

EQUIVALENT SYSTEM METHOD APPLIED TO MULTIVARIABLE CASCADE CONTROL OF INDUSTRIAL TUBULAR FURNACE

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The purpose of this paper is to apply and improve a multivariable advanced control structure on the basis of equivalent system technique for two-flow tubular furnace, which has widespread application in industrial furnace plants. After analyzing the dynamic properties of furnaces, it was concluded that these furnaces are symmetric MIMO processes, having two inputs and two outputs. There are a numerous reciprocal interactions between input and output variables. For this reason, equivalent system method was employed to investigate and develop advanced control structures for these furnaces. According to this method, symmetric MIMO system was divided into two equivalent separate systems. Finally, the equivalent model control design of combined feedback/feedforward multivariable cascade system is given and the results are presented.

Keywords: industrial furnace plant, symmetric MIMO systems, combined feedback/feedforward control structure

Introduction

Furnaces are the basic and most important industrial units of petroleum refineries and petrochemical processes.

The furnaces can have single or multiple flows according to their technological structures. They are made up from the regions of convection and radiation. The heat exchange between chimney gasses and petroleum flows is realized in the regions of convection and radiation. Sufficient quantity of oxygen, required for the control of the burning process in these regions, is obtained from the air. In addition, an optimum amount of air is desired for the economical and ecological sound burning in furnaces.

There appeared many studies in literature about controlling the burning process [1-7]. These studies have shown that furnaces are multivariable, distributed, complex dynamic control systems. In multiple flow furnaces, there are also large delays in their dynamic channels and cross relationships between the control parameters.

In most applications, a linear model was used to present the dynamic behaviour of the process (impulse/step response function, transfer function, state-space model).

Due of these complexities, it is necessary to investigate the more effective multivariable advanced control structures working on the basis of equivalent system technique [8]. The following steps are carried out in the study of the equivalent system method:

- Transformation of the system to the equivalent method.
- Constructing the control algorithms of the system according to equivalent model.
- Application of the control algorithms to separate systems working under different conditions.
- Performance evaluation.

In this paper, an advanced multivariable cascade equivalent control system has been developed for two flow industrial petroleum refinery furnaces. The following sections present the proposed algorithm in detail. The simulation results are given. Finally, discussion and conclusion are presented.

Process description

In the industrial furnace plant, crude oil is passed through two spiral pipes and divided into two flows and then it enters into the burning chambers in the convection and radiation sections. Firstly, the petroleum

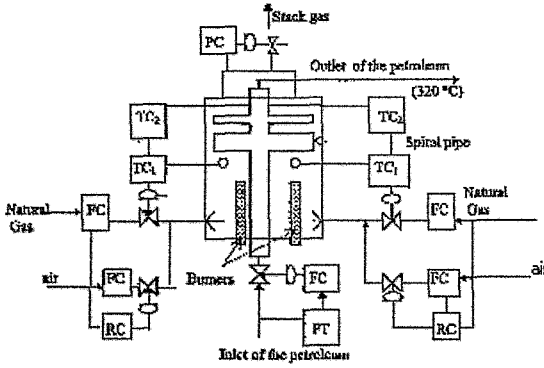


Fig.1 Schematic diagram of tubular furnace. FC: The feed control, PC: Control of pressure, RC: Ratio control, TC₁: Temperature control of the chimney gasses, TC₂: The outlet temperature of the petroleum

flow is heated by chimney gasses, and then at the outlet, two flows are combined by the flame in the burning chamber. The unit operates between 700 and 900 °C intervals with a duty to bring the outlet crude oil to 320 °C, and to leave the stack gases at 750 °C. The outlet temperature of the petroleum in the left and right pipeline is obtained by supplying sufficient quantity of oxygen and natural gas to the right and the left fuel chambers. This creates reciprocal relations between these parallel transfer channels. When these properties of the furnace are considered, it is quite important to develop and apply new temperature control algorithms.

In a burning process, the oxygen/fuel ratio must be $\delta_{\min} \leq \delta \leq \delta_{\max}$. So, the complete combustion affecting the concentration in the chimney gasses that pollute the environment is achieved by adjusting the vacuum required for the furnace. On the other hand, the complete combustion is evaluated by the concentration of the oxygen in the chimney gasses. Besides, the temperature of the combustion depends significantly on the quantity of the used air. The schematic diagram of an industrial petrol refinery furnace is illustrated in Fig.1.

Transfer function of the process

Our industrial research on the dynamic characteristics of furnaces reveal that furnaces consist of a MIMO system with two inputs and two outputs and that there are symmetric reciprocal interactions between the input-output variables. A block diagram showing the dynamic channels is given in Fig.2, where $x_1, x_2, x_f, y_1, y_2, y_{c1}$ and y_{c2} are the consumption of natural gas, given to the left and right fuel chambers. The consumption of the petroleum flow given to furnace, the outlet temperatures of the petroleum in the left and right sides and the temperature of the chimney gasses which enter the left and right sections of the convection chamber, respectively.

The transfer function of the dynamic channels was determined from the reaction curve of the process

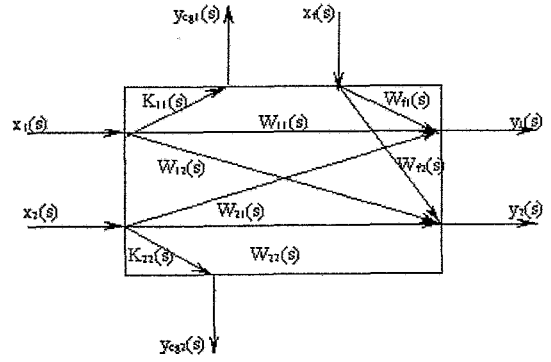


Fig.2 Block diagram of the dynamic channels

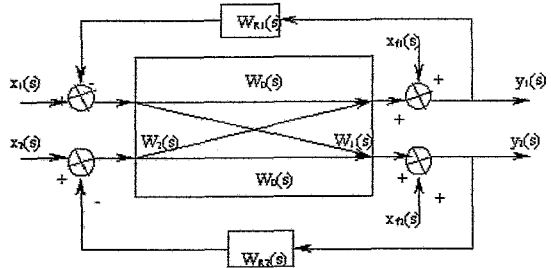


Fig.3 Block diagram of the symmetric control systems with two inputs-outputs

obtained by \pm step disturbances to the fuel inlet of the furnace.

Since the furnace with two flows is a symmetric process, the transfer functions are as follows.

$$W_{11}(s) = W_{22}(s), \quad W_{12}(s) = W_{21}(s), \quad K_{11}(s) = K_{22}(s) \quad (1)$$

The Laplace domain transfer function of the symmetric multivariable system is:

$$W_{11}(s) = \frac{5 \cdot 10^2}{3.56 \cdot 10^6 s^3 + 7.96 \cdot 10^4 s^2 + 4.71 \cdot 10^2 s + 1} e^{-180s} \quad \text{°C / \% max. fuel consumption} \quad (2)$$

$$W_{12}(s) = \frac{4 \cdot 10^2}{8.74 \cdot 10^6 s^3 + 10.9 \cdot 10^4 s^2 + 5.31 \cdot 10^2 s + 1} e^{-180s} \quad \text{°C / \% max. fuel consumption} \quad (3)$$

$$W_{f1}(s) = \frac{1.6 \cdot 10^2}{5.22 \cdot 10^6 s^3 + 8.68 \cdot 10^4 s^2 + 4.88 \cdot 10^2 s + 1} e^{-180s} \quad \text{°C / \% max. fuel consumption} \quad (4)$$

$$K_{11}(s) = \frac{10 \cdot 10^2}{3680s^2 + 280s + 1} e^{-30s} \quad \text{°C / \% max. fuel consumption} \quad (5)$$

Symmetric multivariable control system of the process

Block diagram of symmetric control system with two input-output for two flow furnaces is given in Fig.3.

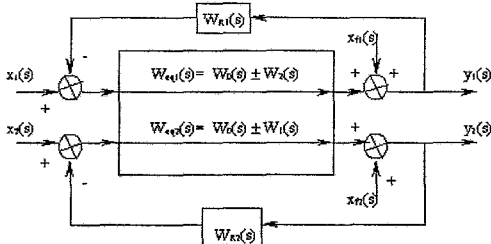


Fig.4 Block diagram of control of the equivalent transfer function

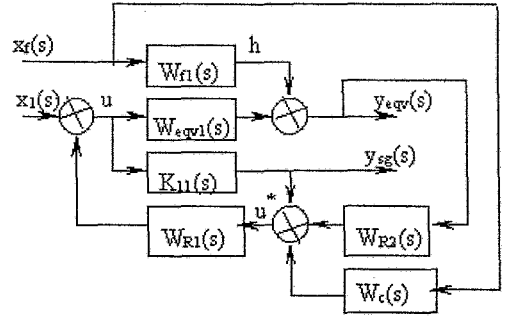


Fig.6 Combined feedforward/feedback equivalent separate system

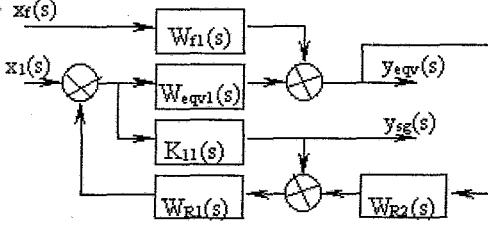


Fig.5 Block diagram of multivariable cascade equivalent separate system

Equivalent decoupled control system

Equivalent block diagram of the relevant control system is given in Fig.4. In this system, because the transfer function of the equivalent channels is symmetric, it is identified as,

$$W_{qv1}(s) = W_{qv2}(s) = W_0(s) \pm W_1(s) \tag{12}$$

The differential equations of this system can be formulated as follows.

$$y_1(s) = W_0(s)u_1(s) + W_1(s)u_2(s) + W_f(s)f_1(s) \tag{6}$$

$$y_2(s) = W_1(s)u_1(s) + W_0(s)u_2(s) + W_f(s)f_1(s) \tag{7}$$

Here, $W_0(s)$ is the transfer function of the main control channel; $W_1(s)$ is the transfer function of the inside cross dynamic channel and $W_f(s)$ is the transfer function of the petroleum flow as a disturbance. Since the system is symmetric.

$$\begin{aligned} W_0(s) &= W_{11}(s) = W_{22}(s) , \\ W_1(s) &= W_{12}(s) = W_{21}(s) , \\ W_f(s) &= W_{f_2}(s) \end{aligned} \tag{8}$$

Due to the symmetry of the system, the transfer function of the main and cross channels are identical and in accordance with the other.

Differential equation of the controller system is:

$$\begin{aligned} u_1(s) &= W_R(s) [x_1(s) - y_1(s)], \\ u_2(s) &= W_R(s) [x_2(s) - y_2(s)] \end{aligned} \tag{9}$$

The form of transfer function matrices

$$Y(s) = [W_0(s)E + W_1(s)A]u(s) + W_f(s)E f(s) \tag{10}$$

where,

$$\begin{aligned} A &= \begin{vmatrix} 0 & 1 \\ 1 & 0 \end{vmatrix} \quad E = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} \quad f(s) = \begin{bmatrix} f_1(s) \\ f_2(s) \end{bmatrix} \\ U(s) &= W_R(s)E[x(s) - y(s)] \end{aligned} \tag{11}$$

Equivalent multivariable cascade control system

A block diagram of the multivariable cascade control of the equivalent system is shown in Fig.5. In this separated system, the object of the control was also divided into two stages.

The transfer function of the internal chimney gas is $K_{11}(s)$ and the transfer function of the equivalent channel is $W_{eq}(s)$. In this system, the same controller could be used for both of two control loops [1-4].

The main feature of the system is that the optimum parameters of the stabilizator and the regulator controller are found in two control loops with different frequencies. For this purpose, firstly the parameters of the stabilizator loop are calculated and then the parameters of the regulator are evaluated within the framework of the calculated optimum parameters.

In this stage, for the evaluation of the parameters of the regulator loop, a transfer function is obtained by the combination of the transfer function of the closed loop stabilizator and the transfer function of the equivalent channel. So the transfer function of the controller object can be written as follows;

$$W_{eqv}^*(s) = K_{11}(s)/1 + W_R(s)K_{11}(s) + W_{eqv}(s) \tag{13}$$

Combined feedback/feed forward control system in equivalent multivariable cascade

As known, these systems consist of two loops. One of them is open loop based on compensating the exterior effects (disturbances) and the other is closed loop based on the feedback control principle [8-10]. Combined

Table 1 The optimum PI parameters of the control systems in furnace

Control Systems	Loop of Regulator		Loop of Stabilization		Loop of Compensation	
	$K \times 10^4$	$T \times 10^4$	$K \times 10^4$	$T \times 10^4$	$K \times 10^4$	$T \times 10^4$
For $W_{11}(s)$	-5.85	0.05	-	-	-	-
For $W_{eqv}(s)$	44	0.01	-	-	-	-
Multivariable						
Cascade	5.5	0.013	70	1.12	-	-
Control						
Combined						
multivariable	5.5	0.013	70	1.12	0.1	20
cascade						

open and closed loop multivariable cascade control structure of the furnace is given in Fig.6.

$$u(s) = x_1(s) - W_{R1}(s)u^*(s); \tag{14}$$

$$y_{eqv1}(s) = W_{eqv}(s)u(s) = [W_0(s) - W_1(s)]u(s); \tag{15}$$

$$h(s) = W_f(s)x_{f1}(s); \tag{16}$$

$$y_{eqv}(s) = y_{eqv1}(s) + h(s); \tag{17}$$

$$y_{cg1}(s) = K_{11}(s)u(s); \tag{18}$$

$$u^*(s) = y_{cg1}(s) + W_{R2}(s)y_{eqv}^* - W_c(s)x_{f1}(s); \tag{19}$$

The transfer function of the whole system between the inputs (x_1, x_{f1}) and the output (y_{eqv}^*) are described as follows,

$$y_{eqv1}^*(s) = \frac{W_{eqv1}(s)}{1 + W_{eqv1}(s)W_{R1}(s)W_{R2}(s) + W_{R1}(s)K_{11}(s)}x_1 + \left[\frac{W_{f1}(s) + W_{R1}(s)K_{11}(s)W_{f1}(s)}{W_{eqv1}(s)} + W_{R1}(s)W_c(s) \right]x_{f1}(s) \tag{20}$$

From this statement, according to provision of the absolute invariant, the transfer function of the compensator is defined as follows.

$$W_c(s) = - [W_{f1}(s) + W_{R1}(s)K_{11}(s)W_{f1}(s)] / W_{eqv1}(s)W_{R1}(s) \tag{21}$$

Mostly, in this type of systems, because the transfer function determined by the principle of the absolute invariant consists of a higher degree of fraction, realization of this statement can be difficult.

This feature can practically be expressed by showing the compensatory as a simplified differential block,

$$W_c(s) = K [Ts / (Ts + 1)] \tag{22}$$

Naturally, the compensator block expressed in this way cannot completely compensate the external disturbances. But, by selecting the appropriate parameters of the K and T , the outlet value of y_{eqv1}^*

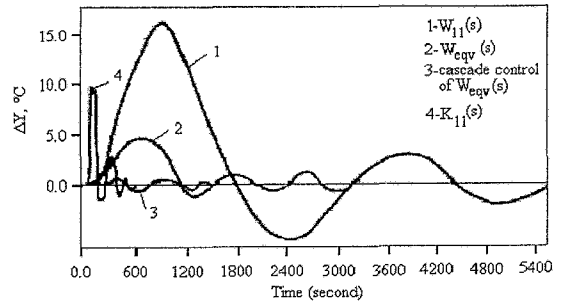


Fig.7 Responses of PI control to the 1- $W_{11}(s)$, 2- $W_{eqv}(s)$, 3- Cascade control of $W_{eqv}(s)$ and 4- $K_{11}(s)$

could be made independently from the external disturbance. Since the block of the compensatory cannot affect the stability of the system there is more freedom to determine its parameters. When the system was designed, optimum parameters of the closed loop system were selected and the parameters of the compensator were calculated in a way to reduce the dynamic deviations to minimum.

Application results

In this section the results are presented obtained from application of the combined multivariable cascade advanced equivalent control structure in industrial tubular furnace.

The responses $W_{11}(s)$, $W_{eqv}(s)$ and $K_{11}(s)$ of PI controller in these systems and combined multivariable cascade controllers were performed in Fig.7 and their optimal parameters were listed in Table 1 [5].

Fig.7 presents the control performance of output temperature of petroleum on $W_{11}(s)$ main dynamic channel, control performance of output temperature on $W_{eqv}(s)$ equivalent channel of the system, performance value of the multivariable cascade equivalent control and control performance of chimney gases on $K_{11}(s)$ intermediate channel, respectively.

Discussion and Conclusion

In this paper, the application was investigated of the multivariable cascade advanced equivalent control structure for an industrial furnace plant.

In this respect, equivalent system model of the process was determined by considering all the disturbance effects of the input-output variables on all dynamic channels of the furnace with two flows.

Finally, experimental tests of the control of temperature in industrial furnace plant using multivariable cascade equivalent control system has also verified the conclusion that equivalent system technique has considerable control performance.

SYMBOLS

A	Unit matrix of the process
E	Unit matrix of the error
FC	The feed control
FT	Temperature of feed
K	The gain value of the compensator
$K_{11}(s)$	The transfer function of the interval channel in left side.
$K_{22}(s)$	The transfer function of the interval channel in right side.
PC	Control of pressure
RC	Ratio control
TC_1	Temperature control of the chimney gasses.
TC_2	The outlet temperature of the petroleum
τ	Dead time
T	Time constant
U	Control vector.
$W_{11}(s)$	The transfer function of the main channel in left side.
$W_{12}(s), W_{21}(s)$	The transfer functions of the inside cross dynamic channel of the furnace
$W_{22}(s)$	The transfer function of the main channel in right side.
$W_c(s)$	The transfer function of the compensator
$W_{eqv}(s)$	The transfer function of the controller object for equivalent channel;
$W_{f1}(s)$	The transfer function of the petroleum, given to the left side as a disturbance
$W_{f2}(s)$	The transfer function of the petroleum flow in right side as a disturbance.
$W_R(s)$	The transfer function of the PI control block.
$W_{R1}(s)$	The transfer function of the PI control block in cascade control of furnace.
$W_{R2}(s)$	The transfer function of the PI control block in cascade control of furnace.
x	Manipulated variable.
x_1	Consumption of the natural gas/air ratio, given to the left chambers.
x_2	Consumption of the natural gas/air ratio, given to the right chambers.
x_{f1}	Consumption of the petroleum flow, given to the right chambers
x_{f2}	Consumption of the petroleum flow, given to the right chambers

y_1	The outlet temperature of the petroleum in left side.
y_2	The outlet temperature of the petroleum in right side.
y_{cg1}	The temperature of the chimney gasses in left side.
y_{cg2}	The temperature of the chimney gasses in right side.
y_{eqv}^*	Output of the equivalent channel which is independent of the external disturbance.

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