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# Modelling of a Thermal Spraying Controller Using MATLAB/Simulink

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Abstract— There are a number of thermal spraying systems, which are based on air flame processes. Stable control of such systems is difficult to achieve due to the complexity of the combustion process in a small burner and varying process parameters. Therefore, modelling of a system control can provide useful information in optimising the performance of thermal spraying systems. In this research, a simulation model of a controller thermal sprav was developed using MATLAB/Simulink software. The model was evaluated by comparing the simulated and actual process parameters. The obtained results indicate that the developed model of system controller provides the main required control parameter, the fuel-air ratio, which corresponds with the optimal value used in the actual control of the thermal spraying system.

Keywords—MATLAB/Simulink, modeling, control

# I. Introduction

Thermal spraying processes based on combustion processes where air is used as an oxidizer are less common than processes with oxygen. However, air flame based spraying processes can provide a number of advantages, for example: lower combustion temperature, which reduces a formation of brittle phases of WC and reduced running costs (Ref 1). In designing a thermal spraying system controller, it is important to achieve an optimal combustion process, while keeping the controller simple, cheap yet robust. Hence, modelling of the processes inside of a thermal spraying system is a valuable simulation tool, which can be applied to achieve the desired performance of a thermal spraying system.

Recent analyses of combustion processes focus on control concepts, which are based mainly on low-order modelling. A relatively new approach is multidimensional simulation, in which an unsteady Navier-Stokes flow solver is coupled with a control algorithm. However, this method of control would be too complex for a basic thermal spraying system. A number of concepts of combustion control have been developed for internal combustion engines and turbines, which are mainly divided in two categories (Ref 2): Operating point control (OPC) and Active combustion control (ACC). In OPC, certain parameters, such as: the stoichiometric ratio in a r equired range is maintained. In ACC, the mixture properties (e.g. fuel flow rate) are modulated by the controller to improve the G Gruhler

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combustion characteristics or to limit combustion pressure oscillations, (Ref 3). Modelling specifically oxy flame combustion and thermal spraying processes was presented in (Ref 4-7). In this research, the modelling approach is based on the operating point control strategy using MATLAB/Simulink, which is a tool extensively used in engineering calculations, for example in (Ref 8). The model consists of sub-models of various stages and units of the control system, such as: the air and fuel supply, the combustion process, the combustion chamber and the nozzle. The model was applied and evaluated on the system controller described in Ref 9.

# п. Theoretical Background

### A. Combustion Model

The combustion model is based on a low order approach of combustion simulation (Ref 10). The model includes the calculation of the adiabatic flame temperature and the composition of the exhaust gas. The adiabatic flame temperature is the temperature that would be achieved if the combustion occurred in an adiabatic, hence in an ideal insulated combustion chamber. Because no heat exchange occurs with the environment, the temperature of the exhaust gas is the same as the flame temperature. In a real application, there is of course always a h eat exchange with the environment. Hence the temperatures of the exhaust gas calculated with this method will be higher than in reality.

The adiabatic flame temperature or the exhaust gas temperature is calculated as follows, (Ref 10):

$$T_{exhaust} = \frac{LHV + \frac{m_{air}}{\dot{m}_{fuel}} c_{p,air} T_{air}}{c_{p,exhaust} \left(1 + \frac{\dot{m}_{air}}{\dot{m}_{fuel}}\right)}$$
(1)

where  $\hat{m}_{exhaust}$  represents the mass flow rate of the exhaust gas,  $c_{p,exhaust}$  the specific heats of air and the exhaust gas,  $T_{air}$  the air temperature, *LHV* the lower heating value of the fuel.

The composition of the exhaust gas is influencing the adiabatic flame temperature and it also affects the operating conditions of the accelerating nozzle. It is assumed that the reaction between fuel and air can be described by a single global reaction. In the case of kerosene the reaction is as follows:

$$C_{12}H_{24} + 24 O_2 \rightarrow 12 CO_2 + 12 H_2 O$$
 (2)

In reality, the combustion of kerosene and air consist of several elementary reactions and would also result in the generation of  $NO_*NO_2$  and CO. The specific heat of the exhaust gas is calculated using the mass fractions of the exhaust gas components. Similar to the specific heat calculation, the molar mass of the exhaust gas can be calculated by using the molar fractions of the exhaust gas components:

$$M_{exhaust} = n_{N2} M_{N2} + n_{02} M_{02} + n_{02} M_{02} + n_{H20} M_{H20}$$
(3)

where  $n_{N2}$ ,  $n_{02}$ ,  $n_{022}$ ,  $n_{H20}$  represent the molar fractions,  $M_{N2}$ ,  $M_{02}$ ,  $M_{022}$ ,  $M_{H20}$  the molar masses of  $N_2$ ,  $O_2$ ,  $CO_2$ ,  $H_2O_2$ 

#### B. Combustion Chamber Model

It is assumed that pressure and temperature in the combustion chamber are constant and location-independent. Furthermore it is assumed that the ideal gas law is applicable. In this case the pressure in the combustion chamber is calculated as follows:

$$p_{chamber} = \frac{m R_{exhaust} T_{exhaust}}{v_{chamber}}$$
(4)

where m represents the mass of the mixture,  $V_{chamber}$  the volume of the combustion chamber,  $T_{exhaust}$  the temperature of the exhaust gas,  $R_{exhaust}$  the specific gas constant of the exhaust gas.

## C. Accelerating Nozzle Model

The jet velocity at the exit of a de Laval nozzle is calculated with the following formula:

$$u_{2} = \left[2\frac{\kappa}{\kappa-1}RT_{1}\left\{1 - \left(\frac{p_{2}}{p_{1}}\right)^{\frac{\kappa-1}{\kappa}}\right\}\right]^{\frac{1}{2}}$$
(5)

where  $T_1$  represents the temperature at the inlet of the nozzle,  $P_1$  the pressure at the inlet of the nozzle, K the ratio of specific heats of the gas, R the ideal gas constant,  $P_2$  the pressure at the exit of the nozzle.

Ignoring the particles of spraying material due to their negligible mass in comparison with the amount of the conveying exhaust gas, the mass flow rate through the nozzle is calculated as follows:

$$\dot{m}_{nozzle} = A_{throat} \left[ 2 \frac{p_1}{v_1} \frac{\kappa}{\kappa+1} \right]^{\frac{1}{2}} \left[ \frac{2}{\kappa+1} \right]^{\frac{1}{\kappa-1}}$$
(6)

where  $A_{\text{throat}}$  represents the cross-sectional area at nozzle throat, P1 the pressure at the inlet of the nozzle, V1 the specific volume of the gas.

#### D. Fuel and Air Supply Systems Models

For modelling the air and fuel supply systems, a pipe with a pressure drop due to friction and turbulence is applied. Using the Bernoulli equation, neglecting the influence of gravity, the flow rate can be calculated as follows:

$$\dot{V} = A \, u = \alpha \, A \, \left[ \frac{2 \left( p_1 - p_2 \right)}{\rho} \right]^{\frac{1}{2}} \tag{7}$$

where A represents the cross-sectional area of the pipe,  $p_1$  the pressure at the inlet of the pipe,  $p_2$  the pressure at the outlet of the pipe,  $\rho$  the density of the fuel,  $\alpha$  the flow coefficient.

The model of the fuel system is derived from equation (7) using the pressure of fuel **Pfuel** instead of **P1** and the combustion chamber pressure **Pchamber** instead of **P2**. To represent the proportional valve, the cross-sectional area can be modified by multiplying it with a factor. Similar to the fuel system, the air system can be modelled. It is assumed that the air flow is incompressible.

By combining the models of the combustion chamber and the nozzle, the model of the thermal spray gun is generated. For modelling of the whole thermal spraying, the fuel and air supply models are added to the model of the spray gun.

# III. MATLAB/Simulink Models

The above mentioned formulae were used for developing the MATLAB/Simulink models of the HVAF thermal spraying system (Figs. 1-5).

Time delays are used in the adiabatic flame temperature model in order to prevent an algebraic loop (Fig. 1). An algebraic loop occurs if the forward and the feedback branches of a signal path only consist of direct feedthrough blocks. Direct feedthrough blocks, are blocks where the input signals are directly passed to the output, such as Gain, Product or Sum blocks.

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*Fig 3: Simulink model of the combustion chamber* 



Fig 4: Simulink model of the thermal spray gun



Fig 5: Simulink model of the HVAF thermal spray controller

# **IV. RESULTS**

Experimentally, the fuel/air ratio for a sustainable thermal spraying process, with powder as a s praying material, was determined as 0.01. For evaluation of the developed MATLAB/Simulink model, selected signals from the model were compared with measurement data of the real process on the thermal spraying system controller, which are shown in Table I.

TABLE I: AIR FLAME PROCESS PARAMETERS

Parameter	Value
Air flow rate (kg/s)	0.234
Pressure in combustion chamber (MPa)	0.680
Fuel flow rate (kg/s)	0.0026
Fuel pressure (MPa)	0.800

Prior to the evaluation, the model was parameterised by adjusting the parameters A and  $\alpha$  in the air and the fuel system blocks according to measurements that where performed in a narrow range around the typical operating point of the thermal spray gun. As the control of combustion in the thermal spraying process is an operating point control, oscillations in the signals are of minor interest, as long as the amplitude is small and the mean value can be seen as constant (Fig. 6).



Fig 6: Simulated and measured fuel flow rate

The simulated and the measured air flow rate were compared. Because the mass flow rate of air was not measured directly, but calculated by equation from the measurement data of the air pressure, the air flow rate and the air temperature sensor, it could result in an adding up of the measurement errors. Due to this fact the focus of the parameterisation of the model was on the flow rate and not on the mass flow rate of air.

## v. CONCLUSION

In this research, a simulation MATLAB/Simulink model of an air fame thermal spray controller was developed. The core of the model is a low order combustion model, which is sufficient for simulation and control of the combustion process for thermal spraying. The model was evaluated by comparing the simulated process parameters with the actual process control parameters used by the controller. The obtained results indicate that the developed model provides the fuel-air ratio, which corresponds with the value used in the actual control of the thermal spraying system.

The simulation model consists of a number of sub-models representing the elements of the system. Hence, the model can be easily modified or expanded, depending on the design requirements.

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