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ELECTROCYCLONE DEVELOPMENT PROGRAM

Quarterly Technical Report for the Period August—October 1981

Work Performed Under Contract No. AC21-80ET17091

General Electric Company
Schenectady, New York

TECHNICAL INFORMATION CENTER
UNITED STATES DEPARTMENT OF ENERGY

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AUGUST - OCTOBER, 1981

PREPARED UNDER CONTRACT
DE-AC21-80ET17091

FOR

U.S. DEPARTMENT OF ENERGY
FOSSIL ENERGY DIVISION

GENERAL ELECTRIC

ENERGY SYSTEMS PROGRAMS DEPARTMENT
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DESCRIPTION OF PROJECT

In response to the need for a high efficiency, high throughput gas cleanup device for Pressurized Fluidized Bed application, General Electric has experimented with an electrostatically augmented cyclone. A principal advantage of the GE Electrocyclone concept is that a twelve-foot diameter unit can be built with performance comparable to a ten-inch conventional cyclone. The use of large Electrocyclones, with individual lockhoppers and inlet/outlet ducts, will avoid the plugging and flow imbalance problems which have plagued the use of multi-clones.

Significant progress has already been made in the development of the Electrocyclone concept. Experimental work on a 12-inch and, subsequently, an 18-inch cold flow model was carried out under the CFCC Program (Contract DE-AC21-76ET10377). Analytical developments and system engineering studies were carried out under a study for DOE Environmental and Safety Engineering Division (Contract No. DE-AC02-79EV10143). This development work will be continued under the present "Electrocyclone Development Program," supported by the DOE Fossil Energy Division and by the New York State Energy Research and Development Authority.

The Electrocyclone Development Program addresses three critical development areas: Performance scaleup; performance at high temperature and pressure; and corona charging. The scaleup of Electrocyclone performance will be demonstrated experimentally by cold-flow testing of a 36-inch diameter unit geometrically similar to the earlier 18-inch model. The performance at high temperature and pressure will be demonstrated by actual PFB tests on an 18-inch model geometrically identical to the earlier cold-flow model. The feasibility of corona charging has been previously established by GE in an actual PFB environment. Under the Electrocyclone Development Program, laboratory experiments will be carried out to determine preferred electrode geometries and to investigate the effects of alkali metal salt vapor on corona current under controlled conditions. Additionally, the Electrocyclone PFB test will confirm the design approach and corona charger performance.

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WORK ACCOMPLISHED DURING REPORT PERIOD

TASK 1.0 COMPONENT DEVELOPMENT

1.1 ELECTROCYCLONE COLD FLOW TEST

Early testing of the 18" Electrocyclone with a 75 kV power supply did not permit optimization of its electrostatic performance. A new 150 kV, 10 mA DC power supply has been installed and is presently being used to apply higher voltages inside the high flow electrocyclone.

The tests have used both CURL second stage flyash and nickel dust. The typical mass size distributions of these dusts are illustrated by Figure 1. The testing has determined the overall mass efficiency and the fractional efficiency of the electrocyclone for various operating conditions by varying parameters such as inlet velocity, dust loading, electrode voltage, etc. Typical results are shown in Figures 2 and 3. In addition, the physical dimensions and characteristics of the electrocyclone have been modified in an effort to optimize performance. The following summarizes the results:

- Increased engagement length of the exhaust duct improved the efficiency of the non-air-shielded configuration. The effect is shown in Figure 4 from the data illustrated by curves ① and ②. Similar testing has indicated that increased engagement length has negligible effect on the efficiency of the air-shielded configuration.
- Dust hopper re-entrainment, or "base pick-up," is significant and can be effectively controlled by a vortex shield device above the dust dipleg. This effect is illustrated by a comparison of curves ② and ③ in Figure 4.
- The physical presence of the electrode structure significantly affects the swirl flow; this degradation can be minimized by streamlining the structure and reducing the support rod diameter. Testing with an enlarged electrode insulator to simulate the PFB model design shows a measurable performance penalty. Attempts to mitigate this penalty included streamlining the insulator and moving it further downstream; however, the performance loss was not fully recovered. This electrode size effect on performance is illustrated in Figure 5, by the difference between curve ③, which represents the PFB design and curve ②, which represents a smaller diameter design. The continuation of this trend is shown by curve ①, which represents

Figure 1. Typical Mass Size Distributions of CURL 2nd Stage Flyash and Nickel Dusts as Dispersed by Fluidized Bed

Figure 2. 18" Hi-Flow Electrocyclone Data

Figure 3. 18" High Flow Electrocyclone Data

Figure 4. Inertial Optimization of the 18" Non-Air-Shielded High-Flow Cyclone (Cold-Flow Data)

Figure 5. Effect of Electrode Structure on Inertial Performance of the 18" Non-Air-Shielded High-Flow Electrocyclone (Cold-Flow Data)

the case for no electrode. Quantitatively, this penalty amounts to a 20 to 30% increase in penetration. It is concluded that this central obstruction in the exit tube (11% areal blockage) enlarges the vortex core diameter far upstream and thus degrades performance. Plans have been made to test the PFB electrocyclone model with and without the electrode assembly in place during the CRD cold-test check-out.

- Tests have also determined that an "active" (uninsulated) electrode in the vicinity of the cyclone exit tube rim is essential for maximizing the electrostatic augmentation in a high-flow cyclone. Tests done without insulation in this region show a marked degree of improvement over an insulated electrode. Originally, it was thought that insulation was required here to eliminate premature sparkover. The comparison of electrocyclone performance for insulated vs. uninsulated electrodes is illustrated by curves ② and ③ in Figure 6. Also note that the uninsulated electrode produces a higher corona current, which promotes more dust charging and thus better performance. Curve ① which represents the case for no corona field is shown for comparison.

From earlier tests on the high-efficiency electrocyclone, it was thought that an electrically insulated or "floating" exit tube was required to achieve the enhanced performance as described above. However, owing to the large exit tube diameter of the high-flow design, a grounded exit tube gives comparable results to a

floating exit tube without premature sparkover. This is shown by the data in Figure 7. This is an important finding since a hot-flow electrocyclone with a grounded exit tube offers a more simple electrical design.

Figure 6. Effect of the Corona Field in the Exit Tube Vicinity of the 18" Non-Air-Shielded High-Flow Electrocyclone (Grounded Exit Tube)

The performance of a high flow cyclone operating in a low flow configuration (similar to a part load condition in a CFCC plant) was tested. The performance measured was significantly higher than the normal operating mode due mainly to the increased residence time of the gas in the filter. The longer residence gives the electrostatic forces more time to remove the dust particles from the main gas flow. The effect is illustrated by Figure 8.

The experimental investigation to assess the influence of particulate space charge on electrostatic augmentation has been completed. Using CURL 2nd-stage fly-ash, dust loadings of approximately 5-10 gr/acf produced a corona quench condition and thus no electrostatic enhancement. A four-fold reduction in corona current was associated with this test. However, using a conductive nickel dust at loadings of approximately 16 gr/acf, negligible degradation in electrostatic performance was

Figure 7. Influence of an Electrically Floating Exit Tube in the 18" Non-Air-Shielded High Flow Electrocyclone (No Electrode Insulation)

Figure 8. Effect of Mass Dust Loading on Electrostatic Performance of 18" High-Flow Electrocyclone

observed. The results are illustrated by Figures 8 and 9. This latter test suggests that corona quench will probably not occur at HTHP conditions since the fly-ash will not be insulating. Also, the cold-flow tests represent a worst-case situation due to the very fine nature of the test dusts (typically 2.5-3.0 μm mass mean diameter). Since particle charging is proportional to surface area, a system loading of 3 gr/acf with mass mean of 7 μm (characteristic of a PFB second-stage input dust) would be equivalent to a loading of 1.3 gr/acf with mass mean of 3 μm . Therefore, significant corona quench is not anticipated in the upcoming Curtiss-Wright PFB test.

Figure 9. Effect of Dust Mass Loading on Electrode Corona Current in 18" High-Flow Electrocyclone

The main purpose of the high flow testing has been to optimize the configuration of the electrocyclone to be tested at the Curtiss-Wright facility. The modifications to the original configuration suggested by the testing described above have been incorporated into the test unit design. The final geometry of the test unit is illustrated by Figure 10.

The expected 12" cyclone performance at the Curtiss-Wright PFB facility has been computed based upon the recent cold-flow test results of the 18" (nonelectrostatic) high flow, non-air-shielded cyclone. The cyclone will be placed in the

Ducon (second stage) position so that the inlet dust loading will be approximately 1.8 gr/scf (=3.0 gr/acf) with no dilution. The anticipated PFB gas conditions are

Temperature = 1625°F (885°C)

Pressure = 94 psia (6.4 atm)

Gas Density = 0.122 lbm/cf (1.96 kg/m³)

Mass Flow = 2.4 lbm/s (1.1 kg/s)

Figure 10. Flow Path for PFB Hot Test Electrocyclone

Approximately 4.6 lbm/s of clean, hot dilution air is available at the Curtiss-Wright facility so there exists the flexibility to vary cyclone inlet velocity and inlet dust loading. Therefore, three flow conditions have been chosen for the present calculations. These calculations do not include electrostatic augmentation and thus represent worst cases. Results are as follows:

Total Mass Flow (#/sec)	Inlet Dust Loading (gr/SCF)	Pressure Drop (PSI)	Overall Mass Efficiency (%)
2.4	1.8	0.25	83.13
4.7	0.92	0.96	89.59
7.0	0.62	2.12	92.51

A new computer code has been developed to calculate cyclone fractional (grade) efficiency for our cold-flow testing. The program accepts the raw data directly from the optical particle instrumentation. This routine eliminates the excessive hand calculations and plotting of the past, thereby cutting data reduction time by almost a factor of 10.

1.2 CYCLONE SCALING (NYSERDA FUNDED)

Figure 11 summarizes the overall mass efficiency of the 4", 12" and 36" high-efficiency scaling cyclones as a function of the inertial scaling parameter (Stokes number). The data was gathered over the range of velocities, 20 to 130 ft/s, with typical mass mean diameters of 2.7 μm (flyash) and 3.0 μm (nickel). Note that the data correlation is good, except at high Stokes numbers. This "droop" is attributed to the high probability of wall bounce for large, massive particles (nickel). It should also be noted that the 4" cyclone employs a deswirl cruciform in its dust hopper, which is not found in the 12" and 36" cyclones.

Figure 11. High-Efficiency Scaling Cyclone Summary

Testing of the 4-inch diameter cyclone has been reinitiated to investigate the significance of the dust hopper-mounted cruciform. The cruciform located in the dust hopper of the four-inch diameter model was removed to assure geometric similarity with the larger cyclones. Since the results with flyash exhibit anomalous behavior, similar to that found with triboelectric particle charging, tests were also conducted with nickel and A-C fines (Arizona road dust). All showed the same trend, e.g., approximately constant overall efficiency with inlet velocity. Ground-

ing of the aluminum cyclone and grounding of inlet duct elements showed no effect. The cruciform was reinserted and showed performance degradation, but substantial constant overall efficiency. These features are illustrated in Figures 12 and 13.

Figure 12. Four Inch Diameter Scaling Cyclone

As a result, fractional efficiency data does not correlate with the separative parameter and is significantly higher than found with the 12 and 36-inch diameter models. The consequence is that scaling from small models to prototype size can lead to serious overprediction of performance. The test for validating model performance is to show correlation with the inertial separative parameter through tests over a range in velocity.

Past experience has found that natural triboelectric charging can have as strong an effect as using a corona source with an applied electric field. Also, no known technique has consistently removed this effect. Furthermore, the same test dusts have not shown this behavior in other cyclone models. A working hypothesis is that higher particle-wall impact occurs in this small cyclone. Tests are, therefore, planned using 3rd-stage CURL flyash with a mass mean of ~ 1.7 micron, down from the ~ 2.7 to 3.2 micron size range of the 2nd stage CURL flyash. This will result in

inertial separative parameters of the same order as the 12-inch diameter model test. Another test in preparation will consist of converting the dust hopper into a Faraday Cage. The objective here will be to assess the induced dust charge level. Another point of interest is that this model is constructed of aluminum, whereas steel is used for the larger model.

Figure 13. Four Inch Diameter Scaling Cyclone

1.3 ELECTROSTATIC COMPONENT DEVELOPMENT

Electrostatic "Space-Charge" Effects in Cyclone Separator - In approaching the problem of calculating electric field effects in the electrocyclone, it was thought desirable to begin with the 3-region model developed primarily for calculating the inertial behavior of the cyclone separator. The model has been used successfully in predicting the inertial separation properties of other commercial units. Due to this initial success, the electrostatic calculations have been incorporated into the 3-region model for particle behavior. Upon completion of a numerical integration program for electrostatics, results are compared with the "high-flow" cyclone experimental measurements. This report focuses primarily on comparing the calculated electrocyclone behavior with experimental high-flow cyclone data.

Measurements on the collection efficiency are compared with the calculated values with and without the 80 kV voltage applied to the electrode. Figure 14 indicates the calculated cyclone efficiency versus inlet velocity to the cyclone for two different flyash dust loading levels. Because the inertial performance of the cyclone is relatively independent of the dust loading (grains/ft³) in the range of interest, the effect of "space charge" is indicated by comparing the two curves in Figure 15 which represent dust loading of 0.1 and 1.0 grains/ft³. The principle illustrated by the two curves is that the charged particles in the cyclone body form a "space-charge" which increases the electric field near the cyclone walls. This enhanced electric field results in increased precipitation of dust against the walls as the dust loading becomes higher. The price paid for space-charge field enhancement is that the electric field and the electrode field is partially shielded, eventually causing "corona quench" and reduced particle charging.

In calculating the net expected performance of the electrocyclone, it is useful to divide the result into two parts: separation of particles from the gas due to inertial forces and separation due to electrostatics. Figures 15 and 16 show a comparison of the calculated and measured inertial performance of flyash and nickel dust. The inertial calculation has been performed on a histogram of particle sizes instead of a single particle size.

The 3-regional model is used as a basis for calculating the particle collection at the cyclone walls with electrostatic enhancement. The basic approach is to

calculate the electric field in each region of the cyclone, and then augment the particle velocities by an amount proportional to the electric field times the charge on each particle. A mathematical complicating factor is that the electric field depends on the particle distribution within the cyclone body. However, the particle distribution is what is being calculated in the 3-region model. Thus the equations become nonlinear when "space-charge" significantly alters the electric field from its original value. This problem is solved by postulating the particle distribution in the cyclone, calculating the electric field, and then testing the result for consistency. Using computer programs which employ this method, the electrocyclone efficiency can be conveniently calculated.

Figure 14. Calculated Separation Performance of High-Flow Electrocyclone Using Flyash

These calculations and comparison with experimental data are presented in Figures 17 and 18. The results show close agreement across the range of inlet speeds for both flyash and nickel. Each data point in the figures are accompanied by a dust loading number associated with the measurement. The dust loading value is programmed into the computer calculation and this is reflected in the "space-charge" effect due to the dust. The electrostatic model also assumes the particles

Figure 15. Calculated and Measured Separation Performance of High-Flow Cyclone for Flyash Dust with no Electrode Voltage

Figure 16. Calculated and Measured Separation Performance of High-Flow Cyclone for Nickel Powder with no Electrode Voltage

Figure 17. Calculated and Measured Increase in High-Flow Cyclone Efficiency (including "space-charge" effects) for Flyash Dust

Figure 18. Calculated and Measured Increase in High-Flow Cyclone Efficiency for Nickel Powder

are "pre-charged" by the electrode before penetrating a significant distance into the cyclone body. Despite possible limitations of the 3-region model for calculating the inertial cyclone properties, it is quite useful for predicting the separation enhancement due to the energized electrode.

One significant difference exists between the inertial performance calculation (Figures 15, 16) and the electrostatic enhancement (Figures 17, 18). The inertial calculation, as mentioned, employs a size distribution of particles rather than a single particle diameter. However, the electrostatic enhancement program relies on a single size particle for both the flyash and nickel examples. The particle size employed is the so-called "mass median" which is $2.7\text{ }\mu\text{m}$ for flyash and $2.9\text{ }\mu\text{m}$ for nickel. The single particle size approximation is thought to be a reasonable assumption for calculating the electrostatic enhancement, although a more complex space-charge calculation based on the estimated particle distribution is currently under consideration. The "mass median" particle size distribution for the two dust samples should by no means be confused with the "mass mean" particle size. The "mass mean" is generally higher or lower than the mass median for the example distributions, and therefore a single particle size characterization of the dust samples is an oversimplification, particularly with respect to the inertial calculations.

Conclusions

Several conclusions may be drawn from the preceding analysis and discussion.

- The 3-region inertial model is a "fair" method for estimating the cyclone performance.
- A single "mass-median" particle does not characterize the dust samples well enough to predict the cyclone inertial performance
- A computer program has been developed, based on the 3-region inertial model, to predict electrostatic enhancement in the cyclone.
- "Space-charge" effects play an important part in electro-cyclone performance even at relatively low loading levels ($<1.0\text{ grains/fr}^3$).
- The 3-region "space-charge" model adequately predicts the electrostatic separation enhancement in comparison with the flyash and nickel measurements.
- A more complex calculation is under consideration for incorporating the effect of particle size distributions in the "space-charge" model.

Although not completely finished, the space-charge calculation based on a 3-region model is not the only aspect to be considered. Another problem is to extrapolate the calculation and measurement results to a larger diameter cyclone, say 3m. Consequently, further efforts will be directed towards this objective in the remainder of the program. This includes predicting a corona quenching condition for both a large and small diameter device which would limit the useful range of practical operation.

TASK 2.0 ELECTROCYCLONE PFB TEST

Redesign of the PFB test module concept to incorporate the decision to reduce the cyclone size to 12 inches has been completed and a final design and manufacturing contract has been awarded for the cyclone and pressure vessel. The conceptual design provides a flow path geometry based on cold flow test results as reported in Task 1.1 with the following general features:

- The cyclone is a high-flow design, passing four times the flowrate of the earlier electrocyclone model for a given body diameter.
- The body diameter is reduced from 18 inches to 12 inches. This increases the maximum inlet velocity achievable with the full 7 lb/sec SGT flow capability from 63 to 140 ft/sec, and is more in line with the cold flow test program.
- The air-shielded configuration previously considered is replaced with an equally effective long exhaust engagement length.
- The engagement length is increased to 1.65D from 0.65D, while maintaining the original body length.
- The exit tube spin-up insert has been removed.
- A vortex shield device has been placed above the dust dipleg to control "base pick-up" or dust hopper re-entrainment.
- A centerbody has been added to the outlet collector scroll in order to improve overall pressure recovery.

A schematic of the flow path is shown in Figure 10. The conceptual design also provides guidance for final design of the pressure vessel and support structure for the cyclone. General features include:

- Castable refractory insulation on the inside lower vessel section which houses the cyclone
- A uninsulated upper section containing the air-cooled electrode terminal connections and separated from the lower section by blanket insulation
- Thermocouple installation for purge air control and to measure overall performance
- Air cooled "radial" struts to support the cyclone from the vessel wall.

Analysis has been conducted to define the maximum temperature limits in the HV electrode/feed-through structure based upon electrical resistivity and thermal stress analyses of the alumina insulators. The results show that various "critical sections" of the alumina must not exceed approximately 1100°F or excessive current leakage will ensue. The maximum temperature gradient across any alumina tube wall is limited to approximately 320°F by thermal stress failure. Some analysis effort continues in this area in order to minimize cooling flow requirements.

A drawing showing the interfaces with the Curtiss-Wright Corp. test facility was also completed and a meeting held with CW representatives to discuss specifics. All mechanical interface concerns have been resolved and flange and mounting loads have been calculated. The interface drawing is shown in Figure 19.

TASK 3.0 DESIGN REVIEW

No additional work has been scheduled in this task during this report period.

TASK 4.0 SYSTEM ANALYSIS

No additional work has been scheduled in this task during this report period.

TASK 5.0 PROGRAM MANAGEMENT

A program review was held in Morgantown on Sept. 24, 1981 with representatives of DOE, Curtiss-Wright, General Electric and Gilbert Associates in attendance. The electrocyclone redesign utilizing the 12-inch diameter cyclone was reviewed and approved as is. All open interface questions between GE and CW were either resolved or action items were assigned to the responsible party for further resolution.

Evaluation of quotations from prospective manufacturers for the PFB vessel and cyclone was completed and an award was made. The selected manufacturer was responsive without exception and delivery scheduled for 16 weeks after contract effective date which is October 28, 1981. Delivery is such to provide time for both hot and cold flow testing at GE's Corporate Research and Development Combustion Facility prior to shipment to Curtiss-Wright Corporation.

A meeting was held with the manufacturer of the electrode/feed through assembly to assure compatibility with the current design and quotations have been requested for this item plus a pressure vessel entrance bushing.

Negotiations are being conducted with the electrode manufacturer to assure that this component will not be a limiting item.

Figure 19. Interface Control