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Switching Difference Control of Parallel Streams Temperatures

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Abstract: An industrial furnace with multiple parallel passes and multiple burners is commonly used in petroleum refineries to heat the preprocessed crude oil to a specific temperature. Due to that maintaining multiple outlet temperatures of such parallel passes equal is significant for improving product quality, plant safety, and economic efficiency, etc., great efforts have been taken to control such temperatures. In this paper, a control technique based on switching control schemes, called switching difference control technique (SDCT), is proposed to distribute the inlet oil flowrates such that the outlet temperatures are as identical as possible. The principle of the proposed technique is explained, and several switching policies are introduced. Simulation examples are provided to demonstrate the effectiveness of the proposed strategy. The SDCT technique has the following advantages: it avoids the flow valves too frequently being regulated; it solves the problem of the flow coupling among multiple passes conveniently, etc.

1. INTRODUCTION

An industrial furnace with multiple parallel passes and multiple burners (see Fig. 1) is commonly used in petroleum refineries to heat the preprocessed crude oil to a specific temperature so as to improve heat transfer efficiency and to reduce the possibility of coke formation (Abilov et al. 2002, Cheng et al. 1999, Garg 1999, Wang & Zheng 2005, 2006). Inside the furnace, the heat exchange tubes (HETs) of the parallel passes and the burners are all symmetrically positioned, and each pass is associated with several related burners. Under the ideal status, that is, all the burners fire at the same state and all the oil inlet flowrates of multiple parallel passes are equal, the parallel passes should have identical outlet temperatures. However, although the whole unit is with completely symmetric structure, it is difficult to maintain the furnace being under such ideal status due to various disturbances. For example, a fuel gas pressure variation in one burner may make the outlet temperature of the pass associated with that burner run high or low. For a detailed description of the furnace structure and the crude oil heating process, the reader is referred to (Cheng et al. 1999, Garg 1999, Wang & Zheng 2005, 2006).

Measures should be taken to avoid too high outlet temperatures, which are dangerous as excessively high temperatures can cause rapid scaling of the metal and possible tube rupture. Too low temperatures should be avoided either due to that if some outlet temperatures are too low the furnace must drive some other pass or passes to have a higher outlet temperature to maintain the total fluid at the specified outlet temperature. It can be found from Fig. 1 that the fuel to the burners and/or petroleum inlet flowrate can be selected as the manipulated variable to control the stream temperature. However, for the furnace whose individual burners have only manual-control valves and hence cannot be controlled using automatic signals, the stream flowrate would be the only choice left.

Wang & Zheng (2005) have proposed the difference control technique (DCT) to dynamically distribute the fluid among the passes to maintain the uniformity of the stream temperatures and applied it to a furnace with four passes successfully. The main idea of such technique is that, the flowrate deviation is regulated according to the difference of the two stream temperatures, and such deviation is added to one stream whose temperature is high and at the same time subtracted from another whose temperature is low. Thus, the two outlet temperatures can be controlled using just one controller, and the sum of the two flowrates is kept as a constant, which solves the flow coupling problem conveniently.

The DCT technique is novel and keeps away from complicated controller design. However, for a furnace with N parallel passes, there would need iteratively employing the DCT $N-1$ times to control such system, which is boring especially when N is large. In addition, in some cases where $N=3$ or $N=3\cdot 2^n$, $n = 1, 2, \ldots$, such reiterative employment of the DCT might result in the problem that the flow coupling cannot be decoupled properly. In order to avoid these disadvantages of the DCT technique, Wang & Zheng (2006) have proposed a generalized version of the difference control technique, called differences control technique (DsCT). The proposed DsCT technique retains all the advantages of the DCT technique and keeps away from its above disadvantages.

For both techniques of the DCT and the DsCT, all the N flow valves are regulated through the whole time horizon, which is

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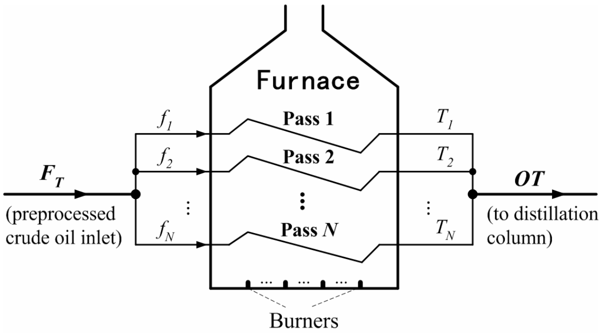


Fig. 1. Schematic diagram of a preheat furnace with N parallel passes

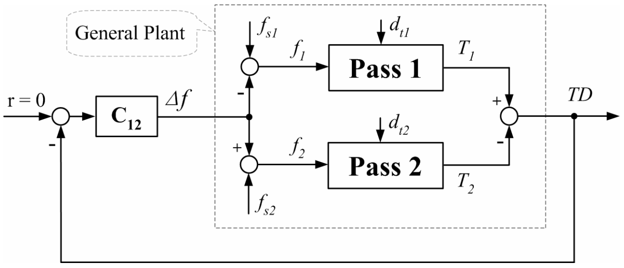


Fig. 2. Principle diagram of the difference control technique (DCT), where Δf is added to Pass 2 and subtracted from Pass 1 simultaneously, and hence the sum of the two stream flowrates keeps at a constant.

disadvantageous for the lifespan of the flow valves. In this paper, a switching control scheme is suggested to control the N parallel passes in a time-sharing manner to reduce the regulation time of the flow valves and hence to help prolong the lifespan of the flow valves.

Section 2 briefly reviews the difference control technique (DCT) and its generalized version, differences control technique (DsCT). Section 3 elaborates the principle of the switching difference control technique (SDCT), and some switching policies are also introduced in this section. In Section 4, some simulation experiments for the proposed SDCT technique are reported. This section also evaluates the performance of the switching difference control system. Finally, some conclusions are given in Section 5.

2. RELATED WORKS

This section first gives the problem formulation for the outlet temperatures uniformity control, and then briefly reviews the difference control technique (DCT) and the differences control technique (DsCT) respectively.

2.1 Problem Formulation

From Fig. 1, it can be found that the stream temperature T_i, $i = 1, 2, \dots, N$, can be regulated using the stream flowrate f_i and/or the fuel to the associated burners. However, in the case where the individual burners have only manual-control valves and hence cannot be controlled using automatic signals, the stream flowrate f_i would be the only choice left. As in (Wang & Zheng 2005, 2006), this paper also considers this case.

It can also be found from Fig. 1 that the stream flowrates f_1 to f_N come from the same source F_T, and hence they satisfy the following equation:

$$\sum_{i=1}^{N} f_i = F_T \,, \tag{1}$$

In practice, the F_T, called total stream flowrate, is given by the management department and is a constant during a given period. Thus, regulating the inlet flowrate of certain pass must regulate that of some other pass or passes simultaneously to keep a constant total stream flowrate, that is to say, loops among the multiple passes are seriously coupled.

A basic problem arising from such system is as follows: how to distribute/control the flowrates f_1 to f_N such that the system has N identical outlet temperatures under the flow constraint of (1)?

2.2 The DCT and the Reiterative DCT

In the case where a furnace has two parallel passes ($N = 2$), the difference control technique (DCT) has been proposed to solve the above problem (Wang & Zheng 2005). The main idea of the DCT technique is illustrated in Fig. 2, where TD, the difference between the two stream temperatures is controlled to be zero by a controller C_{12}, the output of which, denoted as Δf in Fig. 2, is a manipulated variable and is treated as a variation from f_{s1} and f_{s2}, the set-values of the stream flowrates. This variation is added to f_{s2} and subtracted from f_{s1} simultaneously, and hence the sum of the two stream flowrates is always a constant, which makes the flow constraint of (1) be satisfied easily.

When a system consists of three or more parallel passes, the DCT technique cannot be used directly. For such systems, the DCT technique can be used reiteratively to control all the passes. A system with four passes can for convenience be taken as an example to demonstrate how the DCT is reiteratively used. Pass 1 and Pass 2 are formed to be a subsystem, denoted as S_{12}, and Pass 3 and Pass 4 are formed to be another subsystem S_{34}. However, the outlet temperature of Pass 1 (or Pass 2) may differ from that of Pass 3 (or Pass 4) as the two subsystems are independent. The DCT technique is reiteratively employed to maintain temperature equality between subsystems S_{12} and S_{34}.

As pointed out in (Wang & Zheng 2006), although the DCT technique has been successfully applied to a furnace system with four passes, in the case where a system consists of much more passes, it seems that the DCT technique is not so convenient to apply, needing to reiteratively employ the DCT too many times. In addition, in some cases where N=3 or N=$3\cdot 2^n$, 1, 2, …, reiterative employing of the DCT might result in the problem that the flow constraint of (1) does not be satisfied. In order to keep away the above limitations of the DCT technique, the differences control technique (DsCT)

(Wang & Zheng 2006) has been introduced. In next subsection, the DsCT technique is to be briefly reviewed.

2.3 Differences Control Technique

The differences control technique (DsCT) is a generalized version of the DCT and can be canonically applied to the furnaces with any different number of parallel passes. In the DsCT scheme, the N outlet temperatures, T_1, T_2, …, and T_N, are averaged to T_{avrg}. For Pass i, the difference between the T_{avrg} and T_i, $T_{avrg}-T_i$, is the input of Controller i, and the output of which is a manipulated variable to regulate its outlet temperature T_i, $i = 1, 2, …, N$.

Wang & Zheng (2006) have proven that the sum of the N variations is always equal to zero, and hence the flow constraint of (1) is satisfied, if the N controllers are identical. Thus, with the DsCT scheme, the control of the furnace system with N parallel passes is transformed to the N independent single-loop controls, which gives great convenience to the system analysis and controller design.

The above reviewed DCT and DsCT have been successively applied to a real-life furnace with four parallel passes and good control results have been obtained (Wang & Zheng 2005, 2006). However, for both control methods, all the four flow valves are regulated through the whole time horizon, which is disadvantageous for maintaining their lifespan. In order to reduce the regulation time of the flow valves and hence to prolong their lifespan, a switching scheme to control the N parallel passes in a time-sharing manner is to be proposed in next section.

3. SWITCHING DIFFERENCES CONTROL TECHNIQUE

This section first introduces some concepts regarding to the switching control, then explains the principle of the switching difference control (SDCT), and finally discusses some switching policies for the proposed SDCT technique.

3.1 Switching Control

A switched system is referred as a hybrid dynamical system consisting of a family of continuous-time subsystems and a rule that orchestrates the switching between them (Liberzon & Morse 1999). In recent years, the study of switched systems has received more and more attentions, and switching control technique has been widely used in many engineering fields, e.g., industry process controls, intelligent traffic controls, and computer networks, etc. (Morse 1997).

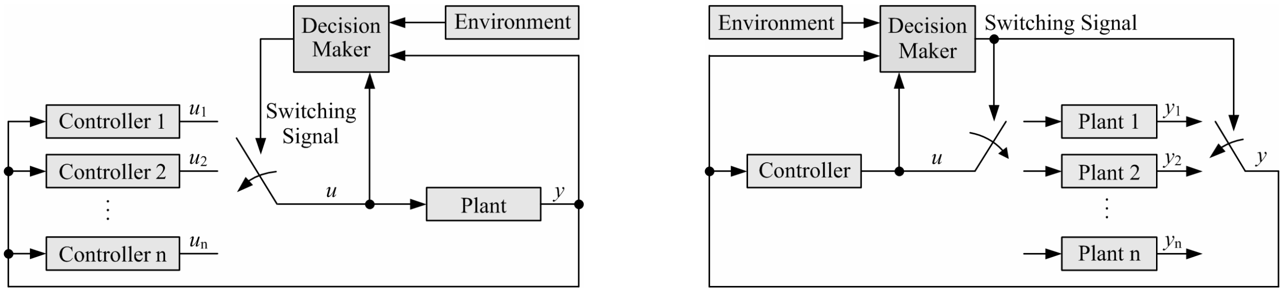
In practice, there exist many systems that cannot be asymptotically stabilized by a single continuous feedback control law, and hence control techniques based on switching among different controllers have been emerged and applied extensively, particularly in the adaptive context, where they have been shown to achieve stability and improve transient response (see Liberzon & Morse 1999 and references therein).

Two basic structures of switched systems are as shown in Fig. 3, where one of them is that multiple controllers regulate one plant in a switching manner to adapt plant nonlinearity and complexity, and the other is that only one controller regulate many plants in a time-sharing manner due to that the controller is scare (Zhao & Zheng 1999), or a plant is expected fewer regulation, for example, the flow valve in industry processes should be regulated as fewer as possible to prolong its lifespan. In this paper, we consider this case.

3.2 Switching Difference Control Technique

Considering that the difference control technique (DCT) can be used to control two passes to obtain uniform outlet temperatures while keeping the flow constraint of (1) being satisfied, just some two “worst needing control” passes are selected from all the N passes to control using the DCT technique, leaving the other passes in no control status temporarily, which makes the flow constraint of (1) be satisfied. With time evolving and based on certain feedback policy, different (two) passes are dynamically chosen to control so that all the N passes can be controlled in a time-sharing manner. Thus, at any given period there are two and only two passes being controlled, and hence the regulation times of all the N flow valves are reduced significantly as a whole. Such switching control scheme based on the DCT is here called switching difference control technique (SDCT).

The SDCT control system is in essence a switched system. The basic switching unit in the SDCT system is a generalized plant, a two-passes system controlled by an SISO continuous-time controller. The controller in the two-passes system can be called “server”, and when the two-passes system comprises Pass i and Pass j, the location of the sever is said to be Loc(i, j). Once one or two passes leave the two-passes system due to that they are no longer the “worst needing control” passes, it is said that the location of the server



(a) A plant controlled switchingly by multiple controllers. (b) Multiple plants controlled switchingly by a controller.

Fig. 3 (a) and (b). Two basic structures of switched systems.

switches. An SDCT control system with the server location being Loc(1, 2) is shown in Fig. 4.

The following two questions: 1) when does the switching take place? and 2) how does the switching take place are needed answering to design a feedback policy to realize switching control among the N passes. In next subsection, some switching feedback policies are to be discussed.

3.3 Switching Polices

For a switching difference control system, how to answer the above two questions of “when” and “how” leads to different switching policies. Some switching policies are given as follows.

1) *First-target-and-then-choose-passes-with-minimum-and-maximum-temperatures (FMM) policy*: Let initial time t_0 = 0. At this time, some two passes are chosen to control using the DCT technique according to the initial outlet temperatures $T(0) = [T_1(0), T_2(0), \ldots, T_N(0)]$. At time t_k, k=1, 2, …, assume that the two passes, Passes i and j, which have the lowest and highest outlet temperatures respectively, are selected to control using the DCT technique, $i, j \in \{1, 2, \ldots, N\}$. (If there is more than one such maximizer and/or minimizer, any of the maximizers and/or minimizers can be chosen.) This regulation run for Passes i and j will continue until the time t_{k+1} at which the two-passes system reaches some given target. At time t_{k+1}, the two passes with the lowest and highest outlet temperatures respectively are chosen from all the N passes to control, and this procedure is repeated.

For this policy, the answer to question “when” is when the two-passes system reaches some given target, and the answer to “how” is choosing the two passes with the lowest and highest outlet temperatures respectively to control.

2) *First-target-and-then-round-round-switching (FRR) policy:* Let initial time t_0 = 0. At this time, any two adjacent passes, say, Pass 1 and Pass 2, can be chosen to control using the DCT. At time t_k, k=1, 2, …, assume that the indices of the two passes in control are i and i+1 respectively. This regulation run for Passes i and j will continue until the time t_{k+1} at which the two-passes system reaches some given target. At time t_{k+1}, the previous two passes, Passes i and i+1, are replaced by Passes i+1 and i+2 for i = 1, 2, …, N-2; or Passes N and 1 for i = N-1; or Passes 1 and 2 for i = N. The procedure is repeated like this.

For the FRR policy, the answer to question “when” is as for the FMM policy, while the answer to “how” is choosing two passes to control in a round-robin manner.

3) *Always-choose-passes-with-minimum-and-maximum-temperatures (aMM) policy:* Let initial time t_0=0. At time t_0, some two passes are chosen to control according to the initial outlet temperatures $T(0) = [T_1(0), T_2(0), \ldots, T_N(0)]$. At time t_k, k=1, 2, …, assume that the two passes, Passes i and j, which have the lowest and highest outlet temperatures respectively, are chosen from the N passes to control using the DCT technique, $i, j \in \{1, 2, \ldots, N\}$. This regulation run for Passes i and j will continue until time t_{k+1} at which the two outlet temperatures of Passes i and j are no longer the highest and lowest ones. At time t_{k+1}, the two passes with the lowest and highest outlet temperatures respectively are chosen to control, and this procedure is repeated.

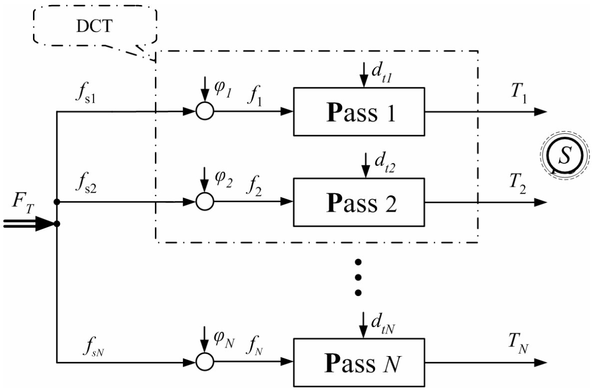


Fig. 4. Schematic diagram showing the SDCT technique, where just two “worst needing control” passes are selected from all the N passes to control using the DCT technique.

For the aMM policy, the answer to question “when” is when one or two passes in the two-passes system do not owe the highest and/or lowest outlet temperatures any more, while the answer to “how” is choosing the two passes with the lowest and highest outlet temperatures respectively to control.

4. SIMULATION EXPERIMENTS

This section reports the simulation experiments for an industrial furnace with four parallel passes at a petrochemical factory, where the operating point of the furnace system is that the outlet temperature is 365 °C and the total flowrate is 140 ton/hour (the inlet flowrate of each pass is 35 t/h). The disturbances on such furnace system mainly include: the petroleum inlet flowrate variations, uneven temperature distribution in the furnace chamber, changes of the fuel gas pressure in gas burners, and variations of the fuel oil flowrate in oil burners, etc., among which the latter two are the dominating ones. These disturbances on the system are looked on as the step changes in the simulation experiments.

4.1 Simulation Model and Simulation Configuration

For most industrial processes, the commonly used approximate model is a first-order-plus-dead-time (FOPDT) or second-order-plus-dead-time (SOPDT) one (Kaya 2001, Saffer et al. 2005, Lee et al. 2002, Majhi & Atherton 1999, Moon & Lee 2003). As in (Wang & Zheng 2006), an FOPDT model is adopted to represent the four parallel passes whose transfer function is given by

$$G(s) = \frac{-5}{120s+1} e^{-60s} . \tag{2}$$

The simulation configuration is implemented in Matlab/Simulink environment. The Simulink model of the furnace system with the SDCT is shown in Fig. 5, where the blocks Transfer Fcn and Transport Delay are used to represent the dynamical models of the four passes. The Subsystem SDCT in Fig. 5 is a compound block, whose inputs and outputs are the four temperatures and the four flowrate deviations respectively, and this compound block are used to realize the feedback switching policy and the continuous-time DCT controller. In the compound blocks Subsys1 to Subsys4, the Step blocks are used to simulate the disturbances on the furnace system, the Band-Limited White Noise blocks and/or the Random Number blocks the unmeasured noises on the outlet temperatures, and the Constant blocks with parameters 365 the temperature operating points of the furnace system. The compound blocks Sub1 to Sub4 consist of the Band-Limited White Noise blocks simulating the unmeasured noises on the flowrates, and the Constant blocks with parameters 35 the flowrate operating points of each pass respectively. In addition, the To Workspace blocks T1 to T4 and F1 to F4 are used to save the corresponding simulation data to the Matlab Workspace. Once the simulation data are obtained from the Matlab Workspace, a data-processing software package is used to display the trends of the temperatures and flowrates of the four passes, and some other software packages are used to evaluate the performances of the control system.

4.2 Simulation Results and Performance Evaluation

Based on the Simulink model described above, many simulations have been done to test the effectiveness of the proposed SDCT technique. Fig. 6 shows the simulation result of the SDCT approach for the furnace with four parallel passes whose dynamical models from flowrate to temperature are as (2) under the aMM (see Section 3.3) switching policy and with the DCT controller being $C(s) = 0.5+0.0015/s$. In Fig. 6, the difference of the four stream temperatures can be controlled within 3 °C at a time percentage of 98.78 % (see Table I), and the difference of the four stream flowrates is within 3 t/h at a time percentage of 95.60 % (see Table II), which shows that the SDCT the effect of the uniformity control of the four parallel stream temperatures under some disturbances is satisfactory. The simulation experiments for the DsCT control system under the same simulation parameters have also been done for comparison, however, due to page limit, the descriptions for the simulation experiments of the DsCT are omitted here.

It can be seen from Tables I and II that the performance of the SDCT control system, such as the maximum (Max), average (Avrg) values, and the variance (σ^2) of the difference of the four stream temperatures; the maximum (Max), average (Avrg) values, and the variance (σ^2) of the difference of the four stream flowrates, etc., seems to be not so good as that of the DsCT control system. However, it should be emphasized that the regulation time of the four flow valves in the SDCT control system differs significantly from that in the DsCT control system (see Table III). As shown in Table III, the flow valves are regulated through the whole time horizon, i.e., the percentage of the regulation time to the whole time concerned is 100 %, for the DsCT scheme, while this percentage reduces greatly for the SDCT scheme, to about 50 % for each of the four flow valves, which is beneficial for prolonging their lifespan.

Other simulation experiments have also been done. For example, the furnace system controlled using the SDCT technique under the FMM and FRR switching policy

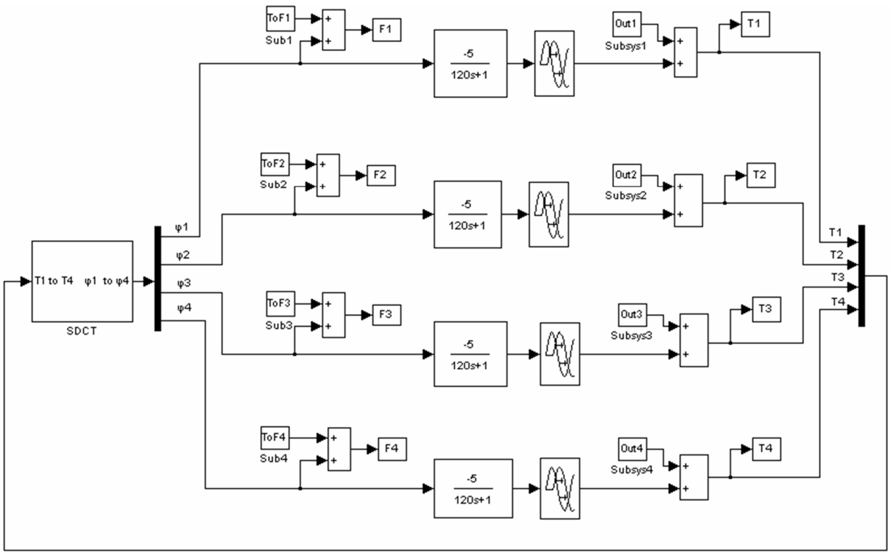


Fig. 5. Simulation model of the SDCT control furnace system.

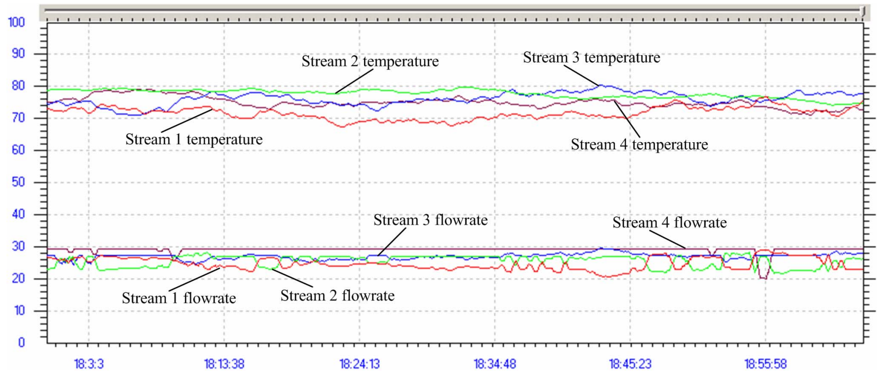


Fig. 6. Trends of the temperatures and the flowrates of the four streams of the SDCT control simulation system.

respectively has been simulated, and the model parameters have been varied to do an analysis of the robustness performance of the controlled system with the SDCT scheme. However, due to page limit, such simulation results are no longer reported here.

Table I. Statistics results for the four streams temperatures of the SDCT and DsCT control system.

	Max(°C)	Min(°C)	Avrg	σ^2	P{Diff<=3}(%)	P{Diff>3}(%)
SDCT	3.652	0.002	1.251	0.318	98.785	1.215
DsCT	4.036	0.003	0.973	0.302	99.185	0.815

Table II. Statistics results for the four streams flowrates of the SDCT and DsCT control system.

	Max(t/h)	Min(t/h)	Avrg	σ^2	P{Diff<=3}(%)	P{Diff>3}(%)
SDCT	4.176	0	1.324	0.908	95.607	4.393
DsCT	2.228	0	0.917	0.088	100.00	0

Table III. Statistics results for the regulation ratio of the four flow valves of the SDCT and DsCT control system.

	Valve 1 (%)	Valve 2 (%)	Valve 3 (%)	Valve 4 (%)
SDCT	49.70	54.50	49.68	46.09
DsCT	100.0	100.0	100.0	100.0

5. CONCLUSIONS

Due to that the uniformity control of parallel streams temperatures, known as pass balancing control, is definitely important to the process industry, great efforts have been being taken to control such temperatures. In this paper, a control technique, called switching difference control technique (SDCT), has been proposed to control the stream temperatures of a furnace with multiple parallel passes. Compared with some existing control schemes, the proposed SDCT technique can maintain the uniformity of multiple parallel temperatures, while reducing the percentage ratio of the regulation time of the flow valves to the whole concerned time, which is favorable for extending their lifespan. In addition, the proposed SDCT technique can solves the problem of the flow coupling among multiple passes conveniently.

Usually, the burners of a furnace have no automatic-control valve. If the fuel valves of the individual burners could be controlled automatically, there would be more control freedom, and the stream temperatures control would be able to make additional adjustments that may result in better control.

This paper has described how to maintain the equality of the temperatures of the parallel streams, whereas not mentioning the control of the total outlet temperature denoted as OT in Fig. 1 at all. In fact, there is an independent closed loop to control this temperature. In this closed loop the manipulated variable is the fuel and air flow, and the total flowrate of parallel streams is manually set to be a constant, say, F_T, and the cascade control is commonly employed to regulate such temperature (Kaya 2001).

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