D. COAL GASIFIER CONTROL : A PROCESS ENGINEERING APPROACH

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Coal Gasifier Control: A Process Engineering Approach

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SYNOPSIS

The approach made here to designing a coal gasifier control system has its roots in process engineering. Our favoured solution is largely based around conventional single input single output loops which control gas calorific value with air flow, gas pressure with steam flow, gas temperature with char flow and bed mass with coal flow. Evolution towards this solution is discussed in relation to three intermediate schemes (in some cases involving non-linear control elements) which were found less effective in terms of the defined performance criteria.

Our favoured solution fully meets the required performance in both the 100% and 50% load cases but at 0% load, whilst responses are all stable, there are constraint violations which are transient following the pressure step disturbance but sustained for the sinusoidal disturbance. An important operational issue to be address in relation to the scheme is the management of auto/manual status transfers for some loops so as to avoid possible system instability.

During the study a number of issues, including equipment design and measurement precision, were identified as important. Their influence on controllability of the gasifier and on the robustness of the proposed control scheme are discussed.

1. GENERAL STRATEGY

The coal gasifier case study system, as described by Dixon (1997), can be viewed as a process reaction system subject to downstream demand disturbances. The characteristics of the gasifier are not that unusual amongst process systems in being non-linear, multi-variable, strongly interactive and stiff. In this context, industrial control practice often equates control system simplicity with good reliability and robustness in operation and we accordingly elected, as a preliminary at least, to make a relatively conventional approach to the problem and to exhaust the conventional control options before resorting to multi-variable or more advanced control strategies. In the event, a set of viable single-input single-output (SISO) control strategies were identified at the 100% load level, though higher levels of performance amongst the set were achieved only at the expense of potential difficulties in safeguarding system stability in the face of individual loop auto/manual transfers, as will be described later. The application of heuristics in evolving these strategies resulted in a need to examine only half of the 24 pairing options available in the 4 SISO loop system. One might anticipate some further performance gains to accrue from additional effort spent in extending the proposed design into a more fully developed multi-variable control approach.

2. INTERACTION AND SINGLE LOOP VARIABLE PAIRING

Viewed as a chemical reaction system aimed at achieving consistent product quality (i.e. off-gas calorific value *Cv*) an intuitive arrangement for control of the gasifier would be to maintain

- bed mass *M* with char removal rate *Fchar* (i.e. maintain material inventory by manipulating the bulk removal rate)
- calorific value *Cv* with coal feed rate *Fcoal* (i.e. carbon content of the off-gas will increase with additional coal feed)
- gas exit temperature *T* with feed rates of steam *Fsteam* or air *Fair* (additional oxygen will increase reaction/burning and hence heat evolution)
- system pressure *P* with gas feed rate *Fair* or *Fsteam* (i.e. system pressure is set by the balance between gas feed and removal rates).

Because of the relatively minor contribution of limestone compared with coal in the total solids fed to the unit, the intuitive choice of keeping limestone feed rate *Flime* in strict ratio with *Fcoal* has been used throughout. To supplement these heuristics, a quantitative overview of favourable controlled and manipulated variable pairings can be gleaned from the system's Relative Gain Array (Bristol, 1966). With the system model given by Dixon (1997) as

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\,\boldsymbol{x} + \boldsymbol{B}\,\boldsymbol{u} \qquad\qquad \boldsymbol{y} = \boldsymbol{C}\,\boldsymbol{x} + \boldsymbol{D}\,\boldsymbol{u}$$

the relative gain array (RGA) can be calculated as Λ from

$$\boldsymbol{K} = \boldsymbol{D} - \boldsymbol{C}\,\boldsymbol{A}^{-1}\,\boldsymbol{B} \qquad\qquad \boldsymbol{\Lambda} = \boldsymbol{K} \times (\boldsymbol{K}^{-1})'$$

Here, $\boldsymbol{K}$ is the system steady state gain matrix and × represents the Hadamard (i.e. element by element) product. Recall that in the RGA, the most favourable measurement/manipulated variable pairings (i.e. those showing lower levels of interaction) are indicated by elements closer to unity. The RGA calculated for the gasifier 100% load case is presented in Table 1, allowing an overview of the 24 alternative SISO pairings involved. The most favourable pairings indicated are *Cv-Fcoal*, *M-Fchar*, *P-Fair* and *T-Fsteam*, largely in line with the heuristics above. However, the magnitude of the RGA elements suggest there will still be significant interaction between these loops, necessitating some trade-offs in controller tuning to meet the system performance targets. Of course, the RGA has limitations (the criterion is based around steady state conditions only and assumes the availability of 'perfect' feedback controllers) but despite this has merit in revealing favourable relationships. An additional feature of particular significance in Table 1 is the appearance of negative elements which indicate that a sign reversal in control loop gain factor will be required on auto/manual transfer for the loop pairings concerned (i.e otherwise positive feedback and unstable operation will result). For this reason pairing on negative RGA elements is generally discouraged (McAvoy 1983).

3. SIMULATION

Gasifier control strategy development and testing was conducted almost exclusively using the full order linear models mounted in SIMULINK and MATLAB was used for system analysis (Math Works 1992). Early examination of gasifier model eigenvalues revealed a stiff system with response times ranging from 68 minutes to 0.03 seconds (stiffness ratio of 1.36e5:1) for the 100% load case. For numerical integration purposes the variable step Runge Kutta (RK45) integration procedure was chosen, though the fast modes in the model produced some numerical noise (see for example Figures 6c and 6f). MATLAB was also used in some evaluation studies using reduced order state space models to cut out the faster modes and achieve quicker and more stable simulation over medium and long time scales. However, all the performance results presented later were generated using SIMULINK and the full order models provided.

4. DESIGN EVOLUTION AT THE 100% LOAD CASE

Design was based solely on the 100% load case. The 50% and 0% load cases were used only to evaluate the performance measures once a potentially viable design had been found.

Scheme 1: The most favourable RGA paring was implemented as in Figure 1 without applying any constraints on control action whatsoever. High gain proportional (P) action in all four loops proved perfectly adequate to meet the output performance specifications. Significantly, amongst the manipulated variables, only *Fcoal* exceeded its maximum constraint whilst all four briefly broke their rate constraints. The rate and value constraints on the manipulated variables were introduced successively to the simulation with adjustments being made to both controller modes used and tuning parameters at each stage as appropriate. A viable design, with IAE values of 6.015e6 in *Cv* and 1.817e6 in *P*, was achieved using P action on the bed mass and PI action in the other loops together with the imposition of tighter rate limitations on *Fsteam* (-0.85/0.4) and *Fair* (-0.325/0.185) than strictly called for by the hardware constraints (±1 in both cases). The rate constraint feature imposed by the equipment characteristics was found to be most significant in shaping the system response in the short term following the process step disturbance.

Scheme 2: Although Scheme 1 prevents any constraint violations following the test disturbances at 100% load, there are sustained output offsets with manipulated variables running against their value constraints. Further performance gains in reduced IAE on the two primary control variables *Cv* and *P* proved achievable only by re-pairing and slight relaxation of the very high performance on the secondary variables *T* and *M*. The *M-Fchar* pairing was treated as essential and examination of the 6 alternative pairings relating to this choice (including Scheme 1) produced four reject designs and Scheme 2 (see Figure 2) which provides IAE values of 5.351e5 for *Cv* and 8.54e5 for *P*, i.e. superior to Scheme 1. Note that Scheme 2 is simply Scheme 1 with exchanged pairing between *Fsteam* and *Fair* and that the resulting pairing is, like Scheme 1, on only positive elements in the RGA. Enhanced performance in *P* is achieved to some extent at the expense of a higher peak value in

Cv. With the same controller modes as in Scheme 1, a tightened rate limit on only *Fsteam* (±0.7) is required in this case.

Scheme 3: The tight restriction of both the rate and value constraints on *Fcoal* was mentioned earlier. In contrast the responses in *M* under Schemes 1 and 2 fall easily within its allowed limits and it might make sense to take up this 'slack' by pairing it with *Fcoal*, the most tightly constrained input variable. There is also good heuristic sense to this in terms of the bulk solids content of the bed being more strongly related to *Fcoal* than to the relatively minor *Fchar* (respectively 8.55 and 0.9 kg/s at 100% load). Accordingly, the 6 designs involving the *M-Fcoal* pairing were examined by simulation. All proved unviable apart from Scheme 3 (see Figure 3) which yielded a significant performance enhancement over the previous schemes (IAE of 3.806e4 in *Cv* and 1.022e5 in *P*). As before P action was used to control M and PI action in the other three loops. No additional rate limits on the manipulated variables were necessary. Significantly, however, two pairings, *Cv-Fair* and *T-Fchar*, are on negative RGA elements. This means that extreme caution must be exercised here since performance of this scheme is only proven viable with all four loops closed simultaneously. The system will become unstable with some subsets of loops closed, a fact which represents an important operational issue.

Scheme 4: Whilst Dixon (1997) identifies the window of primary interest for performance evaluation as 0/300 seconds following a load change, there is one feature of the Scheme 3 response that is worthy of further consideration. There is a longer term drift in bed mass *M*. In fact, bearing in mind the stiffness of the process model, the focus of attention on the 0/300 seconds timescale for the control system design does seem to raise potential questions in that long timescale viability is also an essential issue. This question will be addressed more generally later but a simple enhancement can be made here to trim the bed mass drift. Because, as has already been highlighted, bed mass relates to the balance between coal addition and char removal rates, we can insert an additional co-ordinating link between *T* and *Fcoal* to compensate. Proportional (fixed gain) compensation only is needed. As well as stabilising the long term drift in bed mass, this addition also provides a significant overall performance enhancement (IAE values of 1.919e4 in *Cv* and 3.017e4 in *P*) and represents our final design (see Figure 4). As a minor modification from Scheme 3, the same comments in regard to pairing on negative RGA elements applies. Controller tuning parameters (i.e. proportional gains and integral action times in seconds) used in the scheme were respectively 2 and 50 for *T-Fchar*, -2e-4 and 1 for *Cv-Fair*, .001 and 5 for *P-Fsteam* and .01 for *M-Fcoal* (P action only) with a compensator gain of 0.4.

5. QUANTITATIVE PERFORMANCE OF THE PROPOSED CONTROL SCHEME

The proposed system design (Scheme 4/Figure 4) was tested at the three load conditions (100%, 50% and 0%) and in response to the defined step and sinusoidal disturbances in downstream pressure *Psink*. Full results in terms of IAE, maximum and minimum values etc. are presented in Tables 2 to 7. The dynamic response plots for the four controlled variables over the 0/300 seconds window are also presented in

Figures 5 to 8 for the step and the sinusoidal disturbance at each of the 100%, 50% and the 0% load cases respectively.

6. RESILIENCE OF THE PROPOSED CONTROL SCHEME

In the course of developing a suitable control scheme for the gasifier some important features of both the system, our proposed solution and of the original performance specifcation have been identified as key factors in a successful outcome and these are summarised below.

Process disturbances: The size of process disturbances defined for performance assessment are quoted in absolute terms. These present a stringent test at 100% load but reach an extreme at 0% load, where the nominal steady state lies close to the minimum equipment constraints and, in relative terms, larger percentage moves about the normal condition are involved. Accordingly this case is the most challenging one to cope with in avoiding the tendency to hit the constraints.

Measurement precision: It is doubtful that performance of such a high order as that predicted in the simulations presented here will be achievable in practice owing to real-world measurement precision being far poorer than that assumed in the performance specification. Accordingly, the specifications for performance on *T*, *P* and *Cv* should all be reviewed in this light.

Manipulated variable limitations: In essence the problem here is one of non-linear control against constraints which, with appropriate relaxation by passive design changes, would call for use of a far less highly tuned active control system. For example, the tightest constraint on 100% load performance attaches to *Fcoal* and increasing capacity of the coal feeder system by only 5% would allow the whole control problem to be simplified.

Long term response stability: Some candidate control schemes met the specification within the 0/300 seconds window but drifted out of limits in the longer term. Such cases were generally rejected. For example at 100% load using Scheme 4 the perturbation in bed mass *M* stabilises within limits at -142.3 after about 2500 seconds. Under Scheme 3 (which we rejected) *M* falls to -48 at 2500 seconds but drifts slowly to its limit of -500 after 16 hours.

Auto/manual transfer: Two pairings in Scheme 4 were on negative RGA elements. This calls for extreme caution as whilst stable with all four loops working, the system will be unstable with certain subsets of loops switched to manual mode. For example the system will be unstable with either the *Cv* or *M* loop only in manual mode. For *T* and *P* it is stable but the output limits will be violated. All 16 possible auto/manual scenarios should be examined for problem cases.

Ease of practical implementation: Scheme 4 has the advantage of transparency to a process operator. The control actions used (P or PI action) are all conventional and familiar in an operating situation. From a commissioning standpoint, tuning of the system can be undertaken manually on the real unit rather than rely on predictions from the dynamic model used here which may mismatch with the eventual full scale plant behaviour.

Model fidelity: Doubt on this point represents one of the main arguments for retaining as low a level of control sophistication as possible. Whilst predictions from the design stage are allowable where model fidelity is good e.g. aerospace applications, this is unlikely to be so for a coal gasifier and implementation of detailed model predictions will be contingent on first obtaining a properly validated model of the full scale unit after start-up. We have avoided an on-line model based approach because of uncertainty on the validity of the available linear model in the face of a) excursions away from the normal operating range in what is a non-linear process and b) non-stationarity that will arise at full scale e.g. from longer term feedstock variation.

7. CONCLUSIONS

Four SISO control schemes have been found to meet the desired system performance for the step disturbance in *Psink* at the 100% load condition , the best performance prediction having being achieved under Scheme 4 (Figure 4). More broadly, this control scheme proves capable of meeting the desired performance with both step and sinusoidal disturbances at both the 100% and the 50% load conditions. At the 0% load condition the scheme is stable in operation but the constraints on some controlled variables will be violated e.g. within the 0/300 second time scale *P* will exceed its allowable limit and beyond 300 seconds, constraints on *Cv* and *T* will be violated for the sinusoidal disturbance.

In making use of standard control strategies (e.g. PID control) routinely available in modern industrial control systems, practical implementation of the proposed Scheme 4 should be straightforward. In addition, commissioning on the real plant will allow adaption of the scheme (i.e. controller tuning) to the practical, observed characteristics of the operating unit, rather than having to rely wholly on predictions derived from the (possibly inaccurate) linear model provided for this feasibility study. If implemented using modern DCS technology the potential exists to develop the control strategy further in the light of experience on the operating plant. However, there is an important operational issue to be address in managing auto/manual transfers in some loops so as to avoid system instability (arising from pairing on negative RGA elements).
The problem of designing a control system for the gasifier is largely shaped by the hard constraints imposed on the manipulated variables. The strong interactions between variables within the system, whilst not a particular problem in their own right, conspire to compound the difficulty of this non-linear control problem. More specifically, the high level of tuning called for in the active control system as a result, could be relaxed through making a comparatively small (5%) increase in the capacity of the coal feed system. Operability of the unit would be eased considerably as a consequence.

Performance of the unit at the level of precision called for in the original brief will demand far higher measurement precision than is commonly achievable in a process control context and may well prove important in shaping the performance achievable on the full scale plant.

NOMENCLATURE

Cv – product gas calorific value
Fair – air feed rate
Fchar - char removal rate
Fcoal - coal feed rate
Flime - limestone feed rate
Fsteam - steam feed rate
M- bed mass
P - system pressure
Psink - system downstream pressure
RGA - Relative Gain Array
T - process temperature

REFERENCES

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Bristol, E H (1966), *On a new measure of interaction for multivariable process control*, IEEE Trans Auto Cont, AC-11, 133-134.

McAvoy, T J (1983), *Interaction Analysis*, ISA Monograph Series, No 6.

Math Works (1992), MATLAB and SIMULINK User's Guide, The Math Works Inc.

Table 1: RGA analysis

	Fchar	Fair	Fcoal	Fsteam
Cv	0.3298	-.0540	**0.5400**	0.1842
M	**0.6654**	-.0255	0.3387	0.0214
P	0.0100	**0.8802**	0.0411	0.0687
T	-.0052	0.1993	0.0802	**0.7258**

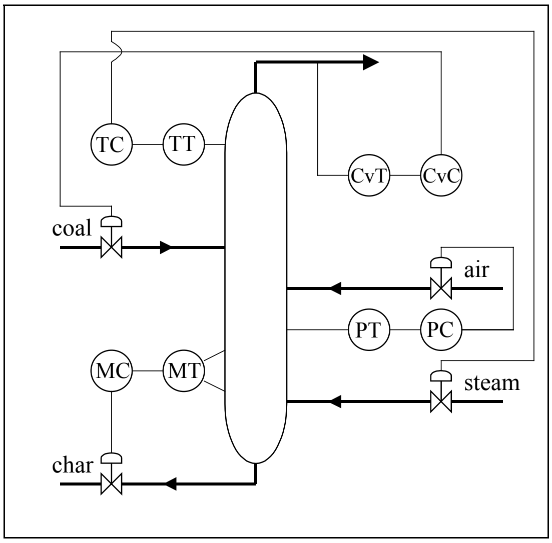


Figure 1: Scheme 1

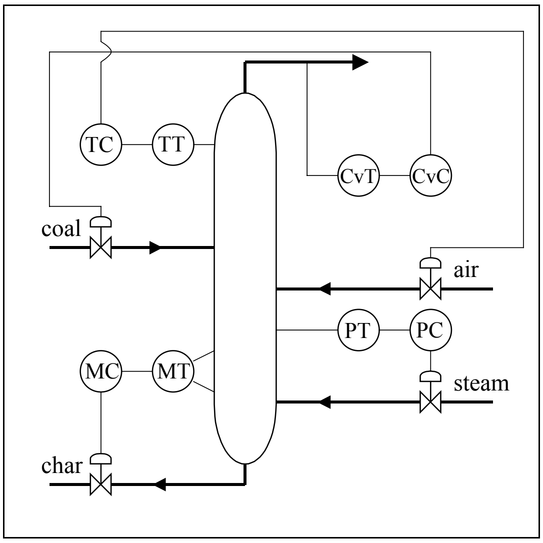


Figure 2: Scheme 2

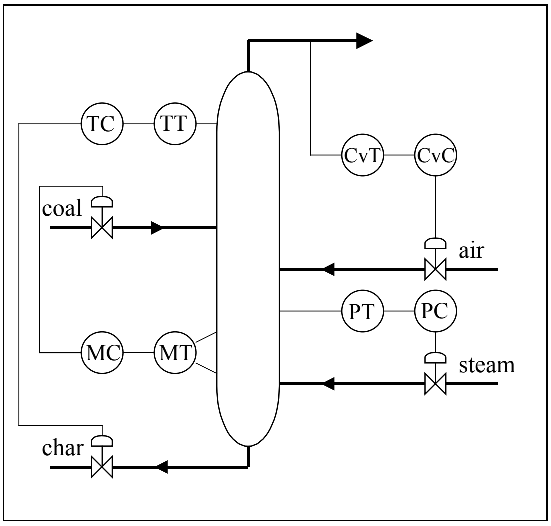


Figure 3: Scheme 3

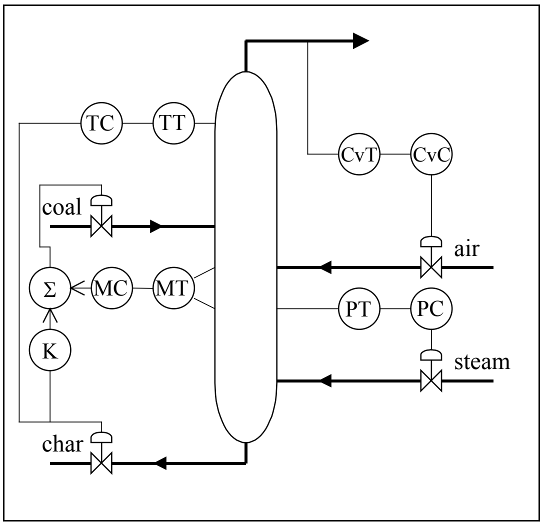


Figure 4: Scheme 4

Legend for Figures 1-4

Variables:		**Functions:**	
Cv	calorific value	C	controller
P	pressure	T	transmitter
T	temperature	K	gain factor
M	bed mass	Σ	summation

Table 2: Response of Control Scheme 4 to a step disturbance at 100% load

	Max Absolute Value	Min Absolute Value	Peak Rate (1/s)	IAE
Control Inputs				
Char (kg/s)	1.3491	0.0505	0.2	-
Air (kg/s)	18.4551	16.0402	1.0	-
Coal (kg/s)	9.1127	8.3862	0.2	-
Steam (kg/s)	4.6434	2.70	1.0	-
Control Outputs				
Calorific Value (J/kg)	4.36835×10^6	4.35695×10^6	3.852×10^3	1.919×10^4
Bed mass (kg)	10000	9941.1	0.8764	-
Pressure (Pa)	2.00003×10^6	1.99467×10^6	9.760×10^3	3.017×10^4
Temperature (K)	1223.4551	1222.7943	1.334	-

Table 3: Response of Control Scheme 4 to a sinusoidal disturbance at 100% load

	Max Absolute Value	Min Absolute Value	Peak Rate (1/s)	IAE
Control Inputs				
Char (kg/s)	1.8825	0.0489	0.2	-
Air (kg/s)	18.6892	15.9366	1.0	-
Coal (kg/s)	8.9001	8.2279	0.2	-
Steam (kg/s)	3.9407	1.3918	1.0	-
Control Outputs				
Calorific Value (J/kg)	4.36148×10^6	4.35825×10^6	1.287×10^3	2.901×10^5
Bed mass (kg)	10007.3161	9994.7743	1.3376	-
Pressure (Pa)	2.00097×10^6	1.99903×10^6	772.1947	1.839×10^5
Temperature (K)	1223.7133	1222.708	0.3613	-

Table 4: Response of Control Scheme 4 to a step disturbance at 50% load

	Max Absolute Value	Min Absolute Value	Peak Rate (1/s)	IAE
Control Inputs				
Char (kg/s)	1.4239	0.0876	0.2	-
Air (kg/s)	12.1776	9.3851	1.0	-
Coal (kg/s)	5.8771	5.2083	0.2	-
Steam (kg/s)	3.8869	1.69	1.0	-
Control Outputs				
Calorific Value (J/kg)	4.49388×10^6	4.48693×10^6	4096	2.165×10^3
Bed mass (kg)	10000	9932.0516	0.8361	-
Pressure (Pa)	1.55004×10^6	1.54271×10^6	1.211×10^4	4.281×10^4
Temperature (K)	1181.3024	1180.6463	2.0893	-

Table 5: Response of Control Scheme 4 to a sinusoidal disturbance at 50% load

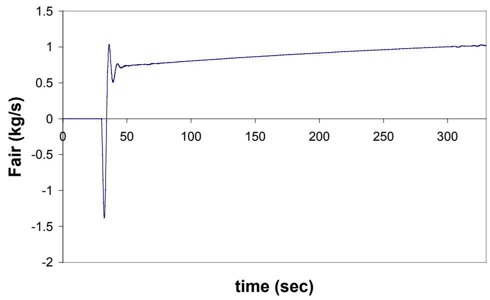
	Max Absolute Value	Min Absolute Value	Peak Rate (1/s)	IAE
Control Inputs				
Char (kg/s)	1.8189	0	0.2	-
Air (kg/s)	12.6960	9.1018	1.0	-
Coal (kg/s)	5.7124	5.0043	0.2	-
Steam (kg/s)	3.3813	0	1.0	-
Control Outputs				
Calorific Value (J/kg)	4.49207×10^{6}	4.48785×10^{6}	1.718×10^{3}	4.092×10^{5}
Bed mass (kg)	10008.1825	9994.3565	1.3136	-
Pressure (Pa)	1.55136×10^{6}	1.54864×10^{6}	1.256×10^{3}	2.511×10^{5}
Temperature (K)	1181.7304	1180.4448	0.6875	-

Table 6: Response of Control Scheme 4 to a step disturbance at 0% load

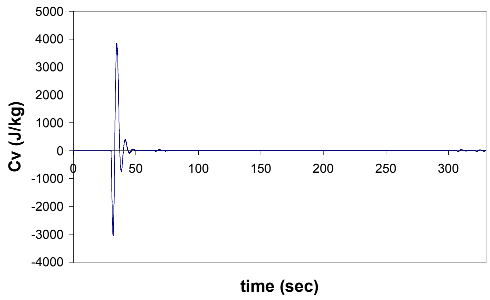
	Max Absolute Value	Min Absolute Value	Peak Rate (1/s)	IAE
Control Inputs				
Char (kg/s)	1.1193	0	0.2	-
Air (kg/s)	6.8935	2.6096	1.0	-
Coal (kg/s)	2.8381	2.136	0.2	-
Steam (kg/s)	3.4350	0.676	1.0	-
Control Outputs				
Calorific Value (J/kg)	4.71326×10^{6}	4.70696×10^{6}	3.614×10^{3}	3.210×10^{4}
Bed mass (kg)	10000	9908.328	1.2423	-
Pressure (Pa)	1.12011×10^{6}	1.10742×10^{6}	2.1907	8.315×10^{4}
Temperature (K)	1116.6748	1114.5177	4.9964	-

Table 7: Response of Control Scheme 4 to a sinusoidal disturbance at 0% load

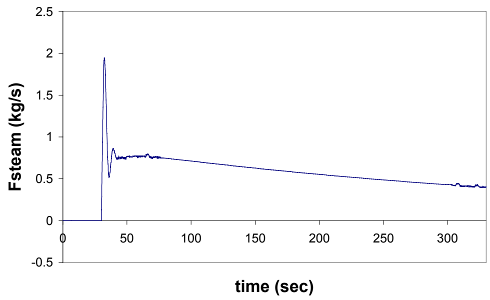
	Max Absolute Value	Min Absolute Value	Peak Rate (1/s)	IAE
Control Inputs				
Char (kg/s)	1.2798	0.2326	0.2	-
Air (kg/s)	5.6073	1.4521	1.0	-
Coal (kg/s)	2.3552	1.7809	0.2	-
Steam (kg/s)	2.8367	0	1.0	-
Control Outputs				
Calorific Value (J/kg)	4.71938×10^{6}	4.70676×10^{6}	7.251×10^{3}	3.950×10^{5}
Bed mass (kg)	10033.8892	10000	0.4743	-
Pressure (Pa)	1.13437×10^{6}	1.09222×10^{6}	5.966×10^{3}	3.687×10^{6}
Temperature (K)	1115.2630	1114.1470	1.7221	-



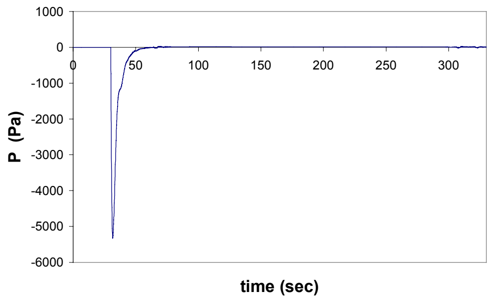
(a) air flow (Fair) perturbation around 17.42 kg/s



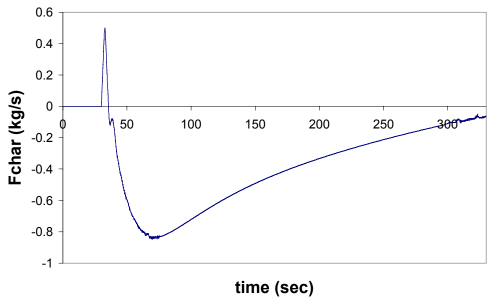
(b) calorific value (Cv) perturbation around 4.36×10^6 J/kg



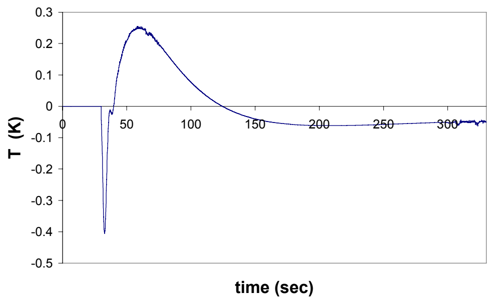
(c) steam flow (Fsteam) perturbation around 2.7 kg/s



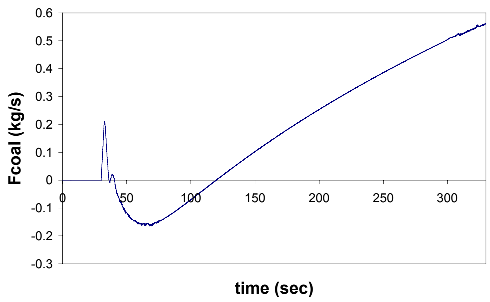
(d) gas pressure (P) perturbation around 2.0×10^6 Pa



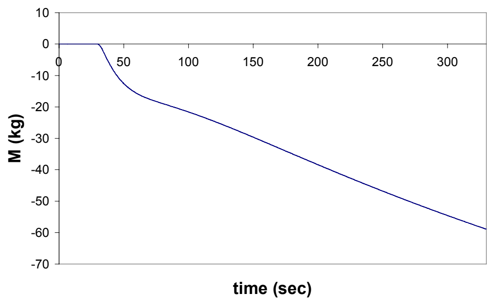
(e) char flow (Fchar) perturbation around 0.9 kg/s



(f) gas temperature (T) perturbation around 1223.2 K

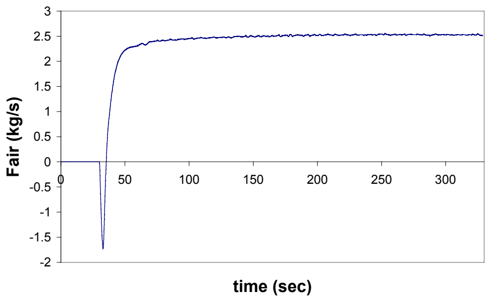


(g) coal flow (Fcoal) perturbation around 8.55 kg/s

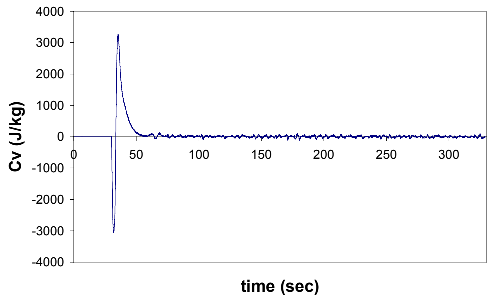


(h) bed mass (M) perturbation around 10000 kg

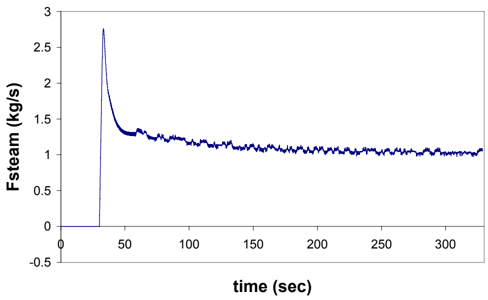
Figure (5): Responses to a step disturbance in the 100% load case. (Manipulated variables: Fair, Fsteam, Fchar, Fcoal; controlled variables: Cv, P, T, M)



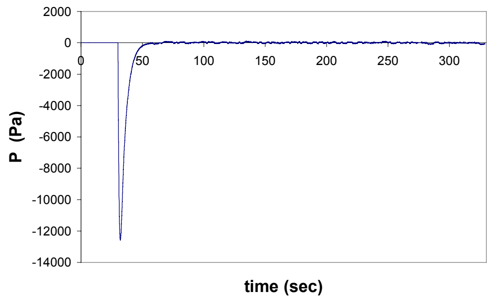
(a) air flow (Fair) perturbation around 4.34 kg/s



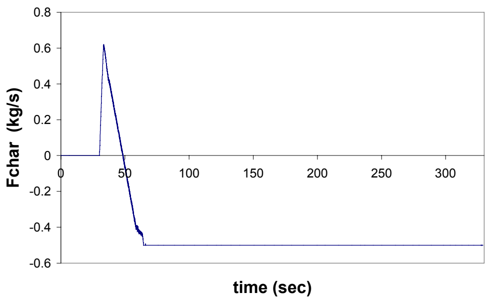
(b) calorific value (Cv) perturbation around 4.71x10^6 J/kg



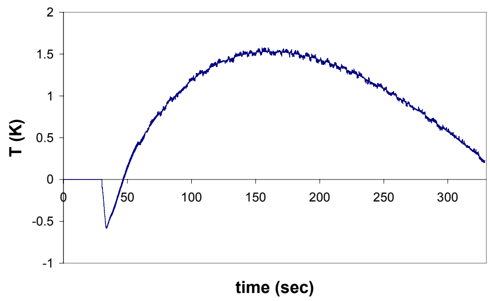
(c) steam flow (Fsteam) perturbation around 0.676 kg/s



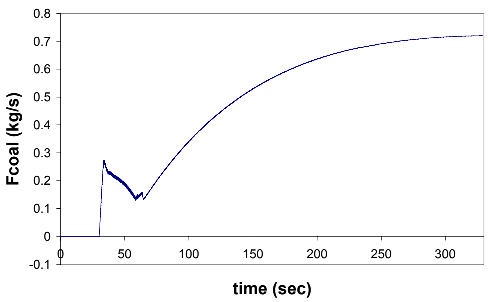
(d) gas pressure (P) perturbation around 1.12x10^6 Pa



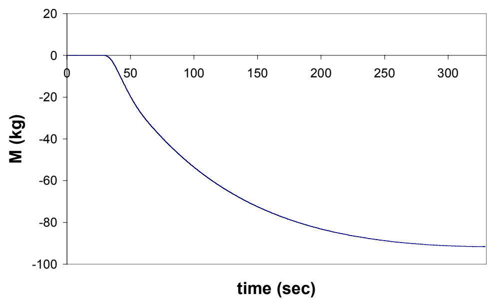
(e) char flow (Fchar) perturbation around 0.5 kg/s



(f) gas temperature (T) perturbation around 1115.1 K

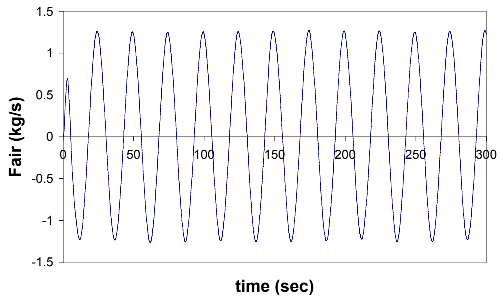


(g) coal flow (Fcoal) perturbation around 2.136 kg/s

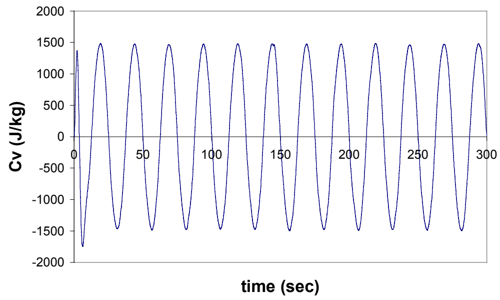


(h) bed mass (M) perturbation around 10000 kg

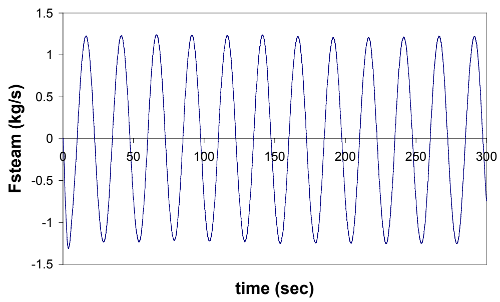
Figure (6): Responses to a step disturbance in the 0% load case. (Manipulated variables: Fair, Fsteam, Fchar, Fcoal; controlled variables: Cv, P, T, M)



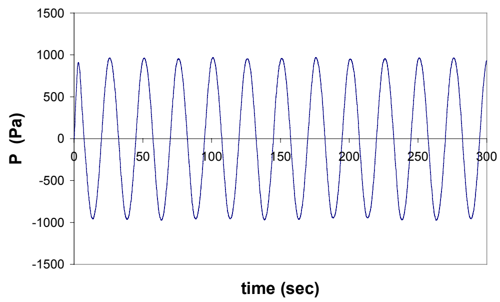
(a) air flow (Fair) perturbation around 17.42 kg/s



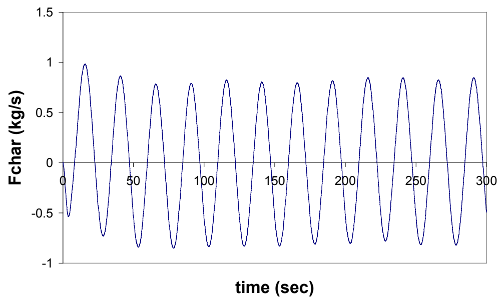
(b) calorific value (Cv) perturbation around $4.36\text{x}10^6$ J/kg



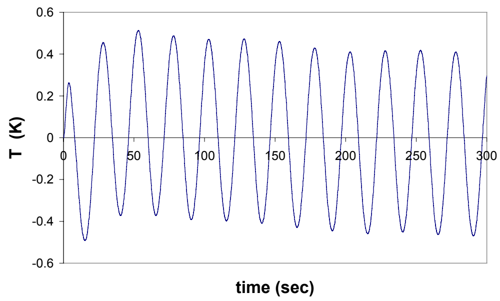
(c) steam flow (Fsteam) perturbation around 2.7 kg/s



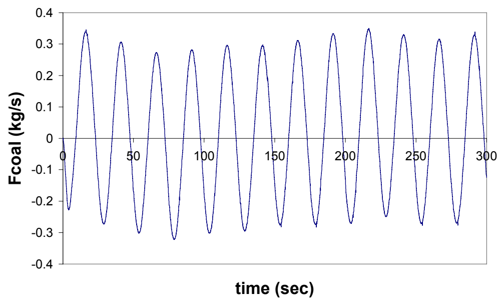
(d) gas pressure (P) perturbation around $2.0\text{x}10^6$ Pa



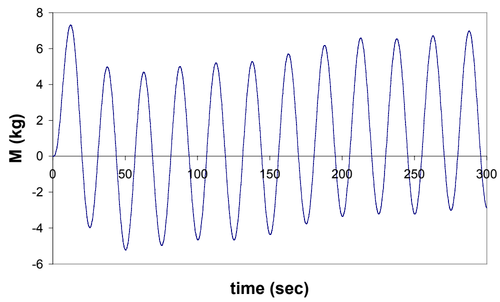
(e) char flow (Fchar) perturbation around 0.9 kg/s



(f) gas temperature (T) perturbation around 1223.2 K

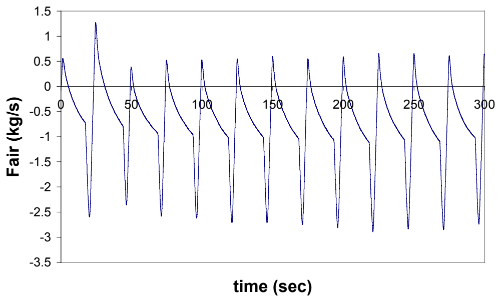


(g) coal flow (Fcoal) perturbation around 8.55 kg/s

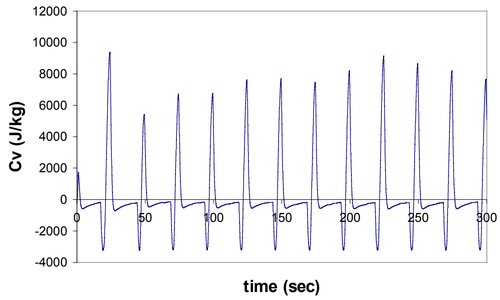


(h) bed mass (M) perturbation around 10000 kg

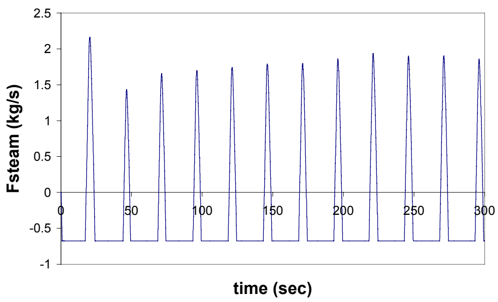
Figure (7): Responses to a sinusoidal disturbance in the 100% load case. (Manipulated variables: Fair, Fsteam, Fchar, Fcoal; controlled variables: Cv, P, T, M)



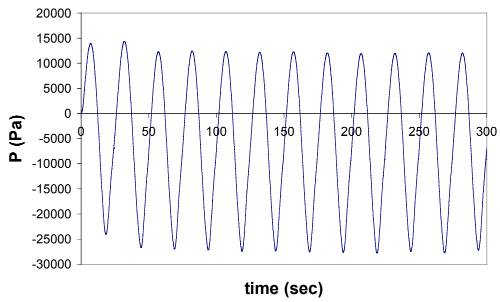
(a) air flow (Fair) perturbation around 4.34 kg/s



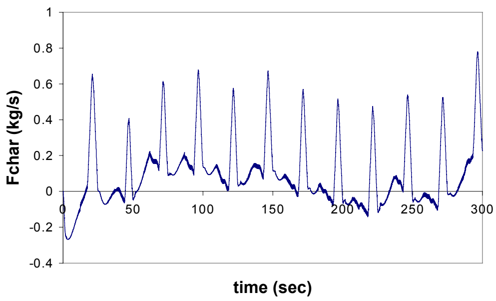
(b) calorific value (Cv) perturbation around 4.71×10^6 J/kg



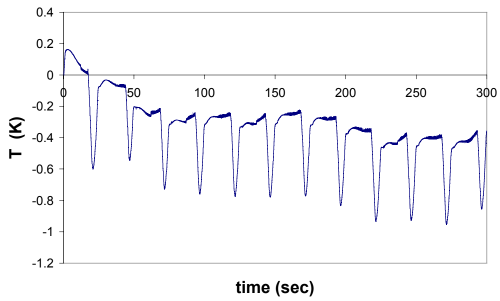
(c) steam flow (Fsteam) perturbation around 0.676 kg



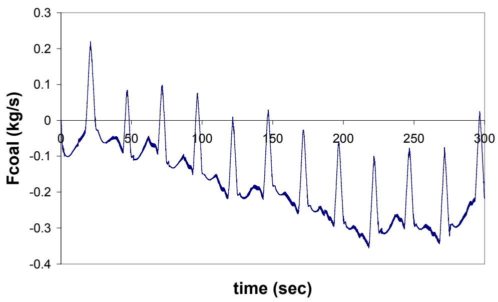
(d) gas pressure (P) perturbation around 1.12×10^6 Pa



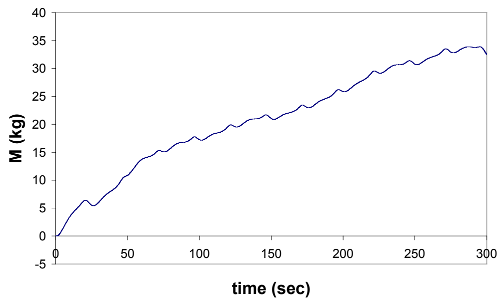
(e) char flow (Fchar) perturbation around 0.5 kg/s



(f) gas temperature (T) perturbation around 1115.1 K



(g) coal flow (Fcoal) perturbation around 2.136 kg/s



(h) bed mass (M) perturbation around 10000 kg

Figure (8): Responses to a sinusoidal disturbance in the 0% load case. (Manipulated variables: Fair, Fsteam, Fchar, Fcoal; controlled variables: Cv, P, T, M)