A.R.A.P. TECH. MEMO. No. 76-11

MODELING TWO-PHASE FLOW
IN A SWIRL COMBUSTOR

Technical Progress Report
for Period October 9 - December 3, 1976

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50 Washington Road, Princeton, New Jersey 08540

December 1976

Prepared for
The U.S. Energy Research and Development Administration
Under Contract No. E(11-1)-4062

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ABSTRACT

This report outlines the progress made toward modeling two-phase flow in a swirl combustor. During the past two months, we have concentrated on developing a phenomenological model to guide proper scaling. This simple model will also serve as a skeleton for the more detailed computer model which will be developed in the next few months. Our scaling relations indicate that the PERC design for the first stage gasifier-combustor for the CDIF should have a higher carbon conversion efficiency, but is likely to have a slightly higher ash carry-over than that which occurs in PERC's laboratory scale model. If desired, the carry-over may be reduced by decreasing the fraction of small coal particles. It also appears that the total pressure drop will be somewhat larger.

1. INTRODUCTION

On September 1, we initiated a program to develop a model of two-phase flow in a swirl combustor. In our first progress report, Ref. 1, we considered some of the parameters affecting the performance of such a device and outlined a preliminary model. In the past two months, a phenomenological model has been developed in sufficient detail to permit rough calculations of some of the basic performance parameters. The model contains certain empirical constants, which will be determined more accurately by comparison with accurate experimental data. However, even crude estimates of these parameters are sufficient to allow comparisons of existing experimental data with predictions of the model in its present form.

In the next section, the model is formulated, and calculations are made for two different flow conditions in the Atmospheric Vertical Cyclone Combustor. The agreement between these calculations and available experimental data appears to be acceptable, given the uncertainty of both the empirical constants in the model and the experimental data.

Even at its present stage of development, the model can provide scaling relationships to guide the design of large combustors, based on the results of a relatively small laboratory model. Such scaling relationships are developed in Section 3, and are used to draw specific conclusions pertinent to the PERC design of the CDIF first stage gasifier-combustor.

2. MODEL FORMULATION

Our preliminary model divides the combustion chamber into four main regions, as shown in Fig. 1. Region I is the boundary layer on the outer wall. In many respects, it is the most important region in the flow field.

1) Fluid is injected tangentially into Region I with a high velocity. Some of this angular momentum (on the order of 50%) is lost to the outer wall, while the remainder drives the swirling flow in the chamber. In the analysis, this momentum loss in Region I is characterized by a recovery factor, r_f . The magnitude of this parameter controls the efficiency of the device as a swirl combustor, and affects the pressure drop in the chamber as well. The coal particles are heavy enough that they are continually forced to the outer wall. Consequently, virtually all of the coal burning occurs in this region. The entire change in temperature experienced in the chamber also

Figure 1: Flow regions in combustion chamber.

occurs in Region I. The temperature in Regions II, III, and IV may be assumed uniform.

2) A typical coal particle resides in Region I significantly longer than a typical fluid particle, by a factor on the order of 10-100. (Most of the fluid flows from Region I into Region III. Coal particles can leave Region I only by burning, or by flowing into Region II, where the radial velocities are much higher.) Thus, the loading, K , defined as the ratio of the volume-averaged density of coal- and ash-particles to the fluid density, is often larger than 1 in this region. (In the other regions, it is much smaller.) This increased loading increases the momentum loss to the wall, which decreases the swirl in the chamber and the strength of the radial inflow in Region II, which in turn affects the loading.

3) Unburned coal particles which flow into Region II provide a source of particles for both blow-by (in the bottom boundary layer) and carry-over (in the top layer).

4) Slag on the wall provides a sink for ash particles and possibly for some coal particles as well. This loss of particles affects the loading.

5) Turbulent entrainment of the smaller ash particles impedes their flow into the slag layer and provides another source of ash particles for the carry-over.

This list should underscore both the importance and the difficulty of modeling this region correctly.

Region II consists of the two end-wall boundary layers. The radial velocity in these layers is relatively large, in order to provide the radial inflow required to balance the pressure gradient imposed by the flow in Region III. This radial inflow feeds particles from Region I into both the slag port and the exhaust gas. Thus, it is the dominant source of particles for both, even though K may be several times smaller here than it is in Region I.

The dynamics in Region III is relatively simple. The coal loading is effectively zero. There is a slow radial inflow of fluid towards Region IV, with enough flow into Region II to maintain constant circulation ($\Gamma = rv$). The dynamics in this region becomes more complicated if all the radial inflow gets diverted into Region II, but for the present (and proposed) range of parameters such complications do not arise.

The flow from Regions II and III enters Region IV, from which it leaves the chamber. Depending on the flow conditions, there may or may not be a stagnant core along the axis in this region. The flow pattern near the slag port determines which coal particles from the bottom boundary layer enter the slag port as blow-by. The other particles from this boundary layer either return to Region I or escape from the chamber (and contribute to carry-over), depending on their size and the intensity of the swirl. Similarly, particles from the top boundary layer can either return to Region I or escape from the chamber, depending on the detailed flow near the exhaust radius. (The model originally proposed in Ref. 1 also had a Region V, but these effects have been incorporated into Region IV in the present model.)

We now formulate this model quantitatively, beginning with the relevant time scales in Region I. The residence time of the fluid in Region I is given by

$$\tau_1 = \frac{2\pi RL\delta\rho}{\dot{m}_f} \quad (2.1)$$

where R is the chamber radius, L its length, δ is the boundary layer thickness (the width of Region I), $\dot{m}_f$ is the fluid flow rate and ρ is the fluid density.

On the other hand, a coal particle resides in Region I either until it burns or until it escapes into Region II. The combustion time of a coal particle of diameter $2a$, burning in a chamber of pressure p , is assumed to be diffusion controlled, and thus may be represented by (Ref. 1)

$$\tau_c = \frac{C_1 (2a)^2}{p} \quad (2.2)$$

For the present calculations, C_1 , is chosen so that a 100-micron particle at atmospheric pressure burns in 0.2 sec.

The volume flow rate of fluid, F , in either of the end-wall boundary layers (i.e., Region II), is found from (Ref. 2)

$$\frac{dF}{dr} = 4.9(2\pi) \left(\frac{\dot{m}_f R}{\rho_1 A} \right) \left(\frac{C_f}{2} \right) r_f (1 + K_{II}) \quad (2.3)$$

where r_f is the recovery factor in Region I, K_{II} is the particle loading in Region II, and C_f is the drag coefficient (0.005 in the present calculations). Both K_{II} and r_f are unknown. For small K_{II} , the fraction of the total fluid flow that enters Region II directly from Region I is, from Eq. (2.3),

$$\frac{2\rho F}{\dot{m}_f} = \frac{4.9(2\pi)\rho C_f r_f \delta R}{\rho_1 A} \quad (2.4)$$

This can be interpreted as the probability of entering Region II directly from Region I for a fluid particle, and the probability of immediate escape from Region I for a coal particle. Combining this with Eq. (2.1) yields the time a coal particle resides in Region I before entering Region II

$$\tau_r = \frac{4.9(2\pi R \delta \rho)^2 L C_f r_f}{\dot{m}_f \rho_1 A} \quad (2.5)$$

The time spent by a coal particle in Region I is the shorter of the two times given in Eqs. (2.2) and (2.5). In the Atmospheric Vertical Cyclone Combustor, as it is presently operated, the smaller particles appear to be controlled by combustion, while the larger particles are controlled by flow into Region II, and the distribution of particle size plays an important role in the analysis. The simplified scaling relations obtained in Section 3, however, require only one particle size.

The mass of coal in Region I is

$$M = \dot{m}_c \sum_i f_i \tau_i \quad (2.6)$$

where $\dot{m}_c$ is the coal flow rate, f_i is the fraction of particles at a given size, and τ_i is the appropriate time (from Eqs. (2.2) or (2.5)) for that size. The loading in Region I due to these coal particles is

$$K = \frac{M}{2\pi RL\delta\rho} \quad (2.7)$$

If a significant fraction of particles leave Region I only to return to it, they comprise a second source that must also be accounted for in Eqs. (2.6) and (2.7).

The recovery factor is defined as

$$r_f = \frac{v_o}{v_i} = \frac{v_o \rho_i A}{\dot{m}_f} \quad (2.8)$$

where v_o is the tangential velocity at the beginning of Region III. Following Ref. 2, it may be approximated by

$$r_f = \left[1 + \frac{\dot{m}_c}{\dot{m}_f} \left(1 - \frac{v_c}{v_o} \right) + (1+K) \left(\frac{C_f}{2} \right) \frac{2\pi RL}{A} \right]^{-1} \quad (2.9)$$

where v_c is the inlet velocity of coal particles ($v_c \ll v_o$ in the sample calculations). With given input values, Eqs. (2.2) - (2.9) can be solved for r_f , K , and a critical particle size that is combusted before leaving Region I.

The coal flow rate in the bottom boundary layer is, from Eq. (2.4),

$$\dot{m}_{bL} = \frac{4.9\pi\dot{m}_f K \rho C_f r_f R \delta}{\rho_i A} \quad (2.10)$$

The flow of coal particles into the slag port (blow-by) is a fraction of this:

$$\frac{\dot{m}_{BB}}{\dot{m}_c} = n_B \cdot 4.9\pi \left(\frac{\dot{m}_f}{\dot{m}_c} \right) K(\rho/\rho_i) C_f r_f \left(\frac{R\delta}{A} \right), \quad 0 \leq n_B \leq 1 \quad (2.11)$$

Several methods to determine n_B are now under investigation. For $n_B < 1$, the fraction of unburned coal particles in the bottom boundary layer that does not enter the slag port can return to Region I. This additional mass source must be added to that in Eq. (2.6), so that the loading in Region I increases.

The coal flow rate in the top boundary layer is also given by Eq. (2.10). Upon burning, this gives a mass flow rate of ash that is potentially available to be carried over into the exhaust flow. Again, only a fraction of this flow (parameterized by n_T , $0 \leq n_T \leq 1$) adds to the carry-over; the rest returns to Region I and further increases the loading there.

A second potential source of carry-over is the very small particles that are carried inward by the fluid through Region III. Using a balance between centrifugal force and fluid drag on a particle, the maximum diameter, $2a$, of particles that can reach Region IV by this route is

$$(2a)^2 = \frac{9\mu}{\pi L \dot{m}_f} \left(\frac{\rho}{\rho_s} \right) \left(\frac{r A \rho_i}{R r_f \rho} \right)^2 \quad (2.12)$$

where ρ_s is the particle solid density, and r is the exhaust radius. For either the existing laboratory model or the proposed CDIF combustor, this carry-over is negligible. Similarly, one can show that virtually no particles from the bottom boundary layer can reach the exhaust flow directly.

The other source of carry-over is the relatively small ash particles in Region I that are entrained by the turbulent velocity there. Assuming turbulent velocities that are 10% of the swirl velocity gives a maximum particle size for carry-over by this mechanism:

$$(2a)^2 = \frac{9\mu R A p_i}{5\dot{m}_f r_f \rho_s} \quad (2.13)$$

The maximum flow rate of ash available from this source can then be determined from the particle distribution. The total carry-over is obtained by adding that from each of these three sources.

Finally, the total pressure drop comes from three regions: the inlet, the outer boundary layer (Region I), and the main chamber (Regions III and IV). At the inlet, the pressure drop is that required to accelerate the flow

$$\frac{\Delta p}{p_i} = \frac{\frac{1}{2} \rho_i \left(\frac{\dot{m}_f}{\rho_i A} \right)^2}{p_i} \quad (2.14)$$

The pressure drop across Region I is

$$\frac{\Delta p}{p_i} = \frac{\rho(1+K) \left(\frac{\dot{m}_f}{\rho_i A} \right)^2 r_f \left(\frac{\delta}{R} \right)}{p_i} \quad (2.15)$$

The total pressure drop across the chamber is obtained by numerically integrating the pressure drop across the chamber:

$$\frac{\partial p}{\partial r} = \frac{\rho v^2}{r}$$

where $v(r)$ is the local tangential velocity. The total pressure drop is obtained by adding the results of Eqs. (2.14), (2.15) and (2.16).

In order to test the validity of this model, two sample calculations were made using flow conditions corresponding to measured runs of the Atmospheric Vertical Cyclone Combustor, for which some experimental data are available (Refs. 3 and 4). Values of the empirical constants were chosen somewhat arbitrarily. All of this input information is listed in Table I. Predicted and measured results are both listed in Table II. Given the present state of uncertainty of both the empirical constants and the experimental data, the agreement between the predicted and measured results appears reasonable.

3. SCALING RELATIONS

The two most important performance parameters appear to be the carbon conversion efficiency and the ash content in the exhaust gases. We can use the present model to see how these parameters will be affected by simple scaling changes. The four variables to be considered in this scaling exercise are a characteristic length, (L) , mass flow $(\dot{m})$, chamber pressure (p) and a characteristic coal particle radius (a) . We assume that the combustor geometry remains similar, that both the inlet temperature and the stoichiometry of the process are fixed, and that all of the particles are effectively of one size. (As stated in Section 2, particles with much different sizes are controlled by different processes, and the results given here need not apply if several particle sizes coexist.) Given these restrictions, the effect of scale changes on the parameters in question follows directly from the relations given in Section 2.

We have seen that the unburned coal carried into the slag port (the blow-by) is controlled by the boundary layer flow on the bottom end wall. From Eq. (2.11),

$$\frac{BB}{\dot{m}} \sim K r_f \frac{\delta}{L} \quad (3.1)$$

The loading is determined by its total residence time in Region I (including recirculation). With only one particle size, a simplified analysis yields a more convenient relation than Eqs. (2.6) and (2.7), as follows. The mass of coal contained in the chamber at any time is approximately

$$M = \dot{m}_c \left[\tau_c \left(1 - 2 \frac{\dot{BB}}{\dot{m}_c} \right) + 2 \frac{\dot{BB}}{\dot{m}_c} \tau_{bl} \right] \quad (3.2)$$

Here τ_{bL} represents the total residence time of a coal particle that eventually enters either the slag port or the exhaust flow; it includes recirculation of particles, as τ_r does not. With Eq. (3.2) replacing Eq. (2.6), the loading is still given by Eq. (2.7). Combining these with Eq. (3.1) yields

$$\frac{\dot{BB}}{\dot{m}} = \chi / \left[1 + 2\chi \left(1 - \frac{\tau_{bL}}{\tau_c} \right) \right] \quad (3.3a)$$

where

$$\chi \sim \frac{\dot{m} \tau_c r_f}{\rho L^3} \quad (3.3b)$$

The recovery factor, r_f , is given by Eq. (2.9). One can show that for the current laboratory model, significant changes in K effect only minor changes in r_f , so that r_f may be considered constant in Eq. (3.3). After using Eq. (2.2), the net result is that

$$\chi \sim \frac{\dot{m} a^2}{L^3 p^2} \quad (3.4)$$

Equation (3.4) provides the scaling relation appropriate for blow-by. For sufficiently small particles, for which combustion dominates,

$$\tau_c \ll \tau_{bL}, \quad \chi \ll 1, \quad (3.5)$$

$$\frac{\dot{BB}}{\dot{m}} \sim \chi \ll 1$$

For sufficiently large particles, complete combustion is almost impossible within the chamber:

$$\tau_c \gg \tau_{bL}, \quad \chi \gg 1, \quad \frac{BB}{m} \sim \frac{1}{2} \quad (3.6)$$

For intermediate particles,

$$\chi \sim 1$$

corresponds to a particle that is partially combusted as it enters the slag port. The size of such a particle scales as

$$a_{c1} \sim L^{3/2} P/m^{1/2} \quad (3.7)$$

In summary, blow-by is reduced by reducing χ unless the coal particles are bigger than a critical radius which scales according to Eq. (3.7).

We consider next the ash content in the exhaust gases (carry-over). As stated above, there are three contributions to carry-over:

- i) Some unburned coal particles are carried out via the top end-wall boundary layer. The contribution from this source is proportional to the blow-by, and scales with it.
- ii) Some ash particles are too small to be separated out of the main flow. From Eq. (2.12), the maximum particle size that can escape in this way scales as

$$a_{c2} \sim (PL^3/\dot{m}r_f)^{1/2} \quad (3.8)$$

- iii) Somewhat larger ash particles are entrained by the turbulent flow in Region I, and eventually lead out through the top end-wall boundary layer. From Eq. (2.13), the maximum particle size in this case scales as

$$a_{c2} \sim (PL^3/\dot{m}r_f)^{1/2} \quad (3.9)$$

Neglecting changes in r_f , one can conclude from Eqs. (3.7), (3.8) and (3.9) that if the pressure is increased, and if only one particle size exists, it should be possible to decrease both the blow-by and the carry-over. This is true whenever

$$\frac{a_m^2}{L^3} \sim P^n, \quad 1 < n < 2 \quad (3.10)$$

If $n < 2$, then from Eq. (3.4), the blow-by decreases, as does the first source of carry-over. If $n > 1$, then from Eqs. (3.8) and (3.9), the other sources of carry-over also decrease. The optimal choice of (n) within this range depends upon the relative importance of blow-by vs. carry-over.

Scaling of the total pressure drop can be determined directly from Eqs. (2.14), (2.15) and (2.16). The result is

$$\frac{\Delta p}{P} \sim \left(\frac{\dot{m}}{P L^2} \right)^2 \left(1 + c_4(1+K) r_f + c_5 r_f^2 \right) \quad (3.11)$$

where each of the terms in the sum represents one of the three contributions to the total pressure drop.

4. CONCLUDING REMARKS

The current PERC design calls for scaling the laboratory model combustor by increasing the pressure by a factor of 6 and the diameter by a factor of 4, while increasing the mass flow rate by a factor of 100. Using these values in Eq. (3.3) shows that the blow-by in the CDIF gasifier should be significantly less than that in the atmospheric, laboratory model. That is, the critical particle size which can be completely combusted will increase according to Eq. (3.7) by a factor of 5.

The prediction for the carry-over is not as clear cut. The contribution from the first mechanism should be reduced, but those from the second and third mechanisms will be increased if the size distribution of the coal feed remains fixed. The critical particle size will be ≈ 2 times larger. If case A, considered in Section 3 were to be scaled,

the carry-over would remain relatively constant in spite of the fact that the contribution from the second term would increase by a factor of 2.5.

The percentage pressure drop across the chamber will increase principally because the decreased loading should increase the recovery factor. Sample calculations we have made suggest that an increase by a factor of 1.5 is a reasonable expectation.

We conclude that the proposed PERC design scaling is good. There may be some increase in carry-over, but this can be remedied by increasing the minimum coal particle size. In fact, as shown in the last section for a narrow range of coal particle sizes, both the blow-by and carry-over should be reduced. Another way of viewing this is to note that increasing the pressure level will increase the ratio between the critical particle size for blow-by and the critical size for carry-over.

$$\frac{a_{c1}}{a_{c3}} \sim p^{\frac{1}{2}}$$

This indicates that the pressurized chamber should operate acceptably over a somewhat broader range of coal particle sizes.

The more difficult question of optimum chamber geometry for any given constraints has not been attempted in the present report. This can best be accomplished after our computer program is more developed.

The next steps in our model development are to program the present calculation procedure, make more detailed comparisons with available laboratory data, and refine the analysis of the flow regions which are most critical to the combustor's performance.

In connection with the second step, we would like to suggest some specific test data which may be obtained from the current PERC laboratory model. First we would like to see the results of burning a coal mixture with a much more narrowly defined distribution of sizes. The present analysis suggests that if the input coal-particle-size range is limited on the lower side by the carry-over critical radius (Eq. (3.9)), and on the upper side by the blow-by critical radius (Eq. (3.7)), then both of these performance figures of merit should be improved. A good size to test would be to limit the mesh sizes to between 60 and 150.

One of the most critical geometrical parameters is the inlet area. We would like to see tests made with inlet area for the air partially blocked. If blow-by has been controlled by eliminating the larger size particles from the coal feed, this should serve to reduce carry-over. At any rate, data from such a test would provide important verification tests for our model.

TABLE I - INPUT PARAMETERS

	<u>A</u>	<u>B</u>
Run number (from Ref. 3)	137A, 138 or 141	126A
Coal flow rate, $\dot{m}_c$ (Lb/hr)	100	223
Stoichiometric air ratio	.61	.635
Air flow rate, $\dot{m}_f$ (Lb/hr)	690	1600
Weight fraction, f , of particles within given diameter range ($2a$ in μ)		
$2a > 841$	.10	.08
$841 > 2a > 420$	.28	.17
$420 > 2a > 177$	.28	.14
$177 > 2a > 149$	.05	.12
$149 > 2a > 105$	.10	.10
$105 > 2a > 74$	.05	.10
$74 > 2a$	.14	.29
Total:	1.00	1.00
Ash content (%)	11	10
Inlet temp. ($^{\circ}\text{F}$)	1980	1980
Chamber temp. ($^{\circ}\text{F}$)	3500	3500
Inlet density, ρ_i (Lb/ft ³)	0.016	0.016
Chamber density, ρ (Lb/ft ³)	0.010	0.010
Chamber pressure (atm)	1.0	1.0
Chamber length, L (ft)	1.58	1.58
Chamber radius, R (ft)	0.5	0.5
Exhaust radius, r (ft)	0.25	0.25
Inlet area, A (ft ²)	0.07	0.07

TABLE II - OUTPUT FROM MODEL

	<u>A</u>	<u>B</u>
Residence time of a coal particle in Region I (sec)	$.38/r_f$	$.16/r_f$ (with $\delta = 0.1R$)
τ_r (sec)	1.31	0.65 (with $n_T=n_B=0.5$)
K	12.0	15.1
r_f	.29	.25
Maximum diameter of completely combusted particle (μ)	256	180
Coal flow rate in bottom boundary layer (Lb/hr)	41.2	103.4
Coal mass flow rate into slag port (Lb/hr)	20.6	51.7
(Observed mass flow rates into slag port (Lb/hr)	16.5, 14.3, 5.4	31)
Estimated flow rate of ash from top boundary layer into exhaust flow (Lb/hr)	2.1	5.2
Maximum diameter of particles carried through Region III (μ)		
Coal	12	8
Ash	37	26
Maximum diameter of ash particles entrained by turbulent flow in Region I (μ)	87	62
Estimated flow rate of entrained ash particles (Lb/hr)	1.6	5.6
Total estimated carry-over (Lb/hr)	3.7	10.8
(Observed carry-over, as given in Ref. 2 (Lb/hr)	0.6, 1.2, 3.8	0.8, 1.2, 4.0)
(Observed carry-over as given in Ref. 3 (Lb/hr)	1.3	5.8

TABLE II - OUTPUT FROM MODEL (CONTD.)

Pressure drop at inlet (%)	.35	1.88
Pressure drop across Region I (%)	.26	.92
Pressure drop across chamber (%)	.09	.27
Total pressure drop (%)	.70	3.1
Inlet Reynolds No. $\times 10^{-5}$	.75	1.88
(Total pressure drop from Ref. 3 (%)	1.6	3.9)

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