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# PROCESS ANALYSIS AND CONTROL DESIGN FOR COAL GASIFICATION IN RECIRCULATING FLUIDIZED-BED REACTOR

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Abstract: A most widespread method for coal gasification is the use of fluidized bed reactors. A new concept in recirculating fluidized bed gasification is the Judd two-compartment gasifier. The two compartments provide separated zones for gasification with steam and for combustion with air, within the same vessel. The circulation of inert solids transmits the heat from the combustion zone into the gasification zone. Lumped parameter model for the system is formulated by heat and mass balances and a set of simplifying assumptions. Optimal steady state - bringing the gasification rate to a maximum - is defined and the model is linearized about this state. The system is asymptotically stable, controllable and observable. An LQG controller, capable of rejecting input disturbances and measurement noise and improving the dynamical response of the system, has been developed.

Keywords: controllability, observability, reduced order process, LQG design, fluidization, gasification.

## 1. INTRODUCTION

Gasification of coal is a process in which coal or char reacts with an oxidizer and water to produce a fuel-rich product. Main reactants are coal, oxygen, steam and carbon dioxide, while desired products are carbon monoxide, hydrogen and methane. The products are used as substitute for natural gas; synthesis gas for chemicals feedstock; fuel for generation of electric power, steam and heat. Gasification of coal has been practiced commercially for nearly 200 years. Interest in gasification was renewed in the 1970's (the "energy crisis") and many new commercial plants have been built since then. Classical gasification methods, including fluidized-bed techniques, are described in many texts, e.g., Nowacky, 1981. Mathematical models of varying complexity for fixed (or moving) bed and fluidized bed gasifiers were reported, e.g., Adanez and Labiano (1990), De Souza-Santos (1989); Ma, et al. (1988 and 1989); Neogi, et al. (1986); Saffer, et al. (1988).

A special combination of moving bed and fluidized bed reactors is the Judd gasifier, shown schematically in Fig. 1. It is based on a circulating fluidized bed process using draught tubes, e.g., Mirians Kuramoto et al. (1985); La Nause (1976); Judd, et al. (1983); Judd and Rudolph (1986); Yang and Keairns, (1983); Kim et al. (1997); Kim et al. (2000); Mukadi et al. (1999 and 2000); Song et al. (1997); Mleczko and Marschall (1997); Marschall and Mleczko (1999). Judd and Pillay (1991) reported a detailed description of the gasifier and its characteristics. Recently, Kim and co-workers (Lee et al., 1998; Kim et al. 1997) have reported extensive experimental testing of the Judd gasifier, for non-catalytic as well as catalytic gasification of coal, proving its feasibility as a medium calorific value gas generator. Some of the main features of the gasifier are: two separate sections, the inner combustion and the outer gasification, are located within the same reactor, divided by two vertical plates (or a draught tube for circular cross-section) with no mechanical seals. Air is supplied to the inner section, maintaining vigorous bubbling fluidized-bed conditions (4 to 7 times the minimum fluidization velocity, $u_{mf}$) where combustion takes place. Solid particles, reaching the top of the draught slot, spill over into the outer zone and supply the heat to that outer section where the gasification occurs. Steam, needed for the gasification reaction, enters the outer section at low velocity (0.6 to 1.0 times $u_{mf}$) and provides the conditions for the downwards-flow of the solids in this compartment. Thus, the solids circulate up the draught slot region, where the combustion reactions take place, and downwards on the outside, where the gasification reactions occur. Due to the pressure difference between the regions, the circulating solids from the gasification section flow under the vertical dividing walls back into the combustion section.

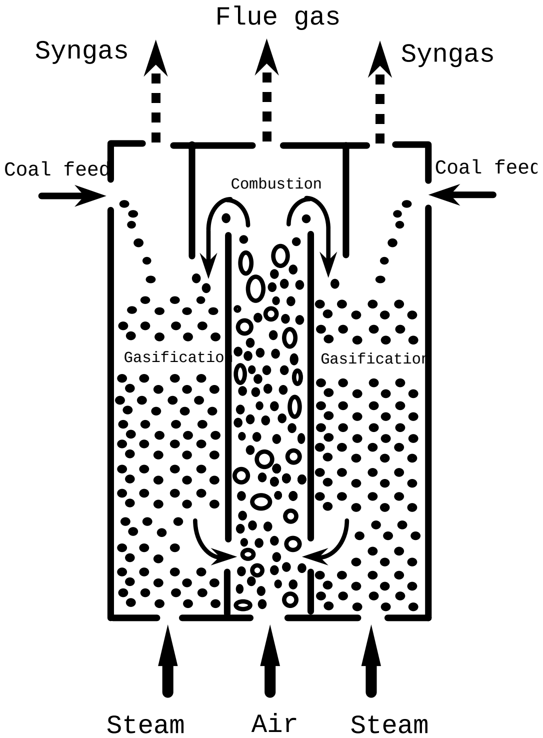


**Figure 1:** Scheme of the Judd gasifier.

Seals of solids are being formed between the two sections and there is very little mixing between the gases generated in these two zones. Thus, the gases are easily separated to the desired syngas and the discarded exhaust flugas. Crossflow or mixing of gases can be minimized to a few percents of the total gas flow by correct geometrical design and carefully balanced operational conditions (Kim et al. 1997, Song et al. 1997).

The goal of this research is to formulate a reasonable dynamical model for the Judd gasifier and the processes involved, examine and assure its stability and controllability. In addition, a preliminary design for a possible controller is suggested. The model is derived in the form of differential equations. These were linearized to yield a set of state equations that are tested for controllability, observability and stability, using linear control tools. A LQG controller is suggested and the expected model-based performance is predicted by simulation.

## 2. MODELING THE JUDD GASIFIER

The details of the Judd gasifier apparatus, the process and the assumptions involved, were given by Judd and Pillay (1991). A summary of the time dependent equations for the system, developed for the simplified schematic of the processes, as shown in Fig. 2, are presented here, following Wolfson et al. (1994). The only reactions considered in the gasification and combustion zones, respectively, are:

$$C + H_2O \Rightarrow CO + H_2\,;\; k_x = k_{r1} = k_4 \tfrac{kmole}{s};\; \Delta H_{r1} \tfrac{kJ}{kmole}$$

$$C + O_2 \Rightarrow CO_2 + H_2O\,;\; k_x = k_{r2} = k_5 \tfrac{kmole}{s};\; \Delta H_{r2} \tfrac{kJ}{kmole}$$

Material (carbon) and energy balances for the outer gasification zone (the moving bed reactor), assuming uniformity at the cross-section, yield a couple of one-dimensional, first-order equations:

$$\frac{\partial c_1}{\partial t} = -Q_{1i}\frac{\partial c_1}{\partial \nu_1} - k_4 c_1 \qquad (1)$$

$$\frac{\partial T_1}{\partial t} = (S\frac{C_s}{C_m} - Q_{1i})\frac{\partial T_1}{\partial \nu_1} - \Delta H_{r1} k_4 \frac{c_1}{C_m} \qquad (2)$$

$T_1$ and $c_1$ are functions of both time and distance.

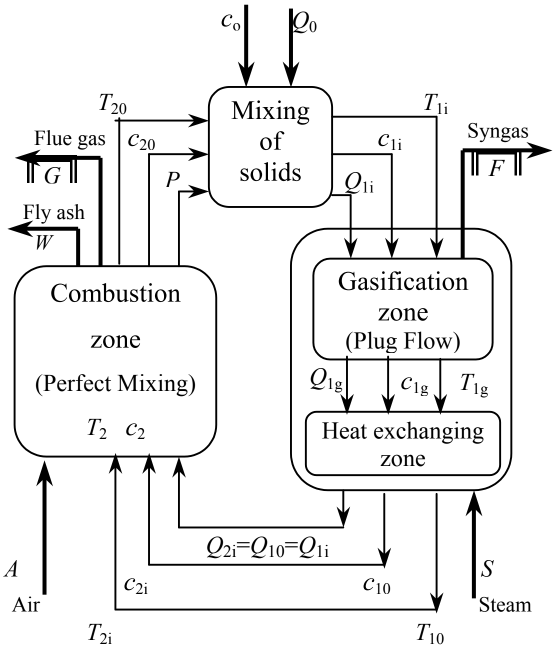


**Figure 2:** General scheme of the Judd gasifier model and nomenclature

Similarly, the carbon balance and heat balance of the combustion zone, assuming stirred tank reactor (STR), yield:

$$\frac{dc_2}{dt} = \frac{Q_{1i}}{V_2}(c_{2i} - c_2)k_5\frac{A}{V_2} \qquad (3)$$

$$\frac{dT_2}{dt} = \frac{Q_{1i}}{V_2}\left(T_{2i} - T_2\right) + \frac{AC_A}{V_2 C_m}\left(T_{Ai} - T_2\right) + \frac{A\Delta H_{r2}}{V_2 c_m} \qquad (4)$$

where $T_2$ and $c_2$ are functions of time only (STR assumption).

Several assumptions are embedded in these equations:

$$r_{x_1} = -\frac{dc_1}{dt} = k_4 c_1\,; \qquad r_{x_2} = -\frac{d(c_2 V_2)}{dt} = k_5 A$$

$$k_4 - k_{4\infty}\exp(-\frac{E_1}{RT}); \qquad k_5 = const.$$

$$W \approx Q_o \;\;;\;\; A \approx F \;\;;\;\; S \approx G \qquad (5)$$

$$V_1 \frac{\rho_s \varepsilon_1}{\rho_p(1-\varepsilon_1)} C_s + V_1 C_m \cong V_1 C_m$$

$$V_2 \frac{\rho_s \varepsilon_2}{\rho_p(1-\varepsilon_2)} C_A + V_2 C_m \cong V_2 C_m$$

In addition, the connection between the two chambers of the reactor is given by:

$$T_{10} = T_{1g} - (T_{1g} - T_{Si})\frac{SC_s}{Q_{1i}C_m}$$
$$c_{1g} = c_{10} \;;\; Q_{1i} = Q_o + P \qquad (6)$$
$$c_{1i} = \frac{c_2 P + c_0 Q_0}{Q_0 + P} ; T_{1i} = \frac{T_2 P + T_0 Q_0}{Q_0 + P} .$$

Rate of inert solids circulation, $P$, is given by (Judd and Rudolph, 1986):

$$P = 60(k_1 \frac{U_0}{U_{mf}}(U_d - U_{mf})^{k_3} - k_2 Q_x) . \qquad (7)$$

Fig. 3 depicts a computed map of efficiencies (E=Kg of gasified carbon/Kg of fed carbon) and constraints for the process running low-grade South African coal in the experimental size reactor as suggested by Judd and Pillay (1991). The general steady state solution is derived and the best working conditions, for the gasification, are calculated. Point "A" on this map represents the "desirable working conditions" for the process. It lies within the boundaries of the constraints, close to the highest possible efficiency and allows variation (controllable operation conditions) in the flows of both air and steam. It is, therefore, used for the working point around which the linearization of the process is carried out.

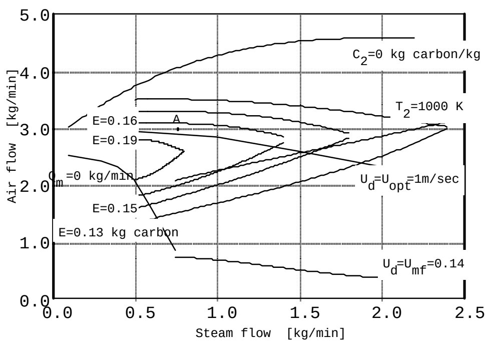


**Figure 3:** Efficiencies and constraints of the Judd gasifier model on the air-steam plane.

Due to the fact that the steady state solution for the gasification plug flow section is practically linear with respect to the reactor length, it is possible to reduce the total number of state variables from four ($c_1$, $T_1$, $c_2$, $T_2$) to two ($c_2$, $T_2$) and obtain, after the linearization, a set of two state equations only. However, because of the distributed nature of the gasifier section the penalty incurred is by introducing time delays in both the state variables and the control variables. The final set of equations can be written in the following form:

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{A}_1\mathbf{x}(t-\tau) \\ &\quad + \mathbf{B}\mathbf{u}(t) + \mathbf{B}_1\mathbf{u}(t-\tau) + \mathbf{G}\mathbf{w}(t) \\ \mathbf{y} &= \mathbf{C}\mathbf{x} . \end{aligned} \qquad (8)$$

The obtained system is a linear time-invariant system with multiple time delays in the state variable and in the control. It is assumed that all the state variables may be directly measured. It is now, possible to apply methods and results of linear control theory in order to investigate the relevant properties of the system, and to design a controller aimed to maintain the nominal steady state. This investigation is carried out for the particular Judd and Pillay (1991) gasifier. For this case the numerical values of the different matrices in Eq. (8) are:

$$\mathbf{A} = \begin{bmatrix} -9.726 & 0 \\ 0 & -9.713 \end{bmatrix} ; \mathbf{B} = \begin{bmatrix} -3.667 & -26.005 \\ 0.001 & 0.0031 \end{bmatrix}$$
$$\mathbf{A}_1 = \begin{bmatrix} 9.701 & 0 \\ 0 & 9.479 \end{bmatrix} ; \mathbf{B}_1 = \begin{bmatrix} 3.787 & 7.255 \\ -0.0024 & -0.0046 \end{bmatrix}$$

and the output matrix **C** is a unity matrix.

## 3. CONTROL OF THE JUDD GASIFIER

*Stability of the system:* The stability of linear time-invariant systems with multiple time delays, represented by

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \sum_{i=1}^{d} \mathbf{A}_i \mathbf{x}(t-\tau_i) \qquad (9)$$

has been studied by Malek-Zavarei and Jamshidi (1987). Their criterion for uniform asymptotic stability is applied to the Judd gasifier system. That is, if **A** is a stable matrix, i.e., all its eigenvalues are in the left half complex plane, then the following theorem applies:

*Theorem:* the system of Eq. (9) is uniformly asymptotically stable if the symmetric matrices **Q** and **R**, associated with the Lyapunov equation,

$$\mathbf{A}^T\mathbf{Q} + \mathbf{Q}\mathbf{A} + (d+1)\mathbf{R} = \mathbf{0} \qquad (10)$$

satisfy the following conditions of positive definiteness:

$$\mathbf{R} > \mathbf{0} \quad ; \quad \mathbf{R} - \sum_{i=1}^{d} \mathbf{Q}\mathbf{A}_i\mathbf{R}^{-1}\mathbf{A}_i^T\mathbf{Q} > 0 . \qquad (11)$$

This scheme depends on the number of delays $d$, but it is independent of the values of these delays. Checking the stability of the gasifier by applying the Lyapunov equation to the matrices **A**, $\mathbf{A}_1$, while taking the arbitrary positive-definite matrix **R** as $\mathbf{R}=\mathbf{I}_2$, and $d=1$ (single delay), it is found that the conditions (Eq. 11) of the theorem are satisfied and therefore the system is uniformly asymptotically stable.

*Controllability and observability of the system:* The problems of controllability and observability of continuous systems, with time delay in the state variables or in the control, have been extensively investigated (e.g., Malek-Zavarei and Jamshidi, 1987; Gorecki, 1989) and the necessary and sufficient conditions for controllability of such systems were proposed. Unfortunately, the derived continuous model (Eq. 8) has time delays not only in the state variable vector but in the control as well. That makes it impossible to apply the above-mentioned theorems to the current gasifier process, but simple discretization of the system enables the use of traditional controllability tests:

Consider the system of Eq. (8) without external disturbances, which, after zero-order hold discretization is represented by:

$$\mathbf{x}_{k+1} = \widetilde{\mathbf{A}}\mathbf{x}_k + \widetilde{\mathbf{A}}_1\mathbf{x}_{k-d} + \widetilde{\mathbf{B}}\mathbf{u}_k + \widetilde{\mathbf{B}}_1\mathbf{u}_{k-d}\ . \tag{12}$$

The discrete delay parameter, *d,* depends both on the continuous time delay, τ, and the choice of sampling time $T_S$ :

$$d = \frac{\tau}{T_s}\ . \tag{13}$$

($\tau = V_1 / P \approx 400/2000 = 0.2$ min at working point.)

Replacing derivatives by their finite difference equivalents:

$$\dot{\mathbf{x}} \approx \frac{\mathbf{x}_{k+1} - \mathbf{x}_k}{T_s};$$

$$\mathbf{x}(t) \approx \mathbf{x}_k\ ;\ \mathbf{x}(t-\tau_x) \approx \mathbf{x}_{k-d} \tag{14}$$

$$\mathbf{u}(t) \approx \mathbf{u}_k\ ;\ \mathbf{u}(t-\tau_u) \approx \mathbf{x}_{k-d}$$

yield the system equation in the desired discrete form, where

$$\widetilde{\mathbf{A}} = \mathbf{A}T_s + \mathbf{I};\qquad \widetilde{\mathbf{B}} = \mathbf{B}T_s;$$
$$\widetilde{\mathbf{A}}_1 = \mathbf{A}_1 T_s;\qquad \widetilde{\mathbf{B}}_1 = \mathbf{B}_1 T_s\ . \tag{15}$$

Next, the discrete delay, *d,* is eliminated and, by proper choice of the state variables, the system is transferred to the standard form:

$$\mathbf{z}_{k+1} = \overline{\mathbf{A}}\mathbf{z}_k + \overline{\mathbf{B}}\mathbf{u}_k\ . \tag{16}$$

The new augmented vector of state variables and controls, $\mathbf{z}_k$, in Eq. (16) is defined as,

$$\mathbf{z}_k^T = \left[\mathbf{x}_k^T\ \mathbf{x}_{k-1}^T\ \mathbf{x}_{k-2}^T..\mathbf{x}_{k-d}^T\ \mathbf{u}_{k-1}^T\ \mathbf{u}_{k-2}^T..\mathbf{u}_{k-d}^T\right] \tag{17}$$

where the augmented system matrices are:

$$\overline{\mathbf{A}} = \left[\begin{array}{cccccccc} \widetilde{\mathbf{A}} & 0 & \cdots & 0 & \widetilde{\mathbf{A}}_1 & 0 & \cdots & 0 & \widetilde{\mathbf{B}}_1 \\ \mathbf{I} & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & \mathbf{I} & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ \hline 0 & 0 & \cdots & \mathbf{I} & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 & \mathbf{I} & \cdots & 0 & 0 \\ \hline 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & \mathbf{I} & 0 \end{array}\right] \tag{18}$$

$$\overline{\mathbf{B}} = \left[\mathbf{0}\ \mathbf{0}...\mathbf{0}\ \widetilde{\mathbf{B}}...\mathbf{0}\ \mathbf{I}\right]'\ .$$

The only disadvantage of this approach is the increase in the system dimensions and, therefore, in calculations difficulty. *q=(n+m+1)d is* the dimension of the system, Eq. (16), and it increases with the decrease in sampling time.

Applying the rank criterion to the controllability matrix,

$$\mathbf{C}_{contr} = \left[\overline{\mathbf{A}}\ \ \overline{\mathbf{A}}\overline{\mathbf{B}}\ ...\overline{\mathbf{A}}^{\mathbf{q-1}}\overline{\mathbf{B}}\right] \tag{19}$$

shows that its rank is equal to the dimension, *q*, of the system matrix $\overline{\mathbf{A}}$ , and therefore, the system of Eq. (16) is controllable (reachable).

Obviously, the system is completely observable, as each state variable of Eq. (17) can be measured directly, and the output matrix **C** is a unity matrix, $\mathbf{I}_q$.

*LQG controller design and rejection of disturbances:* The control is aimed to reduce the influence of process noise and to maintain the steady state. The basic approach of the design is the use of a multivariable Linear-Quadratic-Gaussian (LQG) compensator of full state feedback and a Kalman filter. The procedure of the LQG design automatically yields the compensator structure.

To consider the influence of external disturbances the discretized system of Eq. (16) is used with the addition of the disturbance term,

$$\mathbf{z}_{k+1} = \overline{\mathbf{A}}\mathbf{z}_k + \overline{\mathbf{B}}\mathbf{u}_k + \overline{\mathbf{G}}\mathbf{w}_k \tag{20}$$

where, $\mathbf{w}_k$ is the vector of disturbances at time $k$, and **G** is the matrix of the disturbance coefficients given by:

$$\overline{\mathbf{G}}' = [\mathbf{G}T_s\ \ 0\ \ ...0]. \tag{21}$$

In addition, output measurement noise, $\mathbf{n}_k$, is accounted for. This noise is associated with the measurements of combustion temperature and carbon concentration,

$$\mathbf{y}_{k+1} = \overline{\mathbf{C}}\mathbf{z}_{k+1} + \mathbf{n}_k\ . \tag{22}$$

The LQG dynamic regulator design for the system represented by Eq. (20), (21), (22), consists of the following stages:

*LQR state feedback design*. The algebraic Riccati equation,

$$\overline{\mathbf{A}}^{\mathrm{T}}\mathbf{D}\overline{\mathbf{A}} - \mathbf{D} + \mathbf{Q}_c - \overline{\mathbf{A}}^{\mathrm{T}}\overline{\mathbf{B}}(\mathbf{R}_c + \overline{\mathbf{B}}^{\mathrm{T}}\mathbf{D}\overline{\mathbf{B}})^{-1}\overline{\mathbf{B}}^{\mathrm{T}}\mathbf{D}\overline{\mathbf{A}} = \mathbf{0} \tag{23}$$

is solved with respect to a positive-definite matrix **D** and the vector of state feedback gain **K**, is calculate:

$$\mathbf{K} = (\mathbf{R}_c + \overline{\mathbf{B}}^{\mathbf{T}}\mathbf{D}\overline{\mathbf{B}})^{-1}\overline{\mathbf{B}}^{\mathbf{T}}\mathbf{D}\overline{\mathbf{A}} \tag{24}$$

where $\mathbf{Q}_c$ and $\mathbf{R}_c$ are positive semi-definite weight matrices.

*Kalman filter gain design*. The positive-definite matrix **T** is found from the following Riccati equation:

$$\overline{\mathbf{A}}\mathbf{T}\overline{\mathbf{A}}^{\mathbf{T}} - \mathbf{T} + \overline{\mathbf{G}}\mathbf{Q}_f\overline{\mathbf{G}}^{\mathbf{T}} - \overline{\mathbf{A}}\mathbf{T}\overline{\mathbf{C}}^{\mathbf{T}}(\mathbf{R}_f + \overline{\mathbf{C}}\mathbf{T}\overline{\mathbf{C}}^{\mathbf{T}})^{-1}\overline{\mathbf{C}}\mathbf{T}\overline{\mathbf{A}}^{\mathbf{T}} = \mathbf{0} \tag{25}$$

and the vector of the filter gain **L**, is calculated:

$$\mathbf{L} = \overline{\mathbf{A}}\mathbf{T}\overline{\mathbf{C}}^{\mathbf{T}}(\mathbf{R}_f + \overline{\mathbf{C}}\mathbf{T}\overline{\mathbf{C}}^{\mathbf{T}})^{-1} \tag{26}$$

where $\mathbf{Q}_f$ and $\mathbf{R}_f$ are the covariance matrices of the noises $\mathbf{w}_k$ and $\mathbf{n}_k$, respectively.

*LQG dynamic regulator*. Both the feedback gain vector *K* and the filter gain vector **L** are being used concurrently:

$$\hat{\mathbf{z}}_{k+1} = \overline{\mathbf{A}}\hat{\mathbf{z}}_k + \overline{\mathbf{B}}\mathbf{u}_k + \mathbf{L}(\mathbf{y}_k - \overline{\mathbf{C}}\hat{\mathbf{z}}_k) \tag{27}$$

$$\mathbf{u}_k = -\mathbf{K}\hat{\mathbf{z}}_k + \mathbf{r}_k$$

where, $\hat{\mathbf{z}}_k$ is the estimate of state vector $\mathbf{z}_k$; and $\mathbf{r}_k$ is the vector of reference signals. The reference signal $\mathbf{r}_k$ can be taken as zero because the state vector $\mathbf{z}_k$ represents deviations of the state variables from their steady-state values.

Simulation of the open loop system response to non-zero initial conditions is stable but the settling time is rather long. It takes about an hour for $\Delta c_2 = c_2 - c_{2ss}$ and $\Delta T_2 = T_2 - T_{2ss}$ to reach 10% of their initial values.

Based on the open loop response the following weight matrices for the LQR are calculated,

$$\mathbf{Q}_c = \begin{bmatrix} 650 & 0 & 0 & \cdots & 0 \\ 0 & 0.04 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (28)$$

$$\mathbf{R}_c = \begin{bmatrix} 0.1 & 0 \\ 0 & 40 \end{bmatrix}.$$

The LQR alone considerably improves the overall system response.

For the filter design it is assumed that the covariance of the measurement error does not exceed 5% of the measured data and that the standard deviations of coal feed rate $Q_0$ and carbon concentration $c_0$ do not exceed 5% of their nominal values. Thus, the covariance noise matrix $\mathbf{R}_f$ and the covariance matrix $\mathbf{Q}_f$ are chosen as follows:

$$\mathbf{R}_f = \begin{bmatrix} 0.0025 & 0 \\ 0 & 0.0025 \end{bmatrix} \quad (29)$$

$$\mathbf{Q}_f = \begin{bmatrix} 0.0025 & 0 & 0 & \cdots & 0 \\ 0 & 4*10^{-8} & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \quad (30)$$

(The estimation process, i.e., the Kalman filter dynamics, based on the chosen covariance matrices of Eqs. (29), (30) is much faster than the dynamics of the closed loop LQR system.)

The closed loop system response simulation, with the full LQG dynamic compensator is shown in Fig. 4. It can be seen that, according to the separation principle, the process dynamics of the closed loop system correspond to the LQR design, and the estimation process satisfies the Kalman filter.

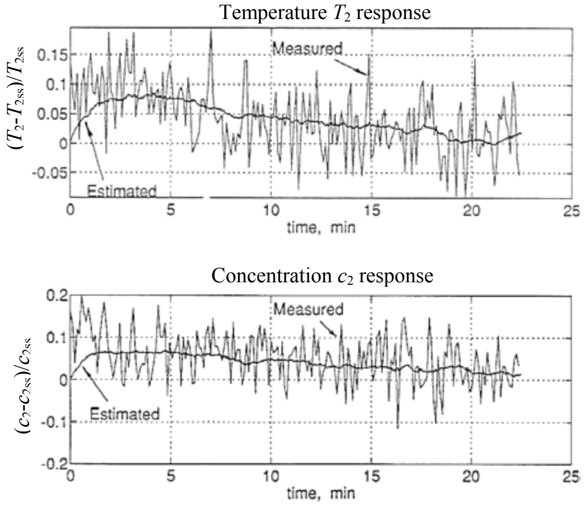


Fig. 4: Simulation of closed loop system response

The control efforts leading to the non-zero initial conditions system response of Fig. 4 are shown in Fig. 5. The maximum deviation of steam or airflow rates is about 10 percent of their steady-state values, which can be interpreted as "small" enough and justifying/satisfying the system linearization given by Eq. (8).

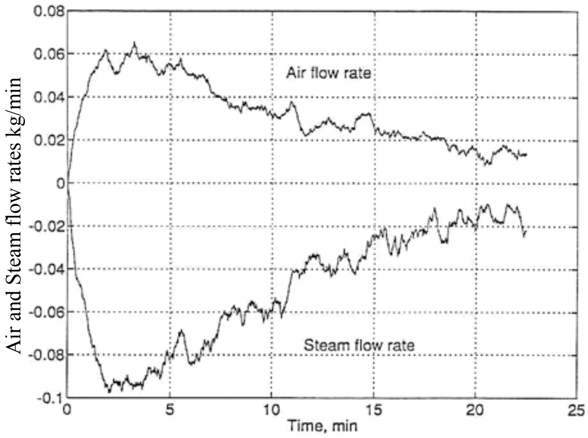


Fig. 5: Control efforts returning the process to steady state conditions from non-zero initial conditions

## 4. CONCLUSIONS AND RECOMMENDATIONS

The novel two-chamber Judd gasifier is investigated from the control point of view. Based on Judd's assumptions, the dynamic model of the gasifier is developed, and the governing equations for the carbon concentration and solids temperature within each zone were obtained.

Assuming small variations around the "optimal working point" yields the steady state profiles and the system equations are linearized about this point. The nature of the general solution for the equations enables the reduction of the model into two state variables, but the remaining two differential equations for the carbon concentration and the solids temperature in the combustion zone, as well as the control inputs (air and steam flow rates), contain time delays.

The linearized and reduced system is analyzed and is found to be asymptotically stable, completely controllable and observable. Because of the significant time delay, the open loop system response is not acceptable and a control strategy for the discretized system is proposed. The control is based on digital LQG design that includes the optimal Kalman filter. Simulation shows significant improvement in the system response, overcoming input disturbances (coal feed rate and carbon concentration) and measurement noise. Improvement in the dynamical properties of the controlled system over the open loop system is also obtained, e.g., the settling time of the temperature response has been decreased by approximately a factor of 5. The control efforts variations, during the time response to the non-zero initial conditions do not exceed 10 percent of the nominal values justifying the linearization.

Further research is recommended in order to alleviate the simplifying assumptions of the physical model and to yield a more detailed and complete model. Other issues, such as the influence of pressurization or the use of catalyst for the gasification, should be considered (Brion et al. 1996; Lee et al. 1998). Then, sensitivity study of the control system as well as applying and comparing different control procedures should be carried out. It should be emphasized, though, that even at this early stage the results of the present study constitute a strong recommendation and support for further industrial development of the Judd gasifier.

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