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

A preliminary analysis of spray booth temperature control using PWM modulation with dynamic trigger period

Abstract

The authors present a concept of the temperature control system for a spray booth equipped with a single burner. The control system uses PWM modulation with dynamic trigger time periods. The paper presents the results of temperature control simulations for different conditions of external air temperature as well as the analysis of external air temperature and trigger time period impact on temperature fluctuation amplitudes inside the spray booth. A dynamic trigger period will minimize the number of burner ignitions with acceptable fluctuation amplitudes of temperature. The minimization of the number of burner ignitions will increase the life time of a burner and decrease the fuel consumption used to start a burner.

Keywords: spray booth, temperature control, PWM control.

1. Introduction

During a spray booth operation in the painting mode inside a work chamber the air is constantly exchanged. The air flow volume is in a range of 20,000 – 30,000 cubic meters per hour. With such air flow volume, a high power heating unit is necessary to heat the air at the air makeup unit. The temperature of fresh air blown into the work chamber is similar to the room temperature (about 20°C). There are many methods of air heating in spray booths [5]. An oil or a gas burner is most often used. There are single burners or two stage burners. In modern spray booths, burners with modulated power are used. The power of burners in refinishing spray booths is in a range of 200 – 300 kW. There are many methods of temperature control. A PID controller is the most popular temperature control unit. During PID control of single or two stage burners the temperature fluctuations occur. Too high fluctuation amplitudes cause discomfort to the painter. Research on spray booth dynamic [4, 6] and temperature control are [1, 3, 7] conducted by academia and business. The conducted research are focused on the minimization of fuel (or power) consumption but do not consider the quantity of burner ignitions. The number of burner ignitions has also the impact on the total fuel consumption. It has also a major impact on burner technical condition and maintenance costs. The research on burner ignition sequencing were made for high power multi burner installations like a steel-making process [8] or typical utility process [9]. The goal of the research was the minimization of power variations, fuel consumption and NO_X emission.

The authors conducted an analysis of the temperature amplitude fluctuation inside the spray booth with a single burner controlled by a PWM controller for different trigger periods. The goal of the analysis was to minimize the number of burner ignitions. The minimization was realised using dynamic trigger periods of PWM control with the acceptable fluctuation amplitude of the temperature inside the working chamber of the spray booth.

2. PWM control of single oil burner

The Pulse Width Modulation (PWM) is realized on the basis of the following parameters: current fresh air temperature T_O, expected air temperature, exchanged air flow volume $\dot{V}$, heat power of the burner Q_B, efficiency of the heat exchanger η_B. Based on the mentioned parameters there can be calculated the average heat power Q_A which is necessary to heat the fresh air with the air flow volume $\dot{V}$ up to the expected temperature T_{SP}. Also the heat flux $\dot{Q}_B$ from burner to the fresh air through the air exchanger can be calculated. During PWM modulation constantly after the same time periods τ_i the pulses are triggered. Each pulse runs the heat source (burner) with constant heat power Q_B. In Figure 1, the idea of the PWM single burner control is shown.

The pulse width (period) τ_B should ensure the adequate heat power necessary to heat the air during the time period τ_i

$$\int_0^{\tau_B} \dot{Q}_B \, d\tau = \int_0^{\tau_i} \dot{Q}_A \, d\tau \qquad (1)$$

Based on equation (1), the percentage period of pulse can be calculated

$$PWM = \frac{Q_A}{Q_B} 100\% \qquad (2)$$

Finally, the time period τ_B of pulse is PWM percent of the trigger period τ_i

$$\tau_B = \frac{PWM}{100\%} \tau_i \qquad (3)$$

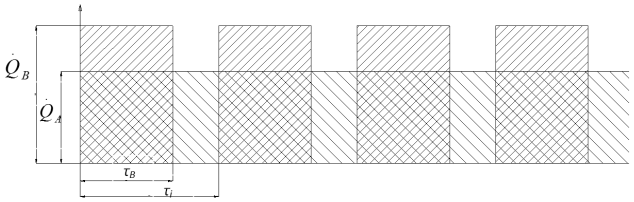

Fig. 1. Pulse width modulation based on the average heat flux necessary to heat the fresh air and heat flux from the burner

3. Real time control experiments

The structure of the control system is shown in Figure 2. A programmable controller with a touch panel (OPLC) is its main element. An OPLC with peripheral devices i.e. a temperature measurement device (PT1000) and a relay connected with a burner are elements of the Direct Digital Control level.

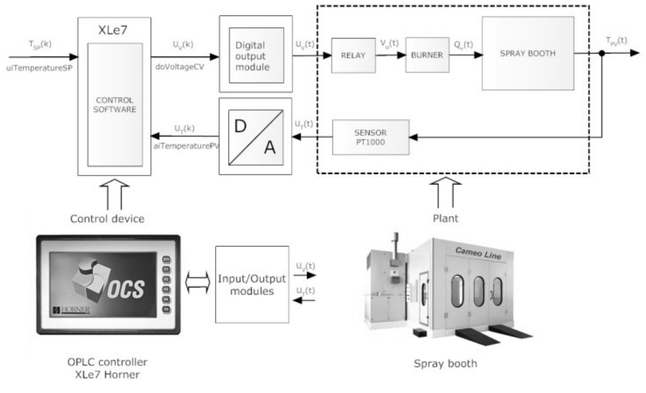

Fig. 2. Structure of the temperature control system of the spray booth

An idea of temperature PWM control is also related to the discrete two state nature of an actuator i.e. a burner. Producers usually use it instead of analog burners to cut price of the final spray boot.

At the current stage of the research, simulations were made using a numerical model of the control system presented in Figure 2. The model was developed by the authors [4], [6]. The spray booth was modeled as a control plant PT2 type (a second order inertial plant.)

Figure 3 shows the PWM factor calculated for different temperatures of the external fresh air. Calculations were made for the expected temperature 20°C for the spray booth equipped with a single burner. The power of the burner P = 300 kW, the heat exchanger efficiency η_B = 90%, the exchanged air flow volume $\dot{V}$ =20,000 m^3/h.

As shown in Figure 3, the minimum temperature of fresh air is equal to -14°C. For the fresh air with teperatures lower than -14°C the burner heat power is too low to heat the air to the expected temperature 20°C.

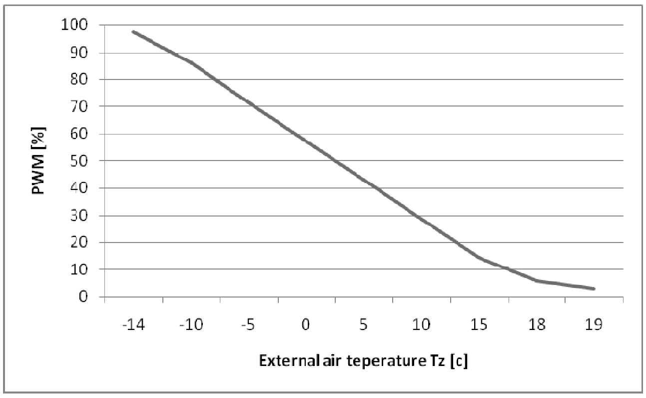

Fig. 3. PWM factor values for different teperatures of external fresh air

The trigger time period τ_i and modulation factor *PWM* influence the temperature fluctuation amplitude. Figure 4 presents simulations of temperature changes inside the spray booth for fresh air temperature T_Z = -10°C and two different trigger time periods τ_i =30 s and τ_i = 90 s. It is obvious that increase in the trigger time τ_i causes increase in the fluctuation amplitudes. Figure 4 shows the lower and upper values of the temperature fluctuation amplitudes for different temperatures of external fresh air. All the presented data are the result of simulations for the spray booth condition presented above ($\dot{V}$ =20000 m^3/h, P=300 kW, η_B = 90%, T_{SP} = 20°C).

The time domain charts depicted in Figure 4 suggest that the minimization of trigger time periods τ_i decreases the amplitude of temperature fluctuations. But taking into consideration the burner as the actuator, the quantity of burner ignitions should be minimized. Minimizations of ignitions quantity increase the burner life time and the consumption of fuel used to start the burner. The pulse width time τ_B also has to be adequate to the burner dynamic.

Hence, the selected optimal trigger time period τ_i must be a result of the compromise between the amplitude of temperature fluctuations and the quantity of burner ignitions. The authors propose to work up the temperature control system for refinishing a spray booth which uses PWM control with a dynamic trigger time period τ_i. The dynamic trigger time period τ_i is determined adequately to the average temperature of external fresh air. The fluctuation amplitudes of Figure 5 show that for extreme temperatures of fresh air (-14°C and 19°C) the trigger time period τ_i = 120 s brings the low amplitude of temperature fluctuations (about 1°C). As shown in Figure 3, temperatures -14°C and 19°C have the extreme values of the PWM factor.

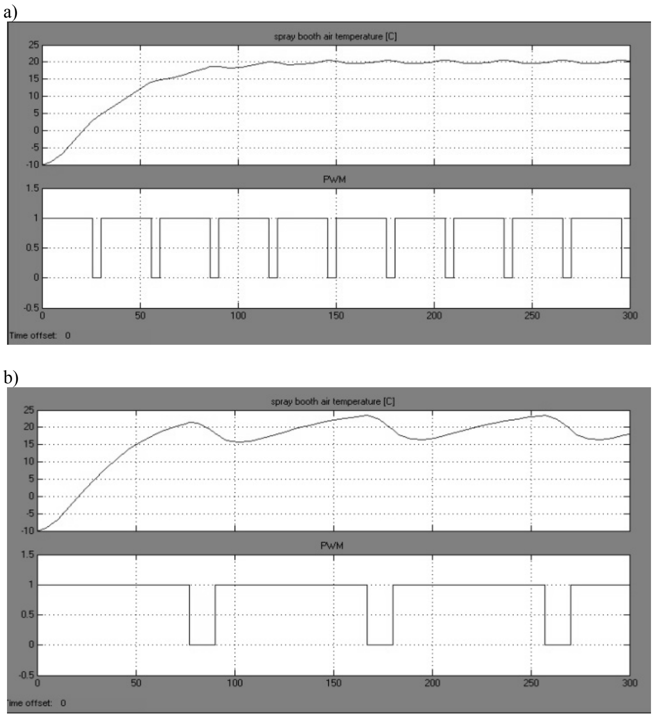

Fig. 4. Changes of air temperature inside the spray booth for trigger periods τ_i=30 s (a) and τ_i = 90 s (b)

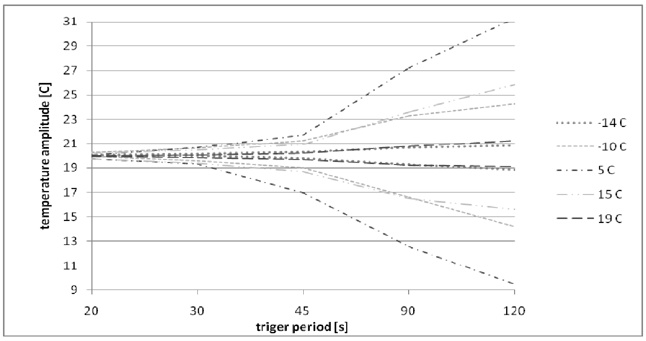

Fig. 5. Lower and upper amplitudes of temperature fluctuations for the expected temperature T_{SP} = 20^{0}C and different trigger periods τ_i

4. Conclusions

Based on the obtained results, one can state that the algorithm of PWM control for a single burner can be implemented. The dynamic trigger time period τ_i can be determined based on the curves of temperature fluctuation amplitudes for different external temperature, as shown in Figure 5. A dynamic trigger period will minimize the number of burner ignitions with acceptable fluctuation amplitudes of temperature. The minimization of the number of burner ignitions will increase the life time of the burner and decrease the consumption fuel used to start the burner. Nowadays control systems are based on PLC controllers. So the proposed algorithm is easy to implement in a spray booth control system based on a PLC controller [2]. The authors work on the autotunnig algorithm for the PWM temperature control system. The system has to learn external air temperature influence on spray booth temperature fluctuations, then will predict correct values of the trigger time period τ_i, which will ensure acceptable temperature fluctuations. The modulation method can also be extended for two stage burners and another heat source used in a spray booth. The developed autotunnig algorithm will be applicable for all kinds of heating units.

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Slawomir JASZCZAK, PhD

Between 1994 and 2002 he, as assistant at the Department of Maritime Technology of the Technical University of Szczecin, conducted research connected with underwater vehicles control using artificial intelligence methods. Since 2002 he has been 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

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 degree from 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