Operating Experience with a Flooded Disc Scrubber - a New Variable Throat Orifice Contactor

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Fundamental concepts in the theory and design of the flooded disc scrubber - a new variable throat orifice contactor are presented. Test data from laboratory, pilot plant, and full scale operations on lime kiln, electric furnace, open hearth, blast furnace, and basic oxygen furnace applications are presented and compared with available data on other scrubbers. Conclusions are that performance on a given problem is primarily a function of power input - thus supporting the correlation concept of Semrau - and that little scale-up factor exists in utilizing pilot plant data in the design of full scale systems.

The flooded disc scrubber is a new variable throat orifice contactor - cyclonic demister which is now operating in some 15 plants and contracted for in some 15 additional plants throughout the United States. Flow capacity of these installations range from approximately 9000 ACFM (actual cubic feet per minute) to over 200,000 ACFM, and some have been in operation for over four years. Yet no comprehensive treatment of either the basic concepts utilized in the design, or the operating characteristics of this device in actual practice, has appeared in the literature. It is the purpose of this paper to review these basic concepts and to present, for the first time, the performance parameters obtained in a number of tests of pilot and full scale installations.

Description of the Flooded Disc Scrubber

The basic configuration of the scrubber system is shown in Fig. 1. It consists of two principal parts: the flooded disc contactor and a demister. The demister shown is of conventional cyclonic design; however, other types of demisters have been used particularly in cases where packed towers are utilized for sensible cooling. Hot, dirty gases enter the contractor section at A, pass down to impact on the flooded disc at B, and are forced through the annular orifice where they are accelerated to velocities in the order of 100 to 400 fps. Scrubber liquor enters at point C, passes upward through the center disc support column, impinges on the liquor distribution cone, and is distributed radially across the face of the disc. The scrubbing liquor, as it passes off the periphery of the disc, is atomized by the shearing action of the high velocity gas stream passing through the annular orifice. Because of the large gas-liquid interface formed by the atomization of the liquor, the gases are quickly saturated. Thus, a system of suspended contaminant particulates, liquor droplets, and saturated gas (all in highly turbulent flow) exists in and immediately downstream of the annular orifice. Collection of the contaminant particles by the liquor droplets is achieved primarily by inertial impaction with the turbulent eddies providing the relative velocity, or driving force. The liquor droplets, which are fairly large (on the order of 50 to 150 microns) are then separated from the gases by simple inertial demisters such as the cyclonic type shown. Collected material in the demister sump may be, and often is, recirculated back to the contactor, thus limiting liquor make-up requirement to that required to replace evaporation losses or limiting the solids content of the recirculated slurries to levels where they can be conveniently handled without excessive operational problems.
Vertical movement of the disc in the converging throat provides a means for varying the area of the annulus over rather broad ranges. This allows flexibility with respect to both maintenance of a fixed system pressure drop under varying process rate conditions or changing objectives with regard to desired cleaning efficiency. Actuation of the vertical motion is accomplished by suitable hydraulic drives which are either manually or automatically controlled.

Fundamental Concepts in the Design

Work by Lapple and Kamack[1] on a number of contacting devices in which energy dissipation took the form of gas pressure drop suggested that the dominant factor in contact efficiency between primary aerosol particles and target droplets was turbulence. Additional work by Semrau[2] further indicated contact efficiency could be correlated with total energy input regardless of the source of energy (i.e., gas pressure drop, hydraulic spray nozzles, mechanical agitators) and that all energy inputs could be expressed in terms of equivalent gas pressure drop. Continuing observations of the relationship of power input and efficiency as cited by Semrau[3] have led to the almost universal acceptance of the power input concept as a means for correlating scrubber performance provided one implicit assumption is met: that scrubbing liquor exists in regions of energy dissipation in quantities sufficient to provide adequate collision cross section for primary aerosol particulates. Our own laboratory experiments further

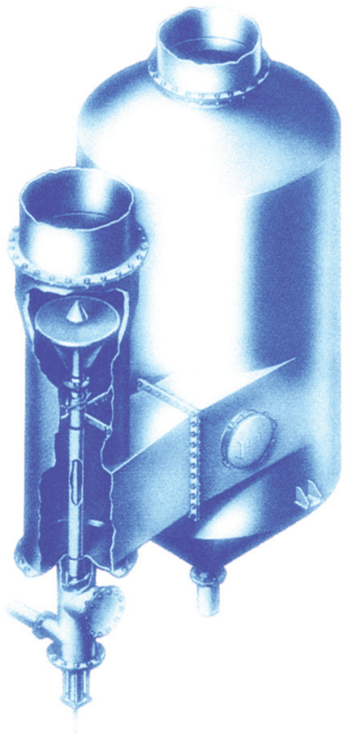

Figure 1. General configuration of flooded disc scrubber with cyclonic demister.

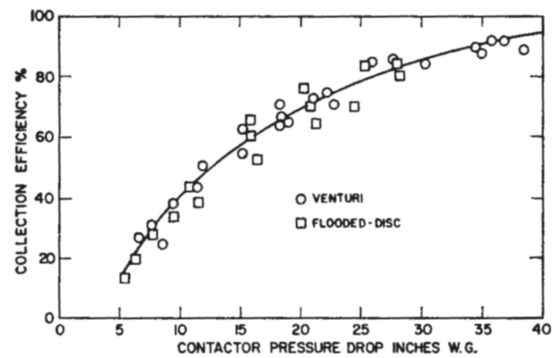

Figure 2. Comparative laboratory scale performance data on 0.7 micron mean diameter oil fume - venturi throat and flooded disc contactors.

confirm this concept as related to the flooded disc contactor. Figure 2 shows comparative data obtained in laboratory scale experiments with a venturi nozzle contactor and a flooded disc contactor. The data were obtained using an 0.7μ mass median diameter oil fume in air. Oil fume was generated using the techniques described by Anderson.[4] Efficiency measurements were made using light scattering techniques as described by Knudsen and White.[5] Data were taken over a range of throat velocities of 150 to 350 fps and liquid to gas ratios from 3 to 25 gallons/1000 ACF (actual cubic foot). The results clearly indicate the independence of the power input (pressure drop) efficiency relationship from contactor configuration, throat velocity, and liquid-to-gas ratio.

Semrau[3] has proposed the following convenient relationships for correlation of scrubber efficiency in terms of energy dissipation:

$$E = 1 - e^{-N_t}$$

$$N_t = a P_t^{\,y}$$

where:

E = fractional efficiency of collection
e = naperian base
N_t = number of transfer units
a = empirical constant depending on aerosol properties
y = empirical constant depending on aerosol properties
P_t = contacting power (energy input per volume gas)

The foregoing empirical approach to correlation of scrubber performance and operating variables is not inconsistent with the more fundamental approach of Johnstone, Field, and Tassler[6] on the basis of inertial impaction theory; for it can be shown that the power input theory can be derived from inertial impaction theory under the special case of a given aerosol-scrubbing liquor system.

The significance of the foregoing is that efficiency has little relation to scrubber design and geometry if coverage of the regions where energy is dissipated is adequate; the efficiency is dependent only upon aerosol characteristics and energy input. Thus, from an engineering point of view, the primary requisite for satisfactory scrubber design is the simplest device which will guarantee adequate energy dissipation or turbulence, adequate distribution of scrubbing liquor into turbulent regions, and operational flexibility and reliability.

The configuration of a coaxially mounted disc in a circular flue cross section seems to be uniquely suited to these criteria for a number of reasons:

1. It induces a high degree of turbulence. A disc in a pipe was first proposed by Stairmand[7] for generation of adequate mixing in circular ducts during dust sampling in gases. He found that such a disc, having an area approximately equal to the area of the annular opening, performed well in providing a representative sample of a circular cross section from measurement at a single point, thus suggesting a close approach to isotropic turbulence. The pressure drop coefficient (i.e., number of inlet velocity heads lost) of annular orifices is in the order of 25 to 30 compared to values in the order of 1 to 5 for venturi nozzles. *Because of these comparatively high pressure drop coefficients, energy consumption levels necessary for achievement of desired efficiency are obtained at lower throat velocities in annular orifices; further, energy consumption levels are not as sensitive to variations in liquid to gas ratios as nozzles or orifices with lower loss coefficients*.

2. It provides a simple means for scrubbing liquor injection in a manner which meets the critical requirement of adequate liquor distribution in the region of maximum energy dissipation. This comes about in two ways: (a) via the effect of gas pressure on the liquor film on the disc face; (b) via the inherently high aspect ratio of the annular orifice. At typical contactor pressure drops, in the range of 20 to 40 w.g., the force on the disc due to dynamic pressure is in the order of 0.75 to 1.50 lb/sq in. The effect on the liquor distribution on the upstream face of the disc is similar to that of heavy rain on the windshield of a vehicle driven at 40 to 70 mph. It is pressed out and delivered to the disc periphery in a film of uniform thickness.

At this point it is injected into the high-velocity gas stream and need only travel a very short distance to achieve complete coverage of the annular orifice. For example, in a typical case of treating 100,000 ACFM of gases at a pressure drop of 30 in., the width of the annulus is about 6 inches and the aspect ratio (i.e., length-to-width ratio) of the orifice is about 35. The unique distribution characteristics of the annular orifice, with liquor evenly introduced along its entire inside edge, is apparent when one considers that an equivalent rectangular orifice of the same width would have to be about 17 feet long; or that the diameter of a circular orifice of equivalent area would be about 38 inches and liquor introduced around the periphery, even if uniformly distributed, would have to traverse a distance of 19 inches to get complete coverage of the throat cross section.
Finally, when the disc is disposed in a converging flue section, small axial displacements of the disc cause large changes in the area of the annular orifice. For example, again in a 100,000 ACFM unit, an axial displacement of the disc of about 8 inches results in a change in annular orifice area of 50%. This provides a sensitive means for adjusting the system pressure drop to a fixed value under varying flow conditions and similarly provides a means for meeting changing objectives on desired collection efficiency without scrubber replacement.

Operating Experience

Operating experience with a number of pilot and full scale installations has generally confirmed the expectations of both the foregoing theory of operation and the unique features of the annular orifice with regard to water distribution and ease of control. Available data on the flooded disc and comparison with published data on other type contactors appears to support the power input concept. The data further indicate that there is little effect of scale-up from pilot to full scale with the flooded disc because of its water distribution capability. The pilot units had a nominal capacity of approximately 1000 ACFM at inlet gas conditions; gas takeoff nozzles were designed to provide isokinetic sampling conditions at the midpoint of the test range. Sampling techniques utilized in both pilot and full scale tests were in conformance with ASME Power Test Code 21 "Dust Separating Apparatus," and Power Test Code 27 "Determining Dust Concentration in a Gas Stream." The following presents a brief description of the operation and available test data on a number of applications.

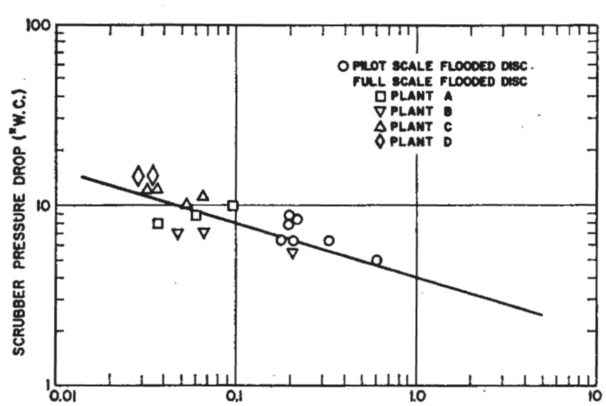

Figure 3. Pilot on full scale performance of flooded disc scrubber on rotary lime kiln.

Plant A 40 000 ACFM @ 400 °F nominal rating
Plant B 30 000 ACFM @ 550 °F nominal rating
Plant C 80 000 ACFM @ 500 °F nominal rating
Plant D 55 000 ACFM @ 600 °F nominal rating

Lime Kiln

Figure 3 presents performance data obtained on one pilot scale and four full scale installations of flooded disc scrubbers cleaning exhaust gases from rotary lime kilns used for calcination of limestone in the preparation of pulp mill cooking liquors. The full scale installations operate at capacities from 40 ()()() ACFM at 400 °F to 100 ()()() ACFM at 600 °F, and are equipped with discs ranging from approximately 3 to over 4.5 feet in diameter. Scrubbing liquors, which are recirculated lime slurries, vary from 3.5 to 5 gallons per 1000 ACF.

The good correlation of pilot and full scale performance is evident. It also appears that, .on the basis of the good correlation of data from a number of full scale plants, scrubber operating conditions on lime kilns do not vary materially from plant to plant.

Electric Furnace

Much of the initial work with emission control of electric furnaces utilized canopy type hoods and fabric filters. However, with the development of the snorkle systems of furnace evacuation, which replaces the canopy hood, wet scrubbers have become the preferred method of gas cleaning. This has resulted from a number of factors:

1. The snorkle system greatly reduces the volume of gases necessary to satisfactorily vent the furnace.
2. The reduction in gas volume results in a considerable increase in exhaust gas temperature. Use of scrubbers, which are relatively insensitive to temperature fluctuations, eliminate the need for sophisticated gas cooling systems which would be required with fabric filters to protect the fabrics from over-temperature as well as fouling from over-spray.

Table 1. Outlet Concentration Achieved on Electric Furnace Scrubber Installations

Description of Installation	Ref.	Pressure (in. wg.)	Inlet Conc. (gr/SCF)	Outlet Conc. (gr/SCF)	Eff.
Plant A Flooded Disc Oxygen blow 4 tests	-- -- --	-- -- 45	-- -- 10.5	Max. 0.035 Min. 0.013 Avg. 0.026	-- -- 99.76
Plant A Flooded Disc Total heat 1 test	--	45	--	0.019	--
Plant B Flooded Disc Total heat 2 tests	-- -- --	-- -- 40	-- -- --	Max. 0.009 Min. 0.003 Avg. 0.006	-- -- --
Venturi Scrubber Oxygen blow 2 tests	-- -- (9)	-- -- 28	-- -- 0.48	Max. 0.040 Min. 0.017 Avg. 0.029	-- -- 94.0
Total Heat 1 test	(9)	28	--	0.016	--

3. The use of scrubbers, particularly variable capacity types, provide a means for maintaining constant cleaning efficiency over the wide fluctuations of furnace draft requirements and temperature which are normal in these operations.

At the present time, there is insufficient data available to establish a power input-performance relationship on electric furnace operations. However, outlet loadings achieved on two full scale flooded disc scrubber installations over a limited range of operating pressure drops give an orientation to the capabilities of this type of equipment. These are shown in Table 1. Plant A was designed to operate at a desired pressure drop of 38 to 50 in. wg, at a water rate of 10 gallons/1000 ACF over an extreme range of volume-temperature conditions from 22000 ACFM at 100 °F to over 200 000 ACFM at 600 °F. It is equipped with a 6.5 foot diameter disc. Actual operation covers a range of liquid to gas ratios of 10 to 60 gallons/ 1000 ACF, since the installation is not equipped with automatic water rate control.

Plant B is designed to clean 20 000 ACFM at 170 °F at a pressure drop of 40 to 45 in. wg. It is equipped with a 2.5 foot diameter disc and operates at liquid-to-gas ratios of 10 gallons/1000 ACF. .

Data of Pettit9 on a 60 000 ACFM venturi scrubber operated at a liquid to gas ratio of approximately 10 gallons/ 1000 ACF are shown in Table I for comparison.

While the available data do not allow precise comparisons, they do indicate that outlet concentrations in the order of 0.02 to 0.03 grains per SCFD (Standard cubic foot dry, 60 °F and 29.92 in. Hg) are attainable at pressure drops in the range of 28 to 45 inches water gage regardless of the type of contactor. Examination of the extreme difference in inlet concentrations further suggests the pressure drop required for a desired outlet concentration is more a function of inlet concentration than contactor type.

Open Hearth

Operating experience with the flooded disc scrubber on open hearth gas is limited to pilot scale tests. Figure 4 shows results obtained in 1964 on an open hearth furnace during oxygen blow periods of the heat.' Inlet loadings in the pilot tests ranged from 3.75 gr/ SCFD to 9.90 gr/SCFD with an average of 6.10 gr/SCFD. Shown for comparison are data on a pilot venturi scrubber reported by Basse10 over a complete heat, and performance of a full scale venturi scrubber on a 200 ton furnace as reported by Bishop.11

Here again, although the inevitable scatter of data due to operating variables is evident, the correlation of performance of inertial

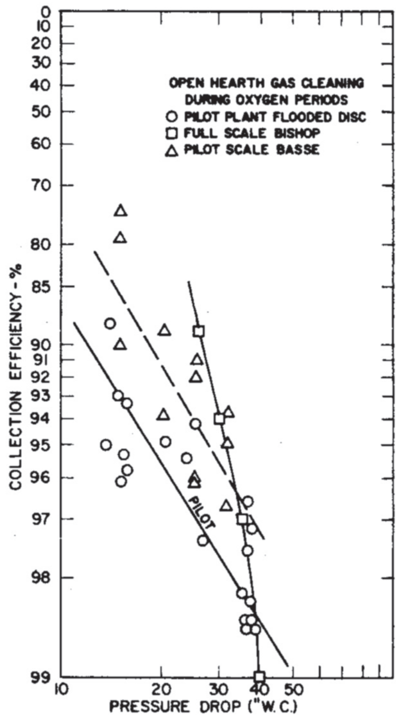

Figure 4. Performance of pilot flooded disc scrubber on oxygen lanced open hearth furnace

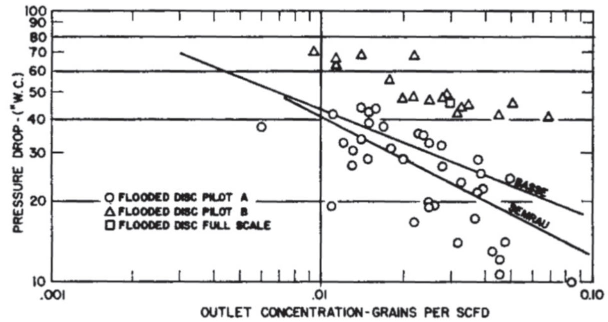

Figure 6. Performance of pilot flooded disc scrubber on basic oxygen furnace.

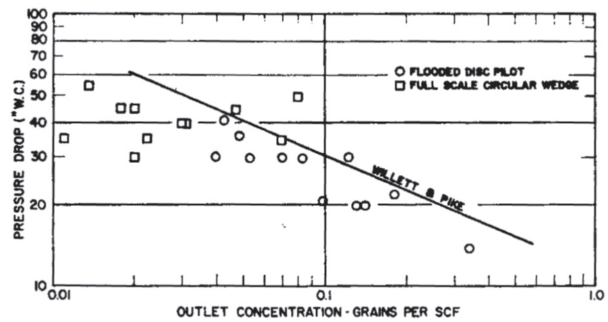

Figure 5. Performance of pilot and full scale flooded disc scrubbers on blast furnace gal

impaction scrubbers on a given application, regardless of the scale or particular design of the contacting device, is apparent.

Blast Furnace

Figure 5 shows performance of two pilot flooded disc scrubbers and one full scale flooded disc contactor operating on blast furnace gas. Data for pilot plant A were obtained with a number of flooded disc contactor configurations on an 800 ton furnace. Inlet concentrations ranged from 0.51 to 3.88 gr/SCFD (60 °F and 29.92 in. Hg) with an average of 2.68 gr/SCFD. Water rates ranged from 2.1 to over 30 gal/1000 ACF with an average of 9.85 gal/1000 ACF.

Data for pilot plant B were obtained on a single flooded disc scrubber of type shown in Figure 1. Inlet concentrations ranged from 1.98 to 7.40 gr/SCFD with an average of 4.35 gr/SCFD. Water rates ranged from 4.5 to 14.9 gal/1000 ACF with an average of 8.0 gal/1000 ACF.

Full scale data were obtained on a unit operating on approximately 120 000 ACFM at 267 °F at 45 in. wg pressure drop. It consists of a 4 ft. - 4 in. diam. disc contactor with automatic control located in the gas main ahead of the primary blast furnace gas washer and thus utilizes the washer as a demister.

Shown for comparison are the data of Basse[10] on both pilot and full scale venturi blast furnace scrubbers and the correlation of Semrau."

Basic Oxygen Furnace

Figure 6 presents pilot data obtained on a conventional ~D Basic Oxygen vessel operated at 230-250 tons/hr on a 60 to 70% hot metal charge. Inlet loadings to the pilot unit ranged from 1.54 to 2.31 gr/SCFD with an average of 1.98 gr/SCFD. Water rates ranged from 3.4 to 12.2 gal/1000 ACF with an average of 7.8 gal/1000 ACF.

Shown for comparison are data obtained on a full scale circular wedge contactor which has been described.[12] Average conditions under which outlet concentrations were determined were as follows:

Gas volume	208,000 to 335,000 ACFM
Gas temperature	420 °F
Inlet concentration	3.68 gr./ SCFD

Also shown is the performance curve for full scale venturi scrubber installations on basic oxygen furnace according to Willett and Pike.[13]

Summary and Conclusions

On the basis of both laboratory tests under controlled conditions and field tests on a variety of applications, it has been shown that the performance of the flooded disc scrubber, a new variable throat orifice contactor, is equivalent in performance to other types of inertial impaction scrubbers - as predicted by both the inertial impaction and energy input theories of particulate scrubbing.

It is further evident, from the correlation of pilot and full scale scrubber operations on given applications, that there is little, if any, scale-up factor required in the application of pilot scale data to full scale design. However, in applications where there is a high degree of variation in process conditions, care must be taken to execute pilot plant tests over the entire range of the process variables or under conditions closely simulating anticipated full scale conditions.

References

1. Lapple, C. E. and Kamack, H. J., "Performance of wet dust scrubbers," Chem. Eng. Prog., 110-121 (Mar. 1955).
2. Semrau, K. T., Marynowski, C. W., Lunde, K. E., and Lapple, C. E., "Influence of Power Input on Efficiency of Dust Scrubbers," Ind. Eng. Chem., 50: (11), 1615-1620 (Nov. 1958).
3. Semrau, K. T., "Correlation of dust scrubber efficiency," J. Air Poll. Cont. Assoc., 10: (3), 200-207 (June 1960).
4. Wendell, Anderson, Naval Res. Lab., Wash., D. C., Private Communication.
5. Knudsen, H. W., and White, L.,
Naval Res. Lab. Rpt P-2642 (1946).
6. Johnstone, H. F., Field, R. E., and Tassler, M. C., "Gas absorption and aerosol collection in a venturi atomizer" Ind. Eng. Chem. 46: (8), 16011608 (Aug. 1954).
7. Stairmand, C. J., "The sampling of dust-laden gases" Trane. Inetn. Chem. Engr. (British) 29: 15-44 (1951).
8. Bintzer, W. W., "Design and operation of a fume and dust collection system for two 100-ton," Iron Steel Eng. (Feb. 1964).
9. Pettit, G. A., "Electric Furnace Dust Control System," Air Poll. Cont. Assoc., Paper 63-32 56th Ann. Mtg. APCA, Detroit, Mich. (June 9-13, 1963).
10. Basse, B., "Gases cleaned by the use of scrubbers" Blast Furn. Steel Plant (Nov 1956).
11. Bishop, C. A., Campbell, W. W., Hunter, D. L., and Lightner, M. W., "Successful cleaning of open hearth exhaust gas with a high energy venturi scrubber," J. Air Poll. Cont. Assoc. 11: (2),83-87 (Feb. 1961).
12. "Adjustable circular wedge scrubber on market in compact unit," Iron Steel Eng. (Dec. 1963).
13. Willett, H. P., and Pike, D. E., "The venturi scrubber for cleaning oxygen steel process gases," I rem Steel Eng. (July 1961).