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Improved Economic Operation of MSWC Plants with a New Model Based PID Control Strategy

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Abstract: Municipal solid waste combustion (MSWC) plant operators are currently under an increasing pressure to optimize the economic performance of their plants. A route with high potential for optimizing this performance is by improving the performance of the MSWC plant combustion control system, which typically is of the PID-type. In this paper, motivated by the industrial need to improve the overall economic MSWC plant performance, a model based approach is taken to optimize this control system, using recently derived black and white box MSWC plant models. More specific, from a closer analysis of the dynamics of these models a new PID-type of MSWC plant combustion control strategy is derived. It is shown that this new control strategy has improved setpoint tracking properties compared to PID-type of combustion control strategies typically encountered in the industry. As a result, a significant improvement of the economic performance of an MSWC plant will be obtained when replacing such a control strategy for the new one. However, no improvement of the disturbance rejection properties of existing PID-type of combustion control strategies has been observed with the new control strategy, which would also lead to a significant improvement of the economic performance of an MSWC plant, indicating that other, non-PID, types of combustion control strategies are required for that.

Keywords: municipal solid waste, combustion, modeling, PID-control, model based control

1. INTRODUCTION

Due to lack of space, combustion of municipal solid waste (MSW; household waste) represents a suitable alternative to dumping in many densely populated parts of the world, despite the associated (assumed) negative effects on the environment. The main aims of MSW combustion are volume reduction and inertisation of the waste and energy production. It is typically performed at large, dedicated plants, see figure 1, consisting of one or more lines with a furnace, flue gas cleaning equipment and a boiler to produce steam from the hot flue gases. The latter is transformed into energy in the form of heat or electricity, which is sold to surrounding plants or communities.

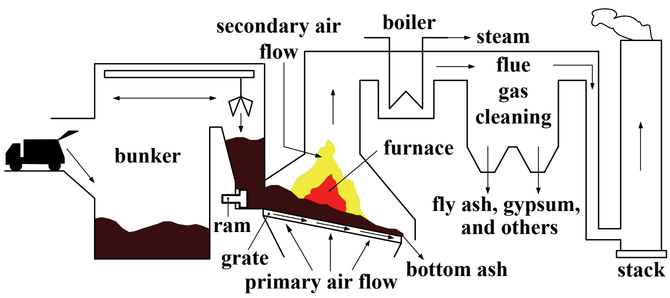

Fig. 1: A typical MSWC plant

Operators of MSWC plants are faced with various operational problems, in particular with problems related to the fulfillment of environmental constraints and to maintenance / lifetime related such problems, e.g. corrosion of the boiler pipes. Another problem for MSWC plant operators, at least in the Netherlands, is that they are under an increasing pressure to perform economically more optimally. This is a consequence of the increasing business character of the environment MSWC plants have to operate in, with market forces and competition increasingly dictating their operation due to developments like privatisation and subsequent public to private ownership changes. With the processed waste and produced energy being the main sources of income for an MSWC plant, the increasing pressure to perform economically more optimally translates to an increasing pressure to combust more waste and produce more steam.

A route with high potential for improving the economic performance of an MSWC plant is by optimizing the performance of its combustion control system, which controls the furnace and boiler part of the plant (see figure 2). This is, first of all, due to its large influence on the average waste throughput and steam production. Additionally, the combustion control system is typically of the (multivariable) PID type, which does not optimally deal with the multivariable and constrained character of the MSWC plant control problem. Also, the combustion control system is typically based on imprecise knowledge of the plant dynamics, which also leads to an underperforming combustion control performance.

Motivated by the industrial need to operate economically more optimally and by the high potential of establishing this through optimization of the conventional MSWC plant combustion systems, research has been carried out both by industry and academia to improve these systems. As a first candidate, fuzzy control has been considered. This control strategy, however, has not led yet to a significant improvement in combustion control performance (El Asri and Baxter, 2004). Another route that has been followed is that of model based control, in particular that of model *predictive* control (MPC). See e.g. Leskens *et al.* (2008). This control strategy has the advantages of dealing systematically with the multivariable and constrained character of the MSWC plant combustion control problem and of employing a (more) precise description of the plant dynamics in the form of a model. Simulations on a first-principles model show that the MSWC plant combustion control performance can be considerably improved with MPC (Leskens *et al.*, 2008).

Even though the usage of MPC may lead to a considerable combustion control performance improvement, a valid question is whether the performance of the conventional, PID type of combustion controller can already significantly be improved without resorting to another, in particular advanced control strategy such as MPC. The main advantage of such an approach is the much easier and cheaper implementation. In particular by taking again a model based approach, i.e. by avoiding controller design on the basis of imprecise knowledge on the plant dynamics, a new improved MSWC plant combustion controller of the PID type may be obtained.

Motivated by (i) the industrial need to improve the overall economic performance of MSWC plants, (ii) the high potential of obtaining this improvement through improving their combustion control systems, and (iii) the advantage of PID type of such control systems being easier to implement than other type of such control systems, *the main aim set in this paper is to answer the question whether current, PID-type of combustion controllers can already significantly be improved, i.e. without resorting to another controller type.* A model based approach is pursued, thereby overcoming a major disadvantage of currently employed combustion controllers that their design is based on imprecise knowledge of the plant dynamics. More specific, a new PID-type of combustion control system is proposed which is derived from a closer analysis of the MSWC plant dynamics as exhibited by recently derived black and white box models. By means of a simulation based comparison with an existing PID-type of combustion control system, the performance of the new control system is then assessed and conclusions are drawn on the main question addressed here.

The contents of this paper are as follows. After a brief description of MSWC and MSWC combustion control in section 2, the dynamics of MSWC plants, as exhibited by the mentioned black and white box models, are discussed in section 3. The new PID-type of combustion control system is then derived from these dynamics in section 4. The performance of this new control system is assessed in section 5. The main conclusions of this paper are given in section 6.

2. PROCESS AND CONTROLLER DESCRIPTION

After having been collected from households and transported to the combustion plant, MSW is stored in a large bunker, see figure 1, from which it is transported by cranes into a large chute. At the bottom of the chute the waste is pushed onto a moving grate by a ram. The waste is combusted while travelling on this grate, using O_2 from air flows that are fed through holes in the grate (primary air flow) and furnace side walls (secondary air flow) to the solid waste layer and gas phase above it. The resulting flue gas passes a boiler delivering heat which is transformed into steam and, subsequently, into energy in the form of heat and/or electricity. Having passed the boiler, the flue gas is cleaned from residues that are not allowed to enter the surroundings.

MSWC plants are equipped with two types of control systems: (i) a combustion controller and (ii) controllers related to the flue gas equipment. The interest here lies in the first type of these controllers. The combustion controller is typically of the PID-type with four manipulated variables (MVs), i.e. speed of ram, speed of grate, primary and secondary air flow, and two controlled variables (CVs), i.e. steam production and flue gas O_2 concentration. See figure 2.

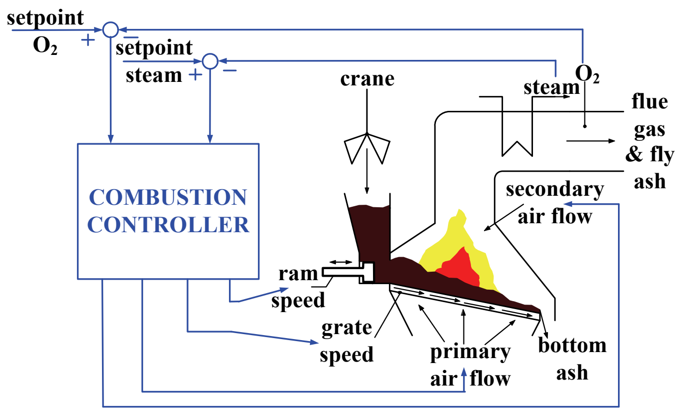

Fig. 2: A typical MSWC plant combustion controller

Main goals of this control system are (i) to maintain the two CVs at their setpoints and (ii) to suppress the fluctuations in steam and O2 induced by the heavily fluctuating waste composition. In this paper, improvements of the combustion controller performance are considered in both these setpoint tracking and disturbance rejection properties, each of which leads to a significant improvement of the overall economic MSWC plant performance. An important note with respect to the first of these properties is that combustion controllers encountered in the industry typically deliver offset free control of only one CV (typically steam).

3. MSWC PLANT DYNAMICS

3.1 Introduction

The dynamics of MSWC plants, including their disturbance dynamics, is discussed here via step responses of steam and O_2 simulated, at a typical MSWC plant operating point, with recently derived black and white box models.

3.2 Plant dynamics

For the discussion of the (non-disturbance) plant dynamics of MSWC plants, first of all, a (discrete-time linear, time-invariant state space) black-box model is used (i.e. a model with no physical interpretation for its equations) that has been estimated from data from a large scale Dutch MSWC plant, experimentally obtained during normal closed-loop operation of this plant, using a dedicated closed-loop system identification method. Correlation functions indicated that this model is of good quality. Additionally, a first-principles model is used for the discussion of the MSWC plant dynamics that consists of macro mass and energy balances and which is a slightly adapted version of one presented in Van Kessel (2003). With the aim to validate this (continuous-time nonlinear time-invariant state space) model, its dynamics have been adapted to the mentioned black-box model through parameter estimation. A well agreement was obtained between black and white box model dynamics as can be observed below in figures 3–5. The step responses of both models are deliberately depicted here together in one and the same figure to provide evidence of the high quality of these models, which is reflected by the well agreement of these responses. An important note is that the dynamics at another operating point of the considered MSWC plant and at other such plants, as observed from other, similar black and white box modeling exercises as referred to here, were found to exhibit different time constants and static gains but were also found to be of the same global shape as to be shown here. As a consequence, the PID combustion control system proposed here, which structure is based on this global dynamic shape rather than the specific time constants and static gains, also can be used at other operating points and plants, though with different controller settings.

For further details about the black and white box model derivation, parameter estimation and validation steps referred to here, see Leskens *et al.* (2002). It is noted that, to the knowledge of the authors, an extensive discussion of the MSWC plant dynamics as given here has not been published before, although there have been references (e.g. Manca *et al.* (1998), Van Kessel (2003)) discussing part of these dynamics.

Responses of steam and O_2 on step on ram speed

See figure 3. It is observed from this figure that an increase in the ram speed (/waste inlet flow) results, at steady state, in an increase in steam and a decrease in O_2. This behavior is explained from the fact that an increase in ram speed is accompanied by an increase in combusting fuel (i.e. waste) on the grate, which results in a higher energy output (steam) but also in a higher O_2 consumption. It can also be seen that steam and O_2 reach their steady state in approx. 100 minutes, which is a typical (dominant) time constant for large scale MSWC plants. Also, before steam rises, it first approximately remains constant for about 10 minutes. Similarly, O_2 remains approximately constant for several minutes before decreasing to its steady state value. In fact, these transfer functions are known to typically exhibit an inverse response (see e.g. Manca *et al.* (1998)) due to evaporation consuming energy before combustion takes over and causes an effectively positive energy production.

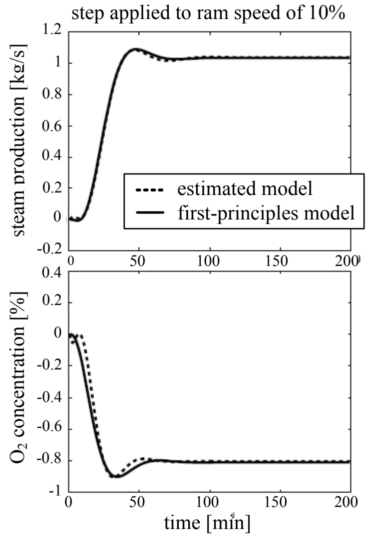

Fig. 3: Responses of steam and O_2 to step on ram speed

The delays here can be interpreted as (almost) flat inverse responses with an explanation for this flatness being that the evaporation has only a small effect due to a relatively high primary air flow temperature. Note that the steam and O_2 responses are, more or less, mirrored versions of each other, with the time axis being the mirror axis.

Grate speed step responses

See figure 4. One can observe in both steam and O_2 a temporary large effect but no change in steady-state value. An explanation for the latter is that a change in grate speed does not deliver new fuel or O_2 to the furnace. The temporary large effect can be attributed to a temporary increase in effective area over which the air reaches the combustible part of the waste. This causes a temporary increase in combusted waste and, as a result, a temporary increase in energy output and a temporary decrease in in O_2.

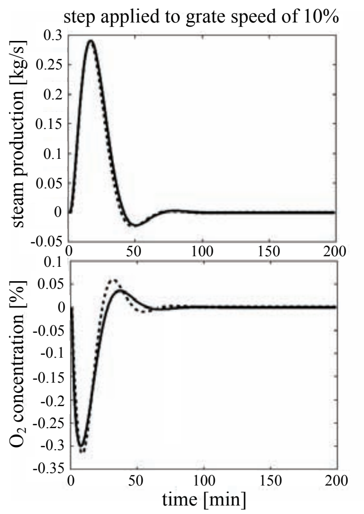

Fig. 4: Responses of steam and O_2 to step on grate speed

This effect is similar to the the so called ‘poke’-effect, i.e. the effect observed when poking with a stick in the fire of the stove back home. Note that, again, steam and O_2 are, more or less, mirrored versions of each other with the time axis as the mirror axis.

Air flow step responses

See figure 5 for the *primary* air flow step responses.

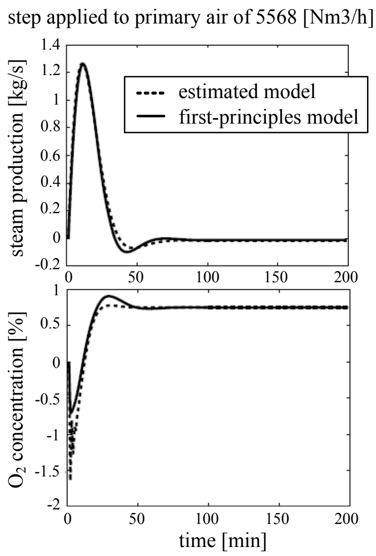

Fig. 5: Responses of steam and O_2 to step on primary air flow

An eventual net increase in O_2 is observed, preceded by a sharp inverse response. The steam response exhibits a large upset similar to those encountered at the grate speed responses, before reaching a slightly positive steady state value. The positive sign of this value is the result of an increased heat flow to the boiler. This increased heat flow is due to an increase in flue gas flow induced by the increase in primary air flow. At the same time, notably, the furnace (i.e. waste layer and flue gas) temperatures drop due to the cooling effect of the primary air flow (which temperature is lower than those in the furnace). Nevertheless, the heat flow to the boiler, which is a function of the product of the flue gas flow and temperature, increases as the increase in flue gas flow is larger than the decrease in its temperature. The size of the steam production steady-state value depends on the specific combustion conditions and the boiler efficiency and typically is small. Here, as can be observed from figure 5, this steady-state value is apparently very small. This low steam production steady-state value is an important assumption to be fulfilled for a proper operation of the new PID combustion control strategy to be presented here.

The responses of steam and O_2 to a step applied to the *secondary* air flow (not depicted here for reasons of space) are largely similar to those for the primary air flow though with much lower amplitude.

3.3 Disturbance dynamics

For the discussion of the disturbance dynamics of MSWC plants, step responses of a black box (discrete-time linear time-invariant auto-regressive type of) time series disturbance model are used. This model was estimated in a similar way as the earlier discussed black-box model from closed-loop data experimentally obtained from a large scale Dutch MSWC plant. Correlation functions were (again) used for validation and indicated that the model is of good quality. With this model the disturbances can be simulated that are acting on steam and O_2 as a function of (two) inputs that can be interpreted as the (white noise) stochastic sources for these disturbances, though without having any physical meaning. When a (unit) step is applied to one of the inputs of the model, steam and O_2 respond as depicted in figure 6.

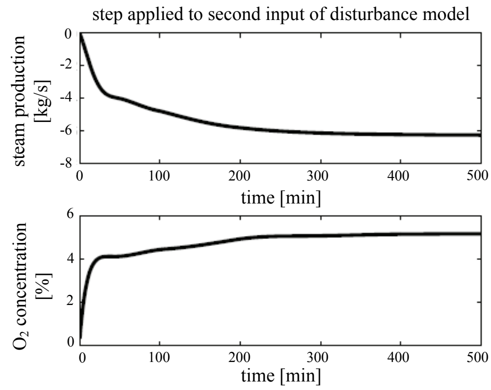

Fig. 6: Step responses of time series disturbance model

The main thing to note here is that the responses are, more or less, mirrored, again. In fact, from simulations with the model, it was found that this type of disturbances accounts for most of the disturbances acting on steam and O_2: approx. 74% for steam and 93% for O_2, in variance sense. Hence, suppression of these disturbances would mean suppression of most of the MSWC plant disturbances, which observation is the main pillar for the disturbance rejection part of the new controller to be proposed here.

The most likely physical source of the ‘mirror’ disturbances discussed here is the waste composition as a step applied to this disturbance also leads to a mirrored response of steam and O_2, as confirmed by simulations with a first-principles MSWC plant model.

4. A NEW PID COMBUSTION CONTROL STRATEGY

The controller proposed here is derived from a closer study of the dynamics discussed above. The following four main parts can be distinguished:

- A part dealing with offset-free setpoint tracking of both steam and O_2
- A part for suppressing the disturbances by manipulating the grate speed
- A part for suppressing the disturbances by manipulating the primary and secondary air flow
- A (small) part steering the grate speed setpoint

Each of these four parts will now be motivated and discussed in more detail. Figure 7 presents a schematic overview of the resulting MSWC plant PID combustion control strategy.

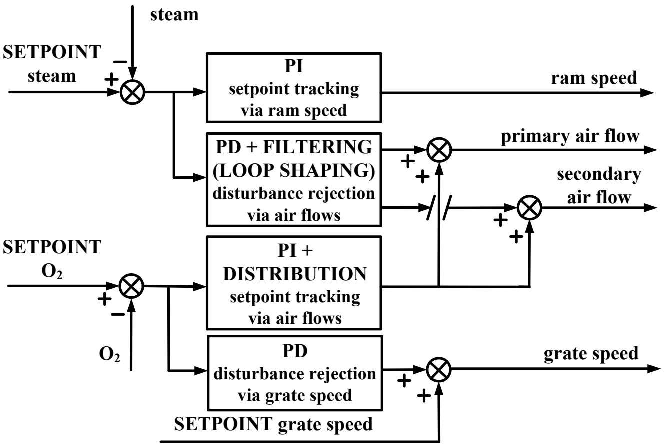

Fig. 7: The new PID combustion control strategy

Offset-free setpoint tracking of steam and O_2

From the step responses of the steam production given above, see figures 3 - 5, one can deduce that only the ram speed has a large static effect on this CV. This implies that the ram speed is effectively the only candidate for steering steam to its setpoint, whereas the usage of other MVs for that purpose leads to excessively large MV amplitudes. To obtain offset-free setpoint tracking for steam, a PI controller is proposed to connect, on the one hand, the error between steam and its setpoint and, on the other hand, the ram speed. The integral action in this steam-ram speed control loop ensures offset-free control of the steam production. Note that the PI controller cannot be tuned too tight when a significant inverse response is present in the ram speed-steam transfer function, as this introduces undesired oscillations. Compensating for this inverse response will lead to a loss in control performance in the sense of a slower closed-loop response for this control loop. This loss will, however, not be too severe as the closed-loop response is slow anyway due to the slow dynamics involved in the ram speed–steam transfer function.

When using only this PI steam-ram speed control loop, O_2 cannot be steered independently to its setpoint. Rather, its steady-state value depends on the steady-state value for the ram speed determined by this loop. In order to also obtain offset-free control of O_2, one needs to use one or more additional MVs that have a significant static influence on this CV. From the step responses discussed above, see figures 4 and 5, one can see immediately that this leaves only the two air flows as candidate MVs as the grate speed - O_2 transfer function, see figure 4, has a zero static gain. Note that a control loop containing these MVs would hardly interfere with the already discussed steam - ram speed control loop because of the low static gains of these MVs towards steam. The proposed O_2 – air flows control loop(s) can be implemented by means of one PI controller acting on the error between measured O_2 and its setpoint to steer the air flows according to some user-defined distribution.

Disturbance rejection via the grate speed

At the discussion of the MSWC plant disturbance dynamics it was observed that the major part of the disturbances acting on steam and O_2 are of the 'mirror' type. It was also observed that these CVs respond 'in a mirror way' to manipulation of the grate speed. See figure 4. Because of this, the grate speed MV is a good candidate for simultaneously rejecting this type of disturbances in both CVs. More specific, it is an ideal MV for the reduction of the middle and higher frequency 'mirror' disturbances due to the small effect this MV has in the low frequency range. The grate speed control loop proposed here may be implemented either using the error between steam and its setpoint or between O_2 and its setpoint to steer, via some PD action, the grate speed. The choice for the O_2 error has the advantage of allowing the suppression of the highest frequency disturbances. This is due to the disturbances acting on O_2 having a larger bandwidth than those on steam, which can be subscribed to the low pass filtering effect of the boiler dynamics on the steam signal. However, one may also choose to suppress these highest frequency disturbances by means of the air flows disturbance rejection loop to be discussed below. Here, arbitrarily, the O_2 error has been chosen for the grate speed disturbance rejection loop and the steam error has been chosen for the air flows disturbance rejection loop.

Steering the setpoint of the grate speed

As the grate speed has no static effect on steam and O_2, the control loop for disturbance rejection via this MV discussed just above also has no static effect on these CVs. As a result, the setpoint of the grate speed is an extra degree of freedom that can be used to control, in a static or low frequency manner, the combustion process in another way than via steam and O_2, e.g. to keep the fire properly positioned on the grate. This may be done manually or automatically, e.g. through a camera monitoring the waste on the grate.

Disturbance rejection via the air flows

With the grate speed disturbance rejection control loop one is already able to obtain a significant disturbance rejection. The sole usage of this control loop may lead, though, to an unacceptably large variation in the grate speed. A solution to that is to also use the air flows for disturbance rejection. In that way, the energy in the MVs resulting from disturbance rejection may be spread over both the grate speed and the air flows, thereby reducing the variation in the first of these MVs. One particular way of implementing the air flows disturbance rejection control loops is by using a PD-controller in combination with loop shaping. The idea here is to shape, via (pre-)filters, the transfer functions from the primary and secondary air flow towards steam and O_2 such that, when given the same MV input, the resulting responses of steam and O_2 are, as much as possible, mirrored with respect to each other. See figure 8 for an example result.

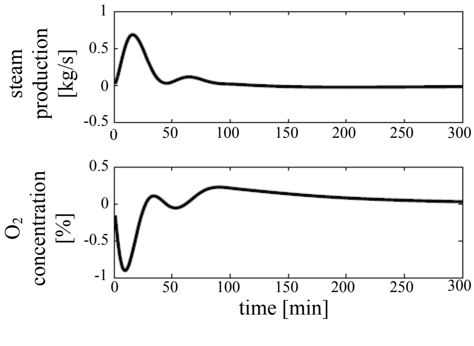

Fig. 8: An example result of loop shaping: 'mirrored' CV responses to same step applied to pre-filtered air flow inputs

A PD controller then simultaneously manipulates the input of the resulting pre-filtered transfer functions, as if it were an MV that has a mirroring effect on the two CVs, in response to either the steam or O_2 error signal. The aim of the resulting control loop is then to counteract the mentioned ‘mirror’ type of disturbances. As mentioned above, the steam error signal has arbitrarily been chosen here as the input for the control loop while the O_2 error signal has been chosen for the grate speed disturbance rejection control loop. A final important note here is that proper operation of the loop shaping control loop proposed here depends on the availability of accurate air flow transfer functions, which may not always be the case.

5. PERFORMANCE ASSESSMENT

Via simulations on a black-box MSWC plant model, using a black box time series model for disturbance simulation, the new controller was compared with an existing, commercially available PID MSWC plant combustion controller. The details of the latter controller are left out here because of reasons of confidentiality and space but its structure is highly different from that of the new controller and allows only for offset-free control of one CV, i.e. either steam or O_2. Apparently, the designers of the control system do not consider offset-free control of both steam and O_2 to be feasible, which is clearly contradicted by the results here. By (still) lack of a systematic tuning procedure of the (many) controller parameters, both controllers were tuned via trial-and-error. Figure 9 shows typical simulation results, i.e. of steam and O_2, obtained with this comparison.

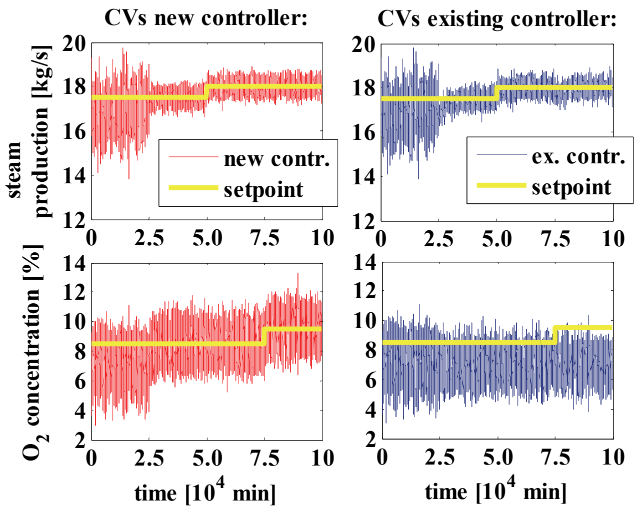

Fig. 9: New versus existing controller

It clearly can be seen that, as expected, the new controller is capable of offset-free setpoint tracking of both steam and O_2, whereas the existing controller is not. In fact, it is only capable of offset-free setpoint tracking of steam. From figure 9 it can also be seen that both controllers are capable of significant disturbance rejection: compare the variation in steam and O_2 before and after the controller is activated at t = 25000 [min]. In fact, the simulation results showed that both controllers exhibit the same disturbance rejection performance, with a recorded maximum reduction in standard deviation of 70% for steam and 30% for O_2, implying that no significant improvement can be made with the new controller in disturbance rejection sense.

As a result of its improved setpoint tracking properties, usage of the new controller leads to a significant economic performance improvement in the sense of not having to lower the steam setpoint, and thereby the average waste throughput and steam itself, to a much lower value to prevent O_2 from violating its law enforced lower bound (= 6%). If present, improved disturbance rejection would also lead to an improved economic performance due to the ability to operate on average closer to the dominating constraint and, thereby, at higher average values for the waste throughput and steam.

Simulations with the new combustion controller on other MSWC plant and disturbance models showed similar results as discussed above, indicating its robustness against variability in plant dynamics.

6. CONCLUSIONS

A new PID-type of combustion control system for MSWC plants has been derived from a closer investigation of the MSWC plant dynamics, as exhibited by recently derived black and white box models. This new control system has improved setpoint tracking properties compared to combustion controllers typically encountered in the industry, but also equal disturbance rejection properties. Due to the improved setpoint tracking properties, the usage of the new controller would lead to a substantially improved overall economic performance for MSWC plants. To improve on the disturbance rejection properties, other, non-PID, type of combustion controllers are required, e.g. of the MPC type.

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