of outer disturbances (temperature outside the booth, air humidity, intensity of sun light etc.);
- variations of the spray booth dynamical model parameters in time;
- technological constraints of burners and fans power (nonlinearity of the model – saturation, dead zone, hysteresis, etc.);
- changes of the set point value.

Generally a spray booth operates in two modes i.e. coating and drying, 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 [6, 7].

The authors decided to separate temperature and pressure control loops and to develop separate control algorithms for them. The main idea was to take a temperature control loop as a master loop and a pressure control loop as a slave loop i.e. a slave loop was a source of disturbance. In both master and slaves loops, PID control algorithms were implemented and tuned to make temperature and pressure signals stable in any mode. From technological point of view, both signals are important, but from control point of view temperature is more difficult to control, mainly because of significant delays and non-linearity of the plant.

2. General description of the control system

A typical spray booth, shown in Fig.1, operates in two basic modes [5]: coating and drying mode. The temperature set point in the coating mode usually equals 20 - 21 Celsius degree and in the drying mode is usually maintained within the range of 40 to 60 Celsius degree. Additionally, a ventilation mode occurs immediately before and after the completion of the basic modes.

The general structure of the temperature and pressure control system is presented in Fig.2. Temperature and overpressure is controlled in two separate loops. The overpressure loop is also a source of disturbance for the temperature loop because of the air stream of changeable outside temperature. Despite of that, there is the possibility to achieve the expected quality in those two separate loops, mainly because the spray booth temperature dynamics is much slower than the overpressure control.

Fig. 1. A refinishing spray booth - outside view [11]

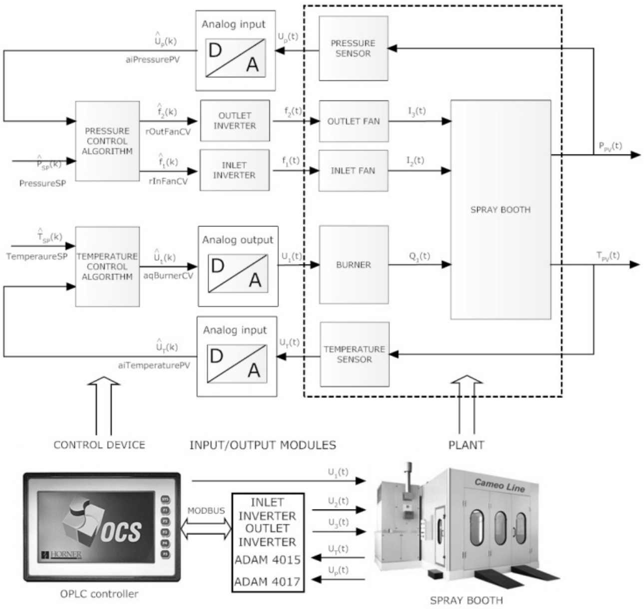


Fig. 2. Functional diagram of the spray booth temperature control

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

No	Signal	Variable	Alias	Description	Type
1	$T_{SP}(t)$	$T_{SP}(k)$	TemperatureSP	The value corresponding with the expected temperature Signal range <20, 25>°C (coating), <40, 60>°C (drying)	INT
2	$U_T(t)$	$U_T(k)$	AirTemperaturePV	The voltage value corresponding with the current temperature Measurement using a PT1000 sensor	INT
3	$P_{SP}(t)$	$P_{SP}(k)$	OverpressureSP	The value corresponding with the expected pressure Signal range <80, 100> mbar (coating)	INT
4	$U_P(t)$	$U_P(k)$	OverpressurePV	The voltage value corresponding with the current pressure	INT
5	$U_1(t)$	$U_1(k)$	aqBurnerCV	The voltage value corresponding with the heating power Signal range <0, 10>V, DC]	INT
6	$f_1(t)$	$f_1(k)$	rInFanCV	The frequency value corresponding with the inlet stream of air Inlet fan control signal <0,100>Hz	INT
7	$f_2(t)$	$f_2(k)$	rOutFanCV	The frequency value corresponding with the outlet stream of air Outlet fan control signal <0,100>Hz	INT

Table 1 contains the detailed description of all signals and corresponding variables used in the control program.

At this stage of the project, the authors examined two basic control algorithms used widely in the industry: the two state algorithm and the classic PID algorithm of ISA type with some modifications (anti-windup protection, dead zone, BIAS, etc.) [2]

The two state algorithm is an effective solution in the case of significant dead times and inertial delays of the plant (like in the case of the spray booth) and a relatively large range of tolerance of the control error. 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).

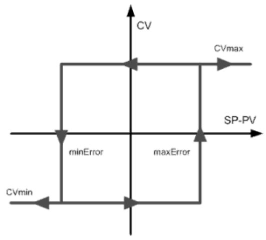


Fig. 3. Static characteristic of the two state control algorithm: *CVmax* – amplitude of the control signal for ON state, *CVmin* – amplitude of the control signal for OFF state, *minError*, *maxError* – the minimum value of error for switch on operation and the maximum value of error for switch off operation. In practice usually: *minError* = - *maxError*

The basic difficulty related to the use of the two state algorithm is a proper selection of *CVmin* and *CVmax*, the values to keep the controlled signal value symmetrically around the set point values *SP*. Usually *CVmin* and *CVmax* values are selected experimentally based on step characteristics for various operating points of the plant [3]. To minimize the controlled signal amplitude, the width of the hysteresis related to *minError* and *maxError* could be decreased even to zero, but it is not technologically correct because it leads to high frequency switching.

When a better quality of control is needed, PID or PID-like e.g. fuzzy PID, algorithms should be taken [9]. In the developed control system, the authors used the classic PID control algorithm of ISA type given by the formula (1).

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(t)\mathrm{d}t + T_d\frac{\mathrm{d}e}{\mathrm{d}T}\right) \tag{1}$$

where: $e(t)$, $u(t)$ – input signal (error signal) and output signal (control signal), respectively, K_p – proportional gain, T_i – integral time, T_d – differential time.

In practice, the algorithm (1) should be modified to make it more flexible and useful. One of the most important modification is anti-windup protection, connected with the integration part of the PID algorithm. In fact, the integrator (part I in the algorithm) should be limited, because all real time control systems have some internal saturations, usually related to actuators e.g. pumps, fans, valves etc. In the developed algorithm, the tracking anti-windup strategy, described in detail in [1], was used.

The next important improvement is a BIAS, which means adding a constant value to the calculated control signal $u(t)$. Sometimes this signal should be greater than zero, when the error signal $e(t)$ equals zero. This constant value is related to the operating point and should be determined according to technological conditions.

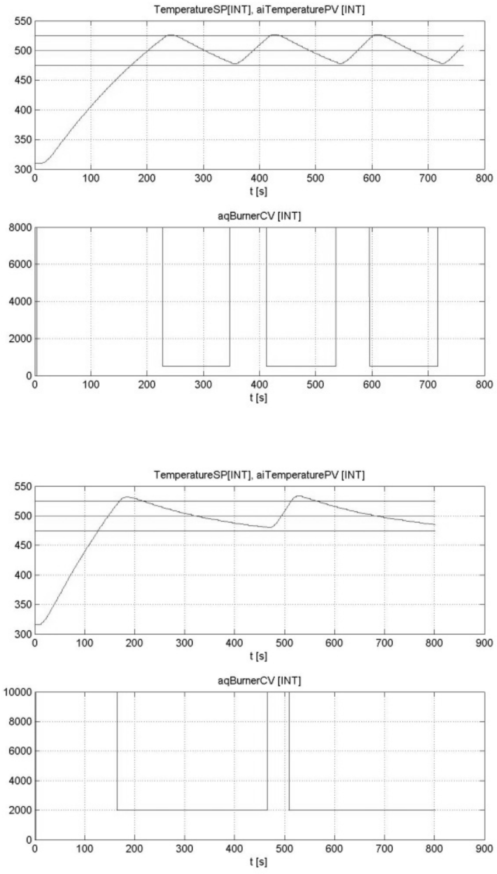
3. Experiments

The developed system was examined with two experimental algorithms, described shortly earlier. In both cases ±5% tolerance of the error for the controlled signal was taken. The authors present selected results of the real time experiments with the temperature control loop.

First, the two state algorithm was tested with two different sets of parameters to show how their values influence the control signal *CV* and the controlled signal *PV*. It should be noted that *CVmax* and *CVmin* were selected based on the experience of the operator. In the first case (Fig. 4 – 1), the amplitude of the *aiTemperaturePV* signal in the steady state is close to the assumed tolerance gap. The period of the ON state is about twice shorter than the period of the OFF state.

In the second experiment (Fig.4 – 2), *CVmax* and *CVmin* values were increased by 25% and 300%, respectively. The maximum value of the controlled signal is a little outside the tolerance gap, but the period of the OFF state is much longer than in the first case.

Generally, an operator has the opportunity to shape the controlled signal to achieve two different results: a better quality of the control and frequent switching of the control signal or a worse quality but less frequent switching. As usual, the final decision should be taken by the operator.


1)

2)

Fig. 4. Temperature stabilization in the drying mode with the developed two state algorithm: 1) *CVmax* = 8000, *CVmin* = 500, 2) *CVmax* = 10000, *CVmin* = 2000

Next the PID control algorithm, with experimentally selected parameters, was examined. In two experiments, the authors tested the influence of the integral part of the algorithm on the quality of the control, which was measured using some quality factors given in Table 2. In the first experiment, the time integral T_i equals 10 s, which means the “strong” integration action. To make integration weaker, T_i was increased to 25 s.

In both cases the control system was stable. It is important that T_i has significant influence on: T_R – control time, T_N – rise time, M_P – relative overshoot, but unfortunately it is impossible to optimize the control system based on all those parameters at the same time.

According to Table 2, the T_R and T_N quality parameters are inversely correlated with the M_P parameter. It means that if we would like to speed up the control, which is related to the reduction of the T_N parameter, it would be always connected with the increase in the M_P value.

Non-linearity of the actuator, i.e. a burner e.g. saturation, dead zone, hysteresis, is another problem of using the PID algorithm. Usually a static function of the burner is unknown and the tuning process of the PID algorithm is harder (e.g. lack of information about real saturation could be a reason for an excessive integration, which causes wind up effect)[1].

Tab. 2. List of selected quality control factors for the system with the PID algorithm, where T_R – control time, T_N – rise time, M_P – relative overshoot, M_{PP} – absolute overshoot, e_u – static error, *ISE* – integral square error, *ISA* – integral absolute error

No	T_R s	T_N s	M_P INT]	M_{PP} %	e_u [INT]	ISE [INT]	ISA [INT]
1	123	212	78	15.6	0	7.83e+5	4.30e+8
2	152	461	37	7.40	0	9.55e+5	6.68e+8

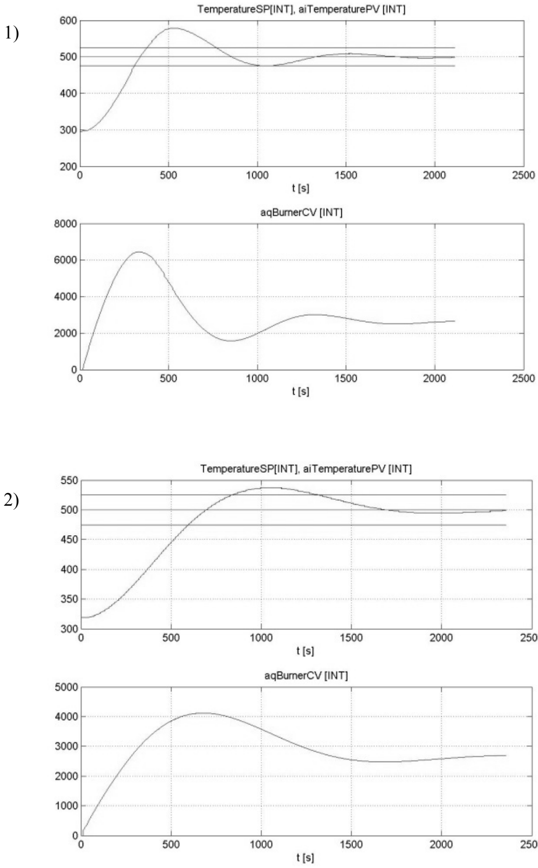


Fig. 5. Temperature stabilization in the drying mode with the developed PID algorithm: 1) $K_p = 1$, $T_i = 10$ s, 2) $K_p = 1$, $T_i = 25$ s

4. Conclusions

At this stage of the project, both developed control algorithms provided the sufficient quality of the temperature control. Unfortunately, a relatively wide range of temperature set points (from 20 to 60 degrees Celsius) has significant influence on the spray booth dynamics as a temperature plant. It means that in both modes i.e. coating and drying, the parameters of the two-state and PID algorithms should be re-tuned to keep the same quality of the control. The changeable outside temperature which influences the dynamics of the spray booth is another problem.

Additionally, the non-linearity of the burner can make the tuning process of the two-state and PID algorithms harder.

In the case of changeable dynamics of the spray booth as a temperature plant other methods should be used to make the control system robust e.g.:

1. robust control [4],
2. fuzzy control [2], [9].
3. autotuning for both two-state and PID algorithms [3];
4. fuzzy supervisory control.

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., Kołodziejczyk J.: A method of fast application of the fuzzy PID algorithm using industrial control device. Lecture Notes in Computer Science, 2012 Volume 7267/2012, 237-246.

[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. 297-300.

[5] Nikończuk P., Chmielowski M.: Stabilizacja przepływu powietrza w kabinach lakierniczych. Nowe rozwiązania techniczne w chłodnictwie i klimatyzacji w zastosowaniach praktycznych, 36 Dni Chłodnictwa Konferencja Naukowo-Techniczna Poznań, SYSTHERM Sp. z o.o, 2004 s 153-156.

[6] 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.

[7] Nikończuk P.: Wstępna analiza zagrożeń w eksploatacji kabin lakierniczych wyposażonych w rekuperatory. Logistyka 5/2014 1183-1188.

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

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

[10] http://cameoline.pl/

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