present study is limited to generating systems whose degree of heat integration increases gradually and will approach a reversible state, the stopping criteria for the repetitive application of the operations f_T, f_P, and f_E should include other factors from practical considerations such as the operability and reliability of the heat integrated system, as well as the economic criteria. In the practical application of the present method, the final decision of choosing the most appropriate system among the synthesized systems is dependent on engineering judgments. As a more rational approach, it is possible to deal with the problem under consideration as a multiobjective problem. The result by this rational approach will be presented elsewhere (Umeda et al., 1979*b*). The advantage of the present approach is its simplicity, ease of use, and clarity of the thermodynamic characteristics of the generated systems.

In addition to the problem of synthesizing the heat integration systems for energy conservation, it is also an important subject to improve the degree of energy utilization associated with the distillation. There exists the loss of available energy in the column internal subsystem. A detailed description on this subject is given elsewhere (Itoh et al., 1979).

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The authors are indebted to Chiyoda Chemical Engineering and Construction Company for permission to publish this paper and for the support of research work. They express their appreciation of assistance rendered them by J. Itoh, N. Suda, and others in the department for developing the present method.

NOTATIONS

f_E = operation to shift the composite heat sink line to the left
f_P = operation to change the pressure of a column or vapor streams which causes a temperature change on the composite lines or their segments
f_T = operation to change the temperature of a segment of the composite lines without pressure change
Q = heat energy, Kcal/hr
Q_c = amount of heat removal, Kcal/hr
Q_H = amount of heat supply, Kcal/hr
Q_R = amount of heat recovery, Kcal/hr
T = absolute temperature of a stream, °K
To = absolute temperature of the atmosphere, °K

Greek Letters

α = factor associated with the annual fixed cost
ϕ_{Di} = investment cost of i^{th} distillation system
ϕ_{Ej} = investment cost of j^{th} heat exchange system
$\phi_{S \cdot R \cdot k}$ = investment cost of k^{th} heat supply or removal system
Φ = economic objective function expressing annual cost
Ψ_{kl} = amount of l^{th} kind of utility in k^{th} heat supply or removal system
ψ_l = unit cost of l^{th} kind of utility

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Transient Behavior of Moving-Bed Coal Gasification Reactors

The transient response of dry ash and slagging moving-bed coal gasification reactors is analyzed for small step changes in feed conditions. The approach to the new steady state for perturbations about the optimum in the Lurgi gasifier has a time scale of about 10 hr. Transients in the slagging gasifier can result in a decrease in the coal bed height, which occurs on a time scale of several hours. There is a rapid initial response in both types of reactors in product gas temperature and heating value.

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SCOPE

The gas produced from moving-bed coal gasifiers is to be used in downstream processes. Thus, an understanding of the transient behavior of a moving-bed gasifier is important, since any performance change in the gasifier will directly affect the performance of downstream units and hence of the overall system. This understanding is particularly important for the projected use in a combined cycle power generation process, in which individual units are closely coupled.

We have shown through steady state analyses of moving-bed gasifiers published previously that in order to

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maintain good gasification performance, it is necessary to control feed rates of coal, steam, and oxygen (or air) near certain optimum ratios. The maximum thermal efficiency in both dry ash and slagging reactors occurs at a carbon to oxygen feed ratio at which performance is very sensitive to feed ratio changes, suggesting possible controllability problems. It is therefore important to know how fast the system responds to a change in operating conditions.

This paper presents an analysis of the transient behavior of moving-bed gasifiers following step changes in feed conditions. The analysis is based on our steady state model of moving-bed gasifiers, and it utilizes a pseudo steady state approximation that is based on the very small residence time of the gas phase relative to the solid. The motion of the temperature profile in the bed is computed from the relative thermal wave velocity.

CONCLUSIONS AND SIGNIFICANCE

The transient response in the dry ash Lurgi reactor has been computed for both oxygen and air operation with low activity Illinois and high activity Wyoming coals. The time to approach a new steady state for all cases for a 10% step reduction in relative coal to oxygen feed rate is of the order of 10 hr. The product gas temperature and thermal throughput show a rapid initial change because of the change in the relative amount of coal to be dried and devolatilized; this is followed by a slow change characteristic of the slow thermal wave response in the combustion and gasification section of the reactor. The product gas composition is relatively insensitive to small feed changes.

A reduction in the relative coal feed rate to a slagging gasifier can result in a sharp decrease in the coal bed height. The new steady state, with a very thin fuel bed, would be reached in approximately 3 hr following a 10% reduction in relative coal feed rate in the Solihull slagging reactor with Donisthorpe coal. The temperature and thermal throughput transients are characterized by a rapid initial change, followed by a period of nearly constant values, with another rapid change as the new steady state is approached. Product gas compositions do not change significantly.

The gas produced from moving-bed coal gasifiers is to be used in downstream processes. Thus, an understanding of the transient behavior of a moving-bed gasifier is important, since any performance change in the gasifier will directly affect the performance of downstream units and hence of the overall system. This understanding is particularly important for the projected use in a combined cycle power generation process (Krieb, 1973), in which individual units are closely coupled.

There are two distinct problems regarding the transient behavior of a moving-bed gasifier. One is the response of the gasifier to small changes in operating conditions; such changes could occur during normal operation because of unexpected disturbances or planned changes. This is the problem on which we will focus in this paper, because an understanding of the response of the gasifier to such changes can be used for control purposes and to lessen the impact on the downstream units. The other transient problem is the response to larger scale changes during start-up, shutdown, or banking. This latter problem is beyond the scope of our analysis here.

We have shown through steady state analyses of moving-bed gasifiers (Yoon et al., 1978, 1979*a*) that in order to maintain good gasification performance it is necessary to control feed rates of coal, steam, and oxygen (or air) near certain optimum ratios. In Lurgi gasifier operation, however the maximum thermal efficiency occurs at a fixed carbon to oxygen feed ratio at which the position of the maximum temperature is very sensitive to changes in the feed ratio. In slagging gasifier operation in which the coal feed rate can be independently changed, a small reduction in coal feed rate below the optimum can require a drastic reduction of coal bed height in order to maintain steady state operation. These factors suggest possible controllability problems near the optimum operating conditions. It is therefore important to know how fast the system responds to a change in operating conditions; the most useful measure of transient response is the time required to reach a new steady state following step changes. This time, and the changes in reactor variables during a transient, can be estimated for small changes by use of the pseudo steady state approximation.

If there is an instantaneous reaction taking place in a plug flow reactor, then transients at the reaction surface are instantaneous, and a steady state analysis is enough to determine transient behavior. If there is a narrow intensive reaction zone in a plug flow reactor, one may similarly apply a pseudo steady state approximation without significant error. This has been done to avoid a difficult computation step arising in the modeling of in-situ coal gasification by Gunn and Whitman (1976*a*, *b*). In a moving-bed gasifier, solid and gas flows can be assumed to be in plug flow, and there is a narrow intensive reaction zone in which most of the fixed carbon is consumed by combustion and gasification reactions. Thus, the pseudo steady state approximation can be used for the transient analysis of this system. The moving bed, however, differs from an in-situ coal bed in that the reactions are limited by available reactor space in the gasifier, while the coal bed is sufficiently long to be assumed to be infinite in in-situ gasification.

PRELIMINARY CONSIDERATIONS

Consider an infinitely long adiabatic cylindrical coal bed with steam and oxygen (or air) being fed from the left at constant feed rates, as shown in Figure 1. Since the coal is stationary, the location of the maximum temperature around which intensive reactions are taking place moves to the right. The coal reaction speed, which is proportional to the linear velocity of the location of the maximum temperature, represents the burning rate capacity of the gaseous reactants fed at constant rates. Thus, insofar as the reaction temperature profile is fully developed in the coal bed, the travel velocity will be

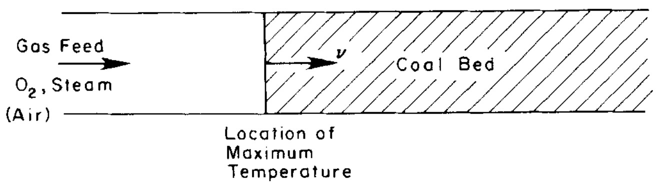

Fig. 1. Fixed-bed coal gasifier with infinitely long coal bed.

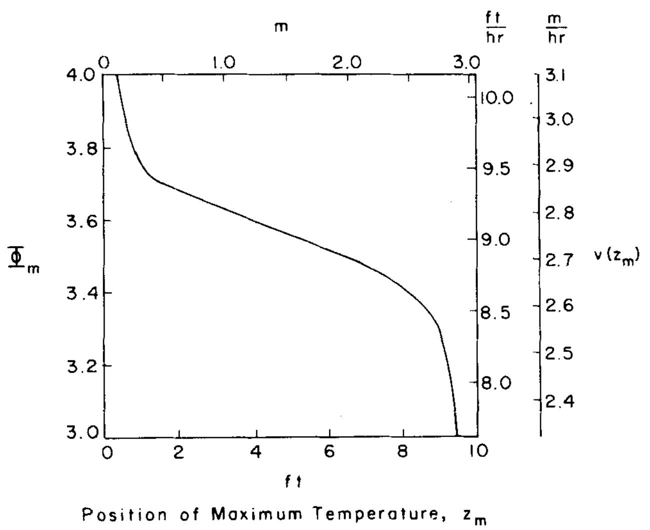

Fig. 2. Burning rate capacity of gas feed in moles of carbon per mole of feed oxygen Φ_m and temperature wave velocity relative to coal particles $v(z_m)$ as function of position of maximum temperature for Wyoming coal in an oxygen blown Lurgi gasifier.

constant. This constant velocity ν is the temperature wave velocity through the fixed infinitely long coal bed, and it depends on such bed characteristics as coal reactivity, density, composition, and porosity, as well as such operating conditions as pressure and feed rates and temperature of gaseous reactants. It is clear that this system is always in a transient state. It is not necessary to include the time variable in the system equations, however, because they can be transformed to one-dimensional ordinary differential equations in which the space origin moves at the same speed as the speed of the temperature wave by calculation of the new independent variable $\eta = Z - \nu t$. This transformation is known as the pseudo steady state approximation.

If the coal bed moves to the left with a linear velocity equal to ν, the location of the maximum temperature will remain at a fixed position, and the reactor will remain at steady state. If the coal has a linear velocity v to the left, different from ν, then the location of the maximum temperature will move steadily to the right with speed $\nu - v$. It is interesting that for an infinitely long reactor as shown in Figure 1, there is only one coal feed rate countercurrent to the gas flow which supports a steady state at constant feed rates of the gaseous reactants.

Steady state operation is possible for moving-bed gasifiers over a range of coal feed rates for constant feed rates of gaseous reactants, as shown in Yoon et al. (1978, 1979*a*). This is because the burning rate capacity of gaseous reactants in the gasifiers depends on the available space for gasification after completion of combustion. The position of the maximum temperature in the Lurgi gasifier determines the available space for gasification during steady state operation. If the position is high, little space is available for gasification, and the burning rate capacity of the gaseous reactants is small at steady state. In the slagging gasifier, the height of the bed indicates the available space for gasification, since the position of the maximum temperature must always stay near the tuyere level irrespective of coal feed rates. If the bed height is low, the burning rate capacity of the gaseous reactants is small at steady state. Thus, in moving-bed gasifiers, the burning rate capacity of gaseous reactants fed at constant rates can be varied by adjusting the available space for gasification.

TRANSIENT BEHAVIOR OF THE LURGI GASIFIER

Transients in Lurgi gasifier operation can result from any upset in operating conditions which changes the steady state position of the maximum temperature in the bed. During the transient period, the maximum temperature moves away from the old position to the new one. If changes in operating conditions are such that there is no change in the steady state position of the maximum temperature, then the gas burning rate capacity remains equal to the coal feed rate, and the pseudo steady state approximation implies that the system reaches the new steady state instantaneously. The true transient time for this latter case is of the order of the residence time of the gas phase, which is about 10 s, as long as there is no change in coal type.

Possible changes in operating conditions include changes in coal type and feed rate, gas feed rate and temperature, operating pressure, and ash discharge rate by the grate. We first consider in detail the transient behavior resulting from a step change in coal feed rate. The transient behavior resulting from changes in other operating conditions is analyzed in the same way and is discussed subsequently.

We employ the SP model, which assumes shell progressive burning of coal particles, without shrinkage, because the transient analysis is better defined for the SP model than for the AS (ash segregation) model. The two models give essentially the same results for steady state performance (Yoon et al., 1978, 1979*a*). We consider only the transient behavior of the adiabatic core of the Lurgi gasifier, because the boundary layer is insensitive to the operating conditions and has little effect on the overall performance of the gasifier.

The steady state analysis of the Lurgi gasifier assumed that the motion of the grate could be controlled to discharge an amount of ash and unreacted carbon depending on the desired feed rate of coal. We assume here that the coal feed rate is controllable during the transient period as well.

Step Change in Coal Feed Rate

A step change in coal feed rate changes the linear downward velocity of coal in the gasifier. Since the other operating conditions are unchanged, the maximum temperature is no longer at a position such that the gas burning rate capacity is equal to the coal feed rate. This inequality causes movement of the maximum temperature to the position at which the gas burning rate capacity again equals the coal feed rate.

If we assume the pseudo steady state approximation for the transient analysis, the steady state model described in Yoon et al. (1978) can be used to predict the gas burning rate capacity as a function of the position of the maximum temperature for given gas feed conditions. Figure 2 shows the model prediction for oxygen blown gasification of Wyoming coal. The curve in the figure is computed for feed conditions given in Yoon et al. (1978) and is the same as the solid line A in Figure 11 of that paper for the steady state analysis, but we interpret it here as the burning rate capacity of the gaseous feed as a function of the position of the maximum temperature during transient operation. The gas burning rate capacity for a

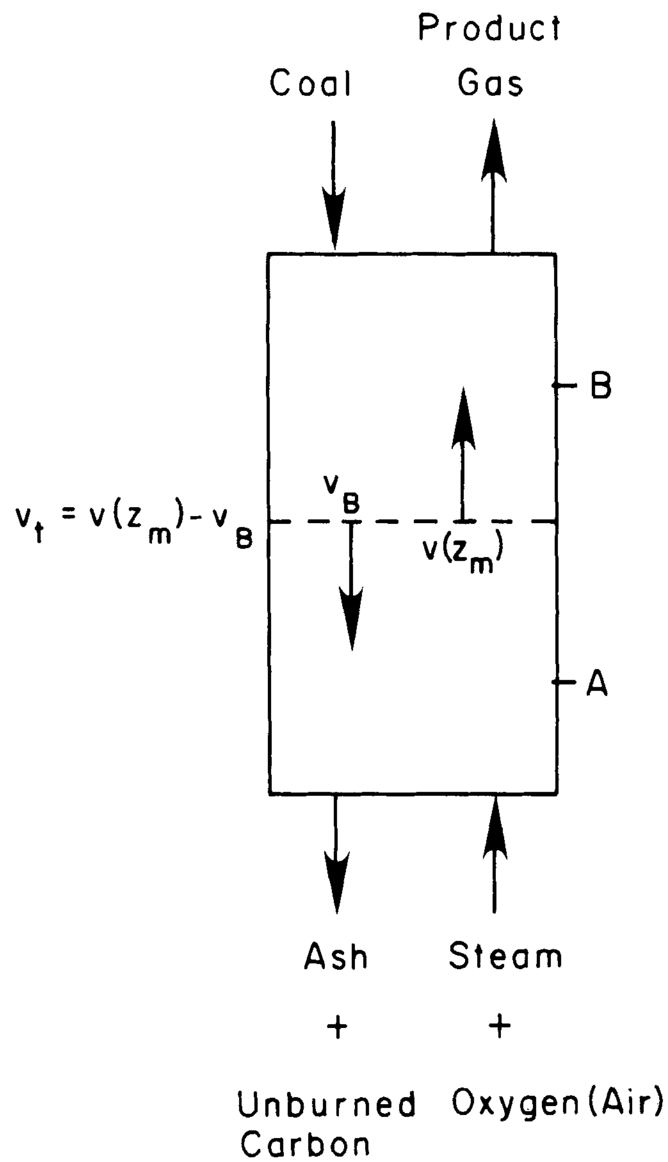

Fig. 3. Schematic of transient in Lurgi gasifier operation.

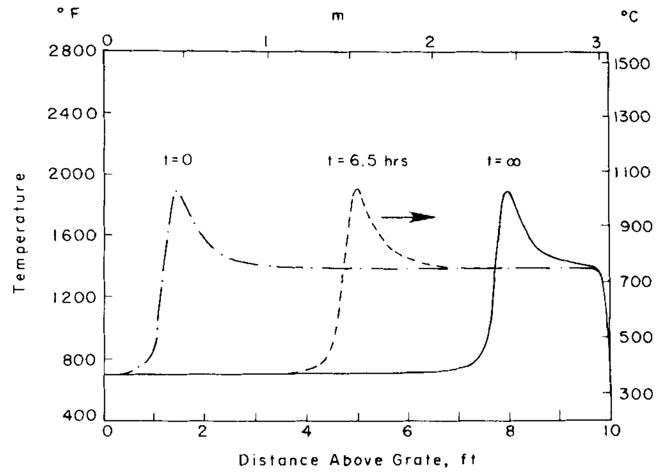

Fig. 4. Temperature wave profile following an 8% step reduction in coal feed rate from optimum for Wyoming coal with oxygen blown Lurgi gasifier.

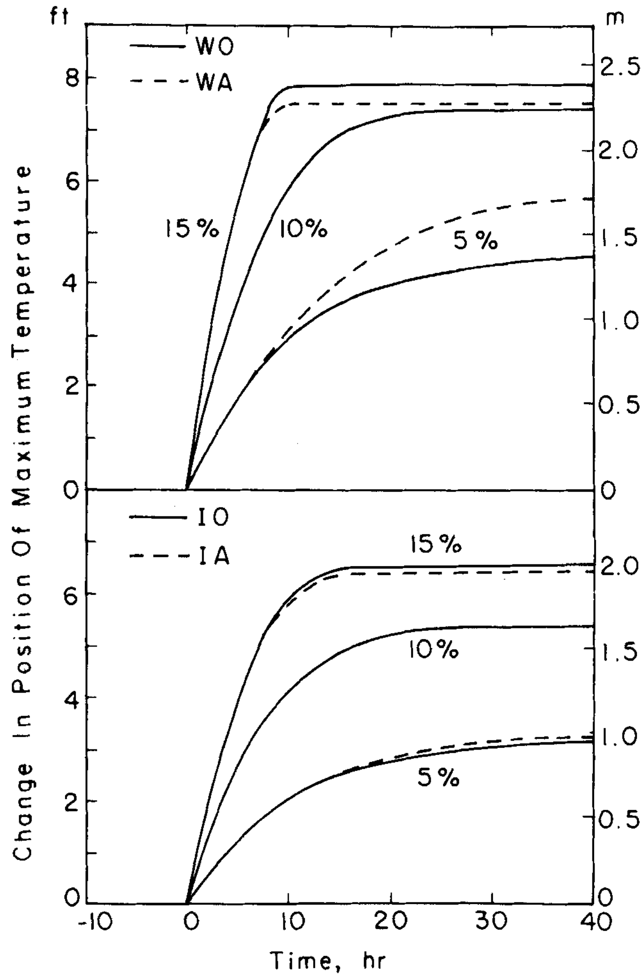

Fig. 5. Change in position of maximum temperature following step reduction in coal feed rate from optimum with Lurgi gasifier.

particular coal can be converted to the temperature wave velocity relative to coal particles $v(z_m)$ using the following equation:

$$v(z_m) = \frac{\Phi_m F^\circ_{O_2} M_c}{\epsilon \rho_p} \frac{f_a + f_c}{f_c} \quad (1)$$

Here, Φ_m is the burning rate capacity of gas feed in moles of carbon processed per mole of feed oxygen; $F^\circ_{O_2}$ is the molar feed flux of oxygen; M_c is the atomic weight of carbon; z_m is the position of the maximum temperature; f_a and f_c are weight fractions of ash and carbon in the coal by the proximate analysis, respectively; ρ_p is the density of coal particles after moisture and volatile matter have been driven off at the top of the gasification zone in the gasifier; and ϵ is the void fraction of the coal bed.

We further assume here that there is no volume change during drying and devolatilization of coal in the gasifier, so that the parameters can be estimated from data on the original coal. The density of fresh coal was taken as 1.3 g/cm^3, and the void fraction of the bed as 0.52 for both the Wyoming and Illinois coals; these were the figures used for the steady state simulations in Yoon et al. (1978, 1979*a*). The right-hand vertical scale in Figure 2 shows the relative temperature wave velocity from Equation (1) for the Wyoming coal with oxygen. It is possible to construct an equivalent figure from the steady state model for any coal, with oxygen or air as oxidant.

Consider steady state operation of the Lurgi gasifier with the maximum temperature at position A in Figure 3. At this steady state, the linear downward velocity of the coal particle is v_A, which is also the relative upward wave velocity. At $t = 0$, the linear velocity of the coal particles drops to v_B because of a step reduction in the coal feed rate. The position of the maximum temperature will then start to travel from *A* to *B;* the latter is the

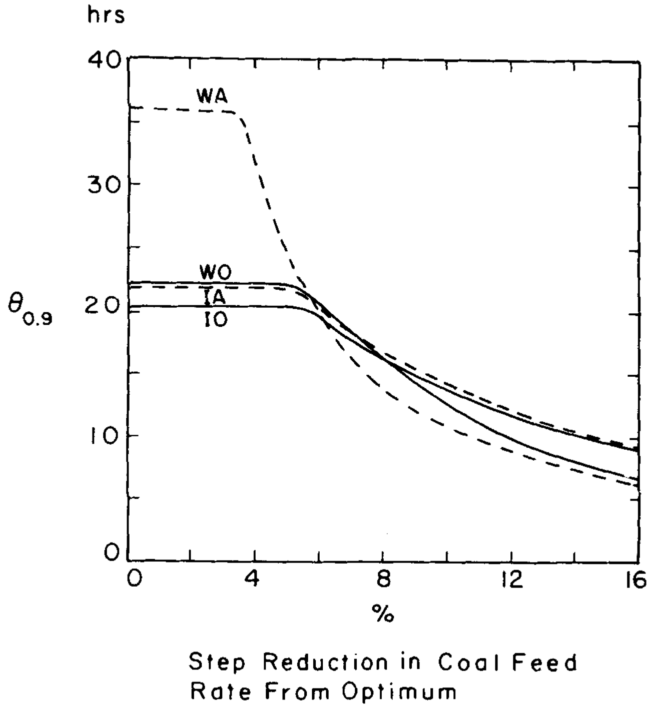

Fig. 6. Time required for position of maximum temperature to approach 90% of new steady state $\theta_{0.9}$ as a function of degree of reduction in coal feed rate from optimum with Lurgi gasifier.

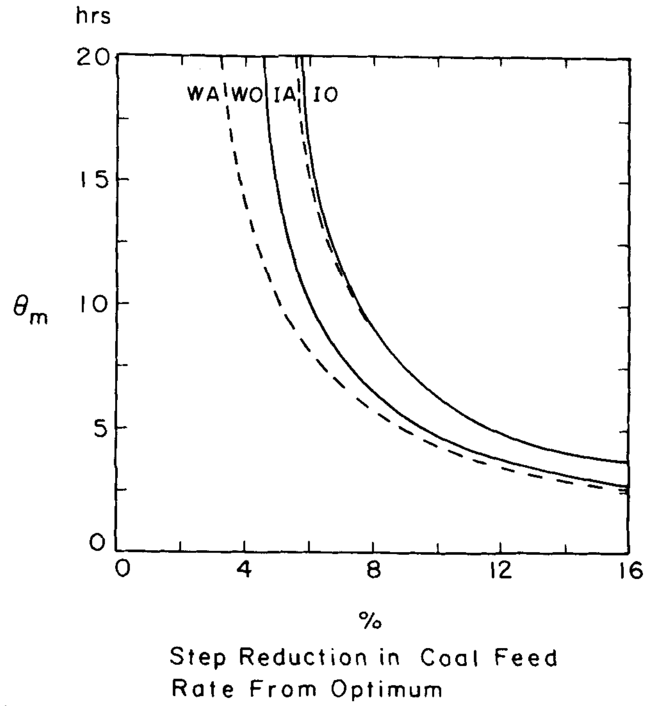

Fig. 7. Time required for position of maximum temperature to arrive at the middle of coal bed θ_m as a function of degree of reduction in coal feed rate from optimum with Lurgi gasifier.

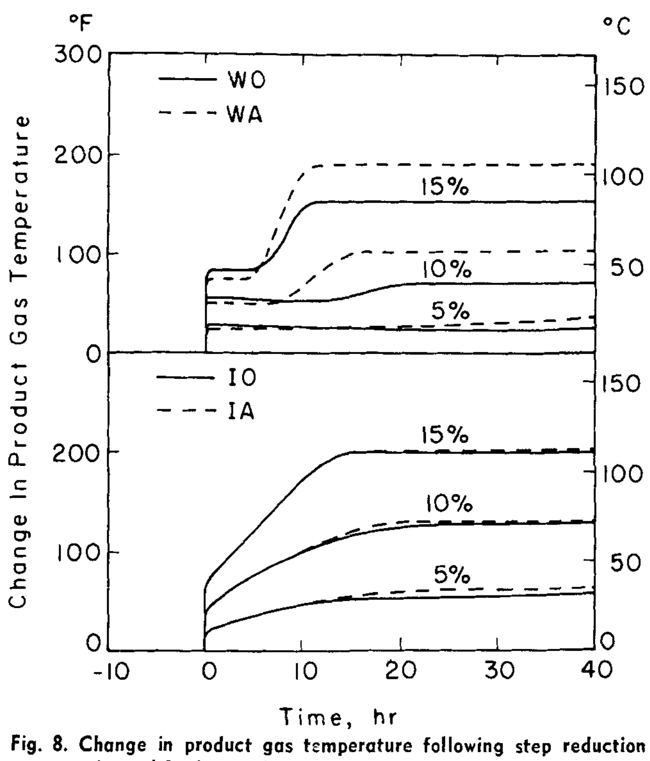

Fig. 8. Change in product gas temperature following step reduction in coal feed rates from optimum with Lurgi gasifier.

steady state position of the maximum temperature at which the gas burning rate capacity equals the new coal feed rate. The relative temperature wave velocity decreases as the position moves from A to B because the burning rate capacity of the gaseous reactants decreases with the loss of available space for gasification. The velocity of the position of the maximum temperature in the gasifier v_t is the difference between the relative temperature wave velocity and the coal velocity:

$$\frac{dz_m}{dt} = v_t = v(z_m) - v_B \tag{2}$$

Rearranging and integration Equation (2), we get

$$t(Z) = \int_A^Z \frac{1}{v(z_m) - v_B} \, dz_m \tag{3}$$

Equation (3) predicts the time required for the position of the maximum temperature to reach the height Z above the grate. Because $v(B) = v_B$, Equation (3) predicts an asymptotic approach to the steady state.

The composition and temperature of the gas stream at the top of the gasification zone during transient operation can be evaluated from the steady state model with the maximum temperature at the same position in the bed. Figure 2 shows the fixed carbon to oxygen molar ratio necessary for defining the corresponding steady state at each position of the maximum temperature. The gas leaving the top of the gasification zone then passes through the drying and devolatilization zones; the processes in these zones are taken as instantaneous. A step change in coal feed rate will thus cause an instantaneous change in the product gas composition, temperature, and thermal throughput because of the instantaneous change in the relative amount of coal and gas in the upper zones of the reactor.

The transient response to a step increase in coal feed rate is analyzed in the same way as described above, and Equation (3) is also applicable to this case.

The transient response of the Lurgi gasifier to a step reduction in coal feed rate from the optimum conditions is the most interesting case, because the reduction causes the position of the maximum temperature to rise in the bed, and the performance of the gasifier becomes poorer.

The functional dependence of the relative temperature wave velocity on the position of the maximum temperature, shown in Figure 2 for the Wyoming coal with oxygen, was interpolated with a piecewise quadratic Lagrange polynomial (Prenter, 1975). For the other operating cases, the results in Yoon et al. (1979*a*) were similarly interpolated. A Runge-Kutta fifth-order method for the integration of Equation (3) was used, and we have used the typical devolatilization distribution for the calculation of the product gas compositions. In the following figures, I and W denote the Illinois and Wyoming coals, respectively, and O and A denote oxygen and air as the oxidant.

Figure 4 shows how the temperature wave propagates from the initial to the final profile for the Wyoming coal with oxygen, following a coal feed rate reduction of 8% from the optimum. The shape of the profile around the maximum does not change during the propagation period, and the intensive reaction zone follows the movement of the temperature peak. The time for the propagation is of the order of 10 hr, so that during the gas residence time (order of 10 s) the movement of the position of the maximum temperature is negligible, and thus the pseudo steady state approximation is valid.

Figure 5 shows the change in the position of the maximum temperature as a function of time, following a step reduction in coal feed rate, for oxygen and air blown gasification of Illinois and Wyoming coals. The initial height is slightly less than 2 ft above the grate in all cases. For the same percentage reduction, the new positions of the combustion zone are higher for the Wyoming coal than for the Illinois coal. This is because the slopes of the lines describing the dependence of the steady state position of the maximum temperature on the fixed carbon to oxygen molar feed ratio are steeper for the Wyoming coal. Most of the change takes place during the first 10 hr of the transient. Figure 6 shows the time required for the position of the maximum temperature to approach to within 90% of the new steady state position. For a coal feed rate reduction of less than 6%, the Wyoming coal, particularly the air blown case, takes longer than the Illinois coal. For a coal feed rate reduction of more than 8%, the transient is longer for the Illinois coal.

For successful operation of the Lurgi gasifier, it is necessary to control the position of the maximum temperature below a certain level, because a high position of the combustion zone reduces the thermal efficiency and throughput of the gasification operation (Yoon et al., 1978, 1979*a*). If we wish to control the position below the middle of the bed, Figure 7 shows how long a control time is available after a step reduction in coal feed rate. Here, we always have more time available for the Illinois coal with either oxygen or air, irrespective of the magnitude of the change. For each coal, more time is available with oxygen than air. This time interval depends strongly on the steepness of the curve representing the functional dependence of the steady state position of the maximum temperature on the fixed carbon to oxygen feed ratio.

Figure 8 shows the change in product gas temperature during the transient period. The instantaneous temperature rise results from the fast response of the drying and devolatilization. For the Illinois coal, with either oxygen or air, the temperature rises continuously until it reaches the new steady state value. For the Wyoming coal, there is a time lag following the instantaneous rise. This difference in behavior follows from the difference in reactivity of the carbon-hydrogen reaction in the gasification zone. The Wyoming coal has a relatively high reactivity for this reaction, while the Illinois coal has a negligible reactivity.

Figure 9 shows the methane content in the product gas on a moisture free basis during the transient period. There is an instantaneous drop in methane content; this occurs because the reduced coal feed rate results in a lower production of methane during devolatilization. For the Illinois coal, the methane content in the product gas then increases to about the original level. This increase occurs

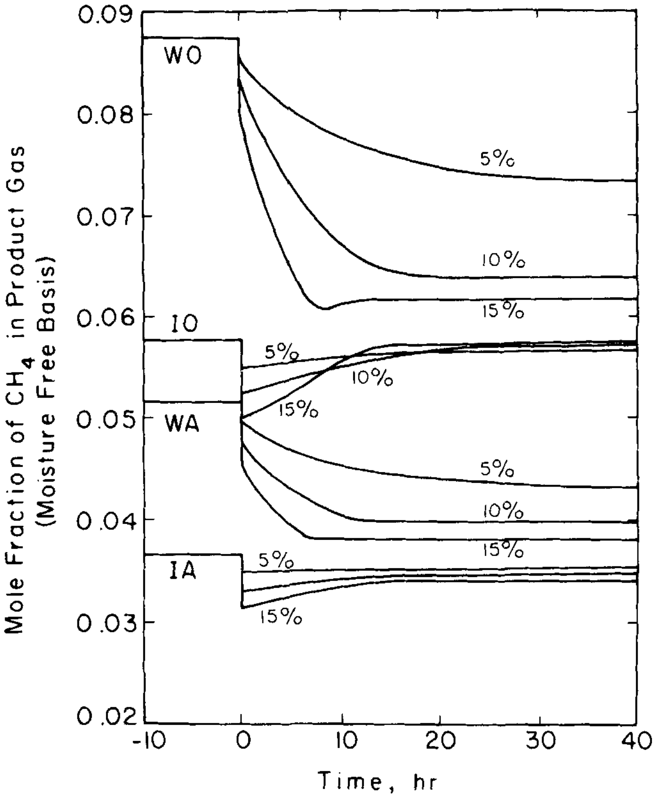

Fig. 9. Methane content in product gas on moisture free basis following step reduction in coal feed rate from optimum with Lurgi gasifier.

because most of the methane comes from devolatilization, and the relative decrease in the total amount of product gas is nearly the same as the decrease in the coal rate. For the Wyoming coal, however, the methane content decreases further to a lower ultimate steady state value because of the reduced extent of the carbon-hydrogen reaction in the gasification zone resulting from the decreased space for gasification. This loss is more than enough to mask the effect of the decreased amount of product gas. Figures 8 and 9 show that product gas temperature and

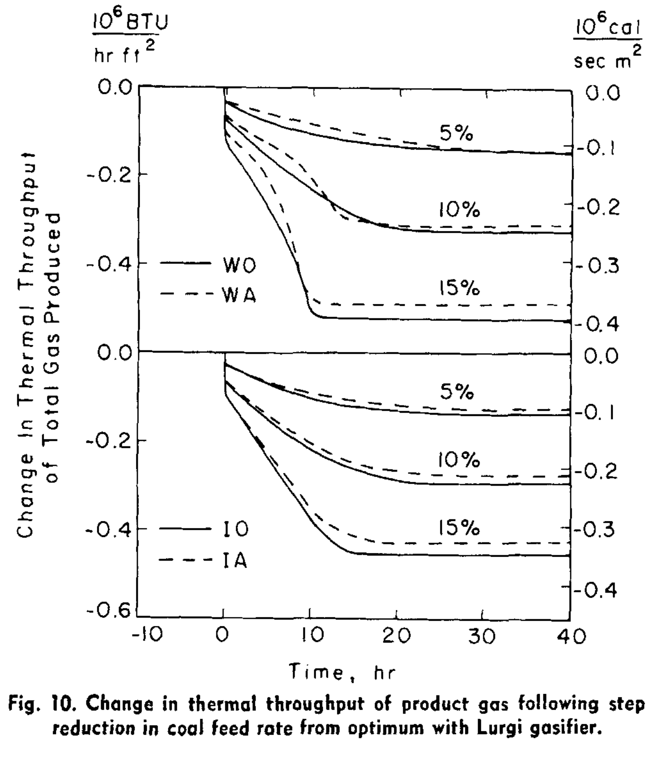

Fig. 10. Change in thermal throughput of product gas following step reduction in coal feed rate from optimum with Lurgi gasifier.

methane content on a moisture free basis are very useful control indicators for the Illinois and Wyoming coals, respectively.

Figure 10 shows the change in the thermal throughput of the product gas during the transient period. There is an instantaneous initial loss because of the reduction of the amount of devolatilization product in the product gas, followed by a subsequent continuous loss because of the loss in gasification efficiency.

Figure 11 shows the response of product gas composition following the 10% reduction in coal feed rate for the Wyoming coal with oxygen. Except for slow changes in hydrogen and methane content in the product gas, the product gas compositions do not change appreciably, and the hydrogen/carbon monoxide ratio remains nearly constant throughout the transient period. Thus, the quality of the product gas is not lessened, even though the loss of thermal throughput may be appreciable during the transient. If the transient is caused by changing the steam to oxygen feed ratio, however, the product gas composition will change considerably.

A step increase in coal feed rate from the optimum causes the position of the maximum temperature to travel downward. The travel distance is rather short, however, as shown in Figure 2, and hence the transient response is very fast compared to the response to the step reduction discussed earlier. Since the position of the maximum temperature does not change appreciably, and thus the available space for gasification remains almost the same during the transient period, gasification performance will not change appreciably in terms of the product gas throughput, temperature, and composition, except for the fast initial changes due to the rapid drying and devolatilization processes. The amount of unreacted fixed carbon will increase in the discharged ash, with a resulting loss in thermal efficiency. The response time for this increase is the travel time of solid particles (ash) from the old position of the maximum temperature to the grate.

Application of Equation (3) is quite general for any step changes in coal feed rate from any steady state, not just the optimum. Thus, this method can be used to predict the time required to reach the optimum steady state from an initially high position of the maximum temperature by changing the coal feed rate.

Change in Coal Type

Consider a case in which there is a change in coal, and a different coal is supplied from the lock hopper at a coal feed rate corresponding to a linear downward velocity of v_B. If the burning rate capacity of the gas feed matches the new coal at a steady state position of the maximum temperature B that is higher than the position A with the previous coal, the position of the maximum will travel upward from A to B as shown in Figure 3. To within the accuracy of the pseudo steady state approximation, however, the movement will not occur until the front of the new coal reaches position A, since the solid is in plug flow and the change of coal type is not noted at the position A until the front arrives. As long as the front of the new coal remains in the interior of the reactor, it is difficult to predict the relative temperature wave velocity because the gas feed reacts with two different types of coal successively in the reactor. It is possible, however, to predict lower and upper bounds for the trajectory of the position of the maximum temperature.

If we assume that all of the coal in the gasifier changes to the new coal as soon as the front of the new coal enters the reactor, then this is the same transient problem as discussed in the previous section, and we can get the lower bound

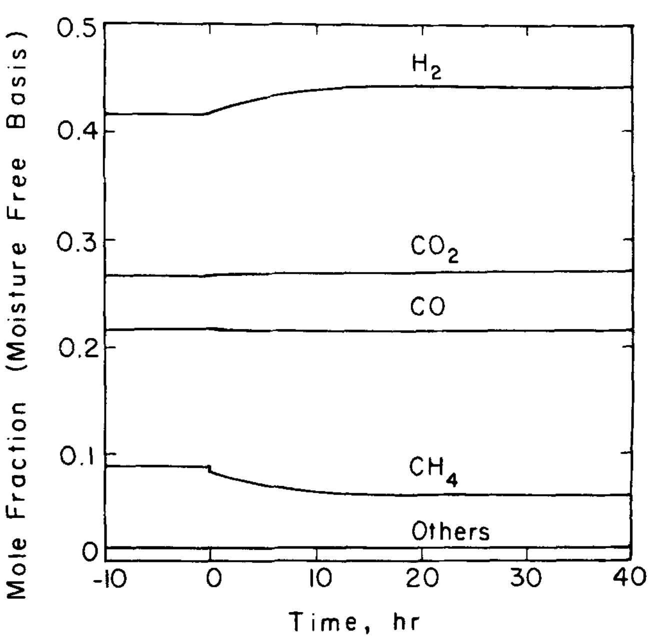

Fig. 11. Product gas composition following 10% reduction in coal feed rate from optimum for Wyoming coal with oxygen blown Lurgi gasifier.

$$t_l(Z) = \int_A^Z \frac{1}{v(z_m) - v_B}\, dz_m \qquad (4)$$

where $v(z_m)$ is obtained from the relation for the new coal between the relative temperature wave velocity and the position of the maximum temperature.

If we assume that the new coal behaves like the previous coal until the front reaches the bottom of the reactor, then the transient response time lags that given by Equation (4) by one residence time. Thus, we have

$$t_u(Z) = t_r + \int_A^Z \frac{1}{v(z_m) - v_B}\, dz_m \qquad (5)$$

Since during the first residence time there are two different coals in the reactor, the actual transient time is bracketed by the two times predicted by Equations (4) and (5):

$$t_l(Z) \leq t(Z) \leq t_u(Z) \qquad (6)$$

Usually, t_r will be much smaller than the time scale needed to obtain the new steady state (of order of 10 hr), and thus the bounds by Equation (6) are quite tight. The same assumptions may be used to obtain bounds on variables such as product gas temperature, compositions, and thermal throughput.

Step Change in Gas Feed Conditions

The analysis of the transient behavior following a change in gas feed conditions is somewhat different in principle from the analysis described in the previous section. Since the residence time of coal is much longer than the residence time of the gas phase, the coal downward velocity directly governs the transient time constant for coal feed changes, and the relative temperature wave velocity is defined in terms of fixed gas feed conditions. We therefore need only one relation describing the relative temperature wave velocity as a function of the position of the maximum temperature for the transient analyses of a range of step changes in coal feed rate. Every change in gas feed conditions, however, changes the dependence of the relative temperature wave velocity on the position of the maximum temperature. Thus, in principle we have to generate the corresponding relation between the wave velocity and the position for every set of gas feed conditions.

We consider here the transient behavior of the Lurgi gasifier following a step increase in gas feed rate without any change in steam to oxygen feed ratio in the gas. Other cases related to the gas feed conditions, such as step change in oxygen (air) or steam feed rate or a small step change in blast temperature, may be analyzed in the same way.

Consider steady state operation of the Lurgi gasifier, with the position of the maximum temperature at A and the linear downward velocity of coal v_B as shown in Figure 3. At $t = 0$, a step increase in gas feed rate occurs, and the position of the maximum temperature starts to travel from A to B; B is the new steady state position of the maximum temperature at which the relative temperature wave velocity again equals the coal downward velocity. It is necessary to have the relation between the wave velocity and the position for the new gas feed conditions. As soon as the gas feed rate increases, the relative temperature wave velocity jumps to the new velocity $v(A)$. As the position of the maximum rises, the relative temperature wave velocity decreases gradually from $v(A)$ to v_B at position B and the new steady state is obtained. Equations (2) and (3) are also applicable to this transient analysis, because it is basically the same phenomenon as the transient behavior following a step reduction in coal feed rate.

If we assume that the relation between fixed carbon to oxygen feed ratio and the steady state position of the maximum temperature remains the same for each operating case with a reduced gas feed rate, then the optimum fixed carbon to oxygen feed ratio also remains unchanged. The assumption will be reasonable for small changes in gas feed rate; Figure 11 of Yoon et al. (1978) shows that the change resulting from a 100% change in throughput is not large. Thus, consider steady state operation of the Wyoming coal with oxygen at 5% lower feed rates of coal, oxygen, and steam than the optimum feed rates. At $t = 0$, the gas feed rate is increased 5.26%. The response to this step change is the same as the response to the 5% step reduction in coal feed rate for the Wyoming coal with oxygen. The responses are the same because with the step increase in gas feed, the gas feed rate is the same as the rate for the case used to generate Figure 2. Thus, the same relation between the relative temperature wave velocity and the position of the maximum temperature applies to this transient. The same analogy can be applied to all the other cases for the Illinois and the Wyoming coals. If the gas feed rates increase 11.11 and 17.65% from the steady state coal and gas feed rates (that is, they are 10 and 15% less than the optimum rates), the transients follow the 10 and 15% step reductions in coal feed rate, respectively. The figures are all applicable except the curves of thermal throughput of product gas in Figure 10. Here, the thermal throughput will experience an instantaneous step increase, rather than the instantaneous step decrease shown in the figure, because of the step increase in gas feed rate.

Discussion

It may not be possible in actual plant operation to reproduce the step changes analyzed here because we have assumed that coal feed rates can be precisely controlled. The analysis does provide the time scales and an analytical framework for transients resulting from changes in operating conditions.

Other types of transients are possible. The intensive reaction zone might rise if ash accumulates in the reactor because of failure of the ash removal mechanism. Such a rise will suppress the feeding of coal and reduce the coal feed rate. If the coal feed rate is reduced in the coal feed device, the bed height will drop but the position of the maximum temperature will not rise appreciably. The amount of unreacted carbon will rise continuously while the bed height is dropping.

The blast temperature directly affects the combustion reaction in the gasifier by changing the lightup distance for combustion. Transient behavior due to a large change in this temperature cannot be analyzed with the pseudo steady state approximation as discussed here. In this analysis, any change in operating conditions is neglected, because for most cases the change is negligible compared to the height of the reactor.

TRANSIENT BEHAVIOR OF THE SLAGGING GASIFIER

If changes in operating conditions in slagging gasifier operation do not change the steady state bed height, then, within the context of the pseudo steady approximation, the system will reach a new steady state instantaneously. A transient in slagging gasifier operation can result from any upset in operating conditions that will change the steady state height of the coal bed.

Since the slag formed in the gasifier falls from the coal bed and is discharged immediately through the tap hole, the discharge rate of ash slag is simply the production rate of the slag in the gasifier and is directly related to the coal conversion rate. Thus, during transient as well as steady state operating periods, the slag discharge rate is self-controlled by the ash production rate in the gasifier; unlike the Lurgi gasifier, it is not necessary to assume controllability of the ash discharge rate.

Because overall slagging gasifier operation does not depend on coal reactivity (Yoon et al., 1979*b*), the transient behavior due to a change in coal type is not considered here. We consider the transient behavior due to a step change in coal feed rate in detail.

Step Change in Coal Feed Rate

The steady state model can be used to predict the gas burning rate capacity in the slagging gasifier. Line A in Figure 17 of Yoon et al. (1978) is the relation for Donisthorpe coal in the Solihull gasifier. The gas burning rate capacity in moles of carbon to mole of feed oxygen Φ_h can be converted to the temperature wave velocity relative to coal particles $v(z_h)$ by

$$v(z_h) = \frac{\Phi_h F^o{}_{O_2} M_c}{\epsilon \rho_p} \frac{f_a + f_c}{f_c} \qquad (7)$$

The calculations assume no volume change during drying and devolatilization, a density of fresh coal of 1.3 g/cm^3, and a coal bed void fraction of 0.52.

If the coal feed rate can be independently regulated, then the change of coal bed height occurs when the fixed carbon to oxygen feed ratio is lower than the optimum ratio of 3.3. If the coal feed rate is reduced below the optimum, the bed height will drop during the transient to the new steady state height, while the maximum temperature remains at the original position. The falling velocity of the coal bed height v_f is the difference between the temperature wave velocity and the linear velocity of coal during transient operation:

$$\frac{dz_h}{dt} = v_f = -[v(z_h) - v_B] \qquad (8)$$

Thus, the falling time of the bed height to height Z can be found by

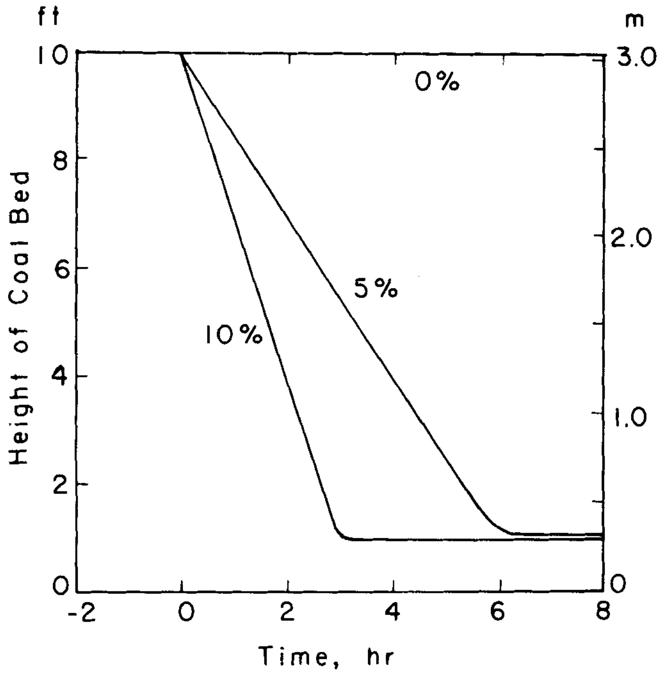

Fig. 12. Coal bed height following step reduction in coal feed rate from optimum for Donisthorpe coal in Solihull slagging gasifier.

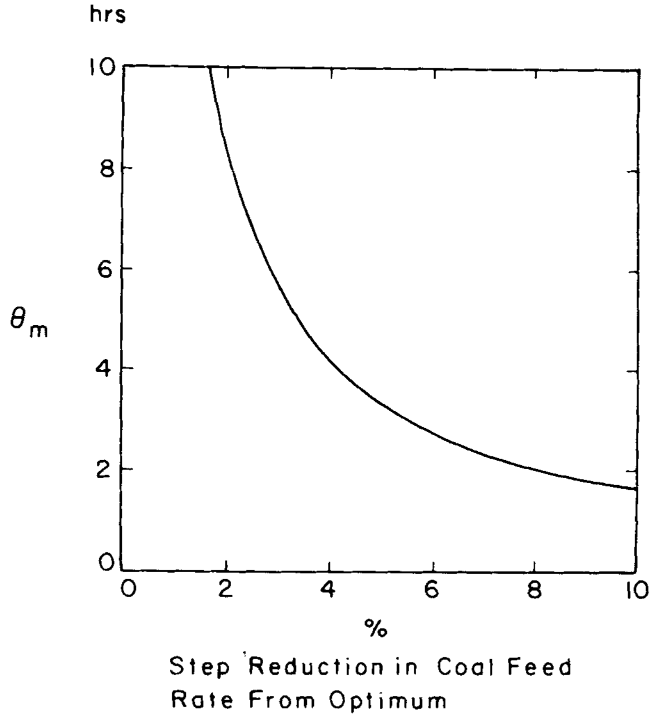

Fig. 13. Time required for coal bed to reduce to half of original height θ_m following step reduction in coal feed rate from optimum for Donisthorpe coal in Solihull slagging gasifier.

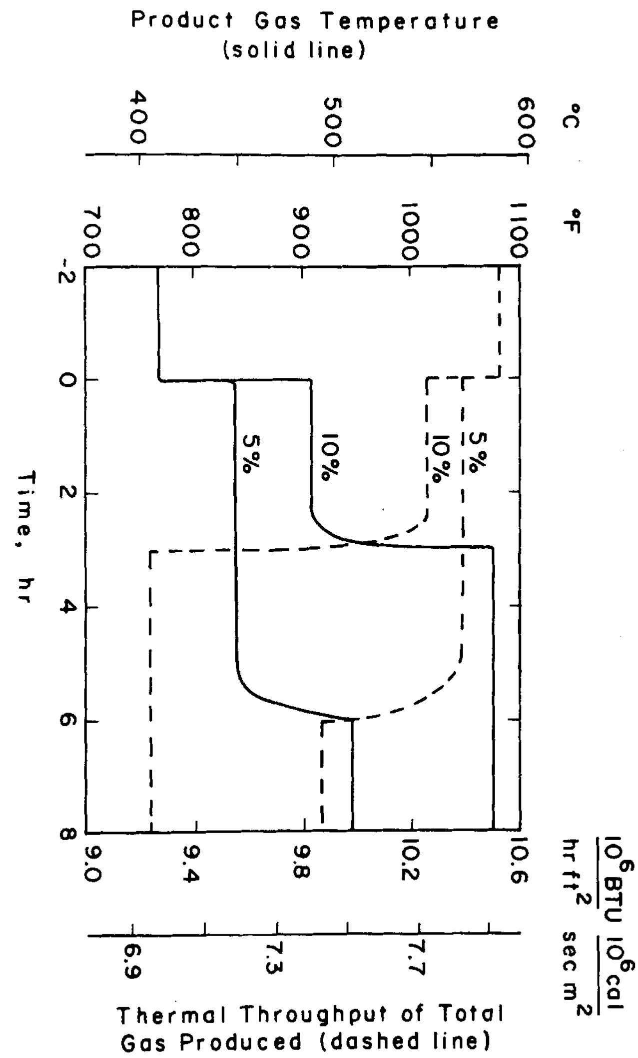

Fig. 14. Product temperature and thermal throughput following step reduction in coal feed rate from optimum for Donisthorpe coal in Solihull slagging gasifier.

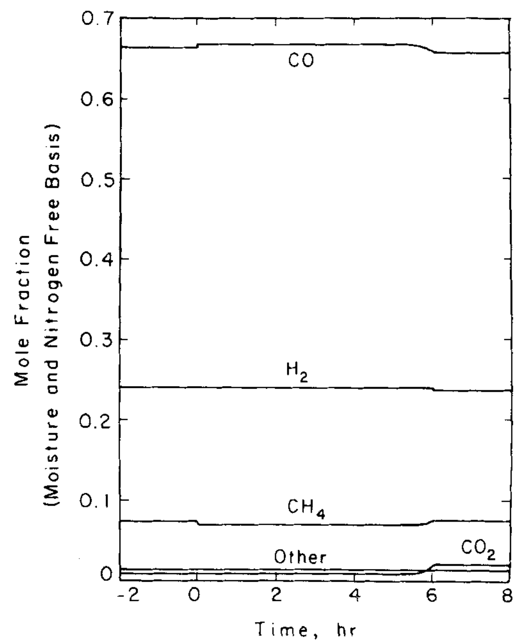

Fig. 15. Product gas composition following a 5% reduction in coal feed rate from optimum for Donisthorpe coal in Solihull slagging gasifier.

$$t(Z) = \int_H^Z \frac{1}{v_B - v(z_h)}\, dz_h \tag{9}$$

H is the height of the coal bed at normal operation, which is 10 ft for the Solihull gasifier. The product gas composition, temperature, and thermal throughput can be found at each time as discussed earlier for the Lurgi gasifier.

Figure 12 shows the linear decrease of the height of the coal bed with time following a step reduction in coal feed rate. The slope of the curve is proportional to the degree of reduction in the coal feed rate from the optimum. If we wish to control the bed height above the hearth to be at least half of the original bed height, then Figure 13 shows the control time available following a step reduction. The time is almost inversely proportional to the degree of reduction, and the relation can be approximated as

$$\theta_m = \frac{16.5 \text{ hr}}{\% \text{ reduction in coal rate}}$$

Figure 14 shows the responses of product gas temperature and thermal throughput during the transient period. The instantaneous increase of temperature and decrease of throughput result from the rapid response of the drying and devolatilization to the feed rate change. During the subsequent steady period, there is no change in the burning rate capacity of gaseous reactants, because the reduced bed height is still adequate for completion of the gasification reaction. Thus, there is no loss of gasification efficiency if the transient is remedied during this steady period. The new steady state is quickly obtained following the steady period.

As shown in Figure 15 for the 5% reduction in coal feed rate, the composition of product gas on a dry basis does not change appreciably during the transient period. This is to be expected, since the steam to oxygen feed ratio is not affected by the coal feed rate change.

A step increase in coal feed rate from the optimum does not change the coal bed height. Thus, the gasifier operation will reach the new steady state immediately within the context of the pseudo steady state approximation. (Actually, the transient period is at least as long as the time of drying and heating up of coal particles in the gasifier.) The increase in coal feed will increase the amount of unreacted fixed carbon in the discharged ash slag. It is likely that only a limited amount of carbon can flow out with the slag through the tap hole, however, so that an accumulation of the unreacted carbon might force the feed rate of coal down, and the system may be self-regulatory for coal feed increases. A more conclusive statement requires a detailed description of the particular slag tap hole and an improved understanding of the interaction of liquid slag and carbon particles.

Equation (9) is also applicable to the transient process of a step increase in coal feed rate to the optimum from a lower feed rate. For this particular case, H is the initial height of the coal bed, which is lower than optimum height.

Step Change in Gas Feed Conditions

We first consider the transient behavior following a step increase in the gas feed rate while keeping the steam to oxygen feed ratio the same. This change has the same effect as a step reduction in coal feed rate. As discussed for the Lurgi gasifier, it is necessary in principle to construct the relation between the gas burning rate capacity and the bed height for every degree of increase in gas feed rate. This is not necessary in fact, however, because the change in the relation is small for small changes in gas feed rate at a constant steam to oxygen ratio. The transient response to a step increase in the gas feed rate is then essentially the same as the response to a step reduction in coal feed rate, if the initial feed ratio combinations are the same and, after the step changes, the operating conditions are the same. Thus, if the gas feed rates increase 5.26 and 11.11% from the steady state rates, then the transients follow the 5 and 10% coal feed step reduction curves, respectively. All figures for the slagger are applicable except the thermal throughput in Figure 14. For the case considered here, the thermal throughput will experience an instantaneous step increase rather than an instantaneous decrease.

For a step change in gas feed rate accompanying a change of steam to oxygen feed ratio, it is necessary to construct the relation between the gas burning rate capacity and the bed height for the transient analysis. The steady state model can be used for the construction. An appreciable change in product gas composition is to be expected during the transient period for this case.

Since the reactions are limited by their stoichiometries in the slagging gasifier, a small change in the blast temperature will not change the relation between the gas burning rate capacity and the bed height. Thus, during a transient period which is equal to a residence time of the gas phase, only the product gas temperature will change in order to follow the total energy balance.

Discussion

If the slagging gasifier is designed to have a constant full bed height and the coal feed rate is not independently controllable, then the coal feed rate automatically increases if the coal bed height drops. Thus, any unexpected change in operating conditions which tends to drop the coal bed height results in an increase in coal feed rate. In that case, the system is self-regulating, the coal feed rate can be controlled directly by the gas feed rate, and the gasification rate of coal is directly governed by the gas feed rate as observed by Ellman et al. (1977).

CONCLUSIONS

The transient behavior of a moving-bed coal gasifier following a step change in operating conditions can be analyzed effectively with the pseudo steady state approximation; this approximation allows the application of the steady state model to the transient. The predicted transient period following a step reduction in coal feed rate from the optimum depends on the degree of the reduction for both Lurgi and slagging gasifiers. If we wish to control the position of the maximum temperature below the middle of the coal bed for the Lurgi, then the control time available is inversely proportional to the degree of feed reduction. Similarly, the control time to maintain the bed height above the midpoint of the full height for the slagger is inversely proportional to the degree of reduction. The transient times are also dependent on the operating conditions before the step changes for both gasifiers and on the coal type for the Lurgi gasifier. Typical values are about 10 and 3 hr for the Lurgi and slagging gasifiers, respectively, for a 10% coal feed rate reduction.

The responses of performance variables such as the product gas temperature, composition, and thermal throughput to the step reduction are initially rapid because of the fast response of drying and devolatilization of the coal. The rapid responses are followed by rather slow changes in the Lurgi gasifier because of the slow response of gasification and combustion. The responses remain steady in the slagging gasifier after the rapid initial changes until the final stage of the transient period when changes are again rapid. A step increase in gas feed rate with no change in steam to oxygen feed ratio gives the same response as a coal feed rate reduction for both gasifiers.

It is possible to analyze the transient behavior following most other step change in operating conditions with the pseudo steady state approximation. A change in the blast temperature sufficiently large to affect the lightup distance of combustion for the Lurgi gasifier or to cause resolidification of slag in the slagging reactor cannot be treated by this method.

ACKNOWLEDGMENT

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NOTATION

f_a, f_c = weight fraction of ash, carbon by proximate analysis
$F^o_{O_2}$ = molar feed flux of oxygen
IA, IO = Illinois coal with air, oxygen blast
M_c = atomic weight of carbon
t = time
t_l, t_a = lower, upper bound for transient following change of coal
t_r = coal residence time
v = coal velocity
v_t = velocity of position of maximum temperature
WA, WO = Wyoming coal with air, oxygen blast
z_h = position in reactor
Z = height of coal bed
z_m = position of maximum temperature

Greek Letters

ϵ = void fraction
$\theta_{0.9}$ = time for 90% approach to new steady state
θ_m = time for maximum temperature to reach middle of coal bed
ν = velocity of combustion zone in infinite coal bed
ρ_p = density of char
Φ_m = burning rate capacity, moles carbon processed/moles feed oxygen

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Growth of Ice in a Saltwater Drop Falling in an Organic Phase

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Data on the ice formation rate are presented for a saltwater drop suspended by drag forces in a flowing cold organic liquid. The effects of refrigerant undercooling, salt concentration, drop size, and time were studied. Ice formation rates in drops of 3 wt % sodium chloride solution were two to three times lower than in pure water drops. A parallel plate model was used to correlate the data and predict ice formation rates for other drops and refrigerants.

Dispersing drops of brine or fruit juices in a countercurrent cold organic refrigerant is a method of desalination (or freeze concentration) that deserves further study.

SCOPE

Direct contact freezing was reported by Wiegandt (1958) as an attractive method to desalt seawater. The main steps in the process are partial freezing, separating the ice from the brine and washing the ice crystals, and melting the ice. The present study concerns only the first step, wherein an organic refrigerant, for example a C_4 hydrocarbon, is normally dispersed in the precooled seawater. The very large number and the thin shape of the ice crystals formed make the ice brine separation and the washing very difficult. For this study, we reversed the phases in the crystallizer by dispersing the seawater in the cold organic liquid. Larger crystals could be produced most likely because of very limited collision breeding of nuclei for ice growing inside a drop of brine. A higher ΔT could be used, which would give both higher growth rates and larger crystals. The first objective of this study was to test this method of direct contact freezing. For convenience, the work was done with relatively large brine drops suspended by drag forces in flowing naphtha. The second objective was to develop a model which predicts the rate of freezing for other cases such as small drops in butane.

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