BIOMASS GASIFICATION COOLING CLEANING SYSTEM

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If the gas is to be used in a burner application, an updraft gasifier can be used, and no cleanup will be needed. However, if the fuel gas will be fed to an engine, then a downdraft or other tar cracking gasifier must be used; and the gas must be cleaned and conditioned before it is fed to the engine.

The gas emerging from a downdraft gasifier is usually hot and laden with dust, containing up to 1 % tars and particulates. If these materials are not removed properly, they can cause maintenance, repair, and reliability problems much more costly and troublesome than operation of the gasifier itself. In fact, it is likely that more gasifier engine systems have failed because of improper cleanup systems than for any other cause. In particular, the gas is very dirty during startup and should be burned at the gasifier until the system is fully operational.

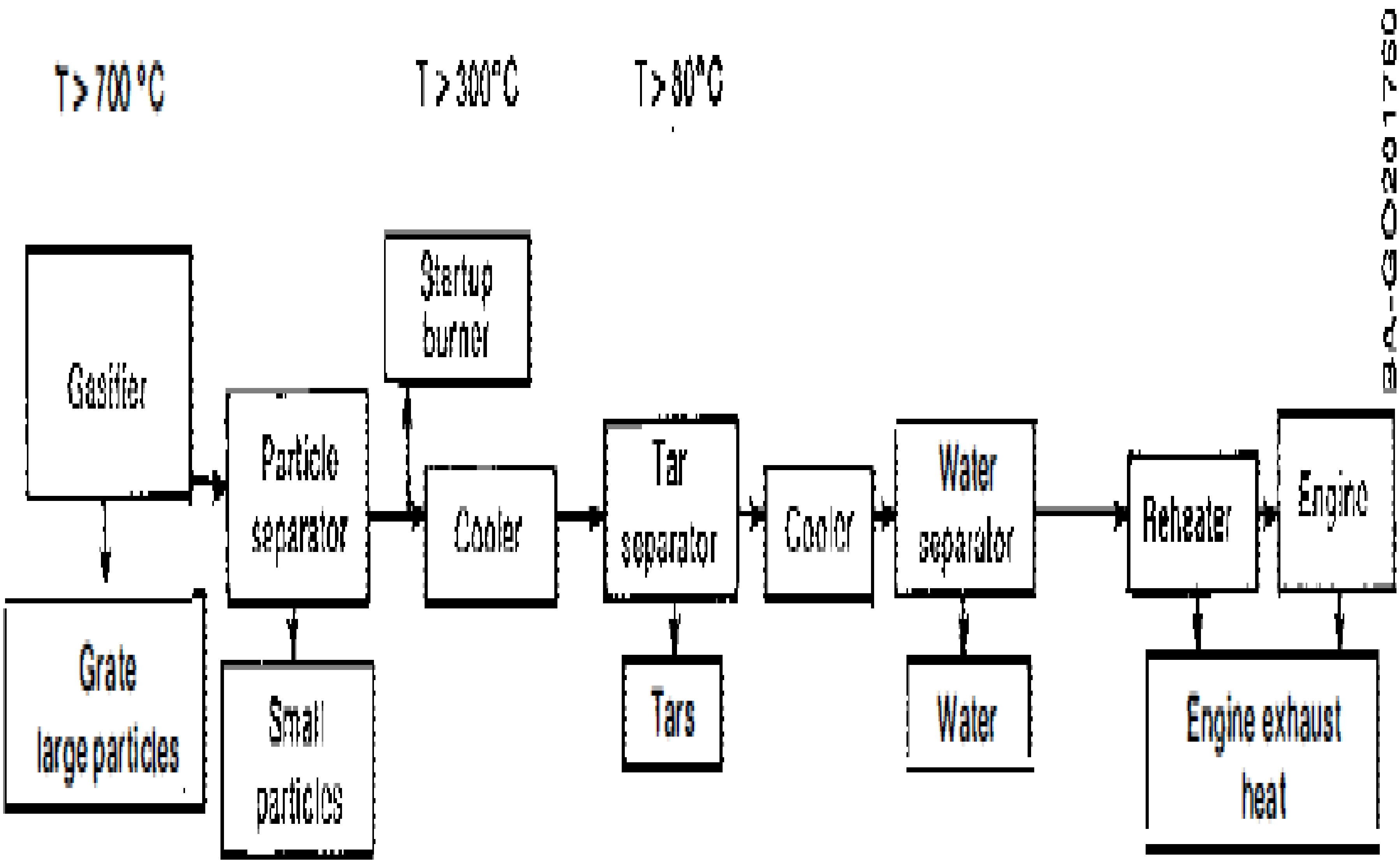
In order to design effective gas cleanup systems, one must determine the magnitude, size, and nature of the contaminants, and then couple that information with knowledge of methods available for their removal. This chapter presents the principles of gas cleanup, the available types of separation equipment and their respective capabilities and suitability, and some approaches for overall cleanup systems.

The basic cleanup system design strategy should be based on the required cleanliness goals (determined by the application], the order of removal, temperature, and the intended deposit site for collected materials. In addition, size, weight, cost, reliability, the need for exotic materials, water consumption, effluents disposal, the time between cleaning cycles, and the ease of equipment servicing must be considered.

The first step toward producing clean gas is to choose a gasifier design that minimizes production of tars and particulates to be removed, such as a downdraft or other low-tar gasifier, and to make sure that the gasifier is operated in a manner that will minimize particulate production by proper sizing. Development of cleaner gasifiers is proceeding in the United States and Europe at a good pace.

The next step, which simplifies the handling of captured contaminants, is to remove particulates, tars, and water in the proper order and at the right temperature. If the gas is immediately cooled and quenched in one operation, then char, tars, and water all are removed at one location to form a sticky, tarry mess. Ifparticulates are removed first at a temperature above the dewpoint of the tars (-300°C), tars are removed next at intermediate temperatures (above 100°e), and water is removed last at 30°-60°C, then each separated contaminant can be handled much more easily. The relation between gas temperature and each operation is shown in Fig. below .

Schematic relationship of gas temperature to contaminant removal



The final step of effective gas cleanup is to wisely choose a site for depositing the collected materials. Devices can be classified as either "in-line" or "offline." In-line devices, such as fabric bags and packed fiber filters, cut off the gas flow as they become filled with the tar or particulate material that they have captured. The pressure drop across the cleanup system steadily rises with the accumulation of captured materials, requiring frequent or automatic cleaning or replacement. Collection efficiency is low for a clean, in-line filter but climbs steadily with the increasing pressure drop as the filter becomes plugged. Collection efficiency measurements of in-line filters should clearly indicate loading effects or be averaged over a full cleaning cycle in order to be meaningful.

Off-line devices, such as cyclone separators, wet scrubbers, and electrostatic precipitators, deposit captured materials outside of the flow path. These devices separate the contaminants into one stream and the gas into another stream. The pressure drops and efficiencies associated with these devices are predictable and independent of the amount of captured materials, eliminating the slow buildup of pressure drop with use. Off-line methods are preferable in applications where they can be used.

Gas Cleanup Goals

- Gas Contaminant Characteristics

  Gas cleanup goals should be based on the degree of contamination, the size, distribution, and nature of the contaminants, as well as the degree of cleanliness required by the equipment. Both solid and liquid contaminants are present in producer gas. The solids are char, ash, and soot, and they cover a wide range of sizes. The liquid is initially a fine mist or fog composed of droplets smaller than 1 μm,, but the droplets agglomerate to increase in size as the gas cools.

- Typical Dirty Gas

  A typical specification for dirty gas might be 100 mg/Nm^3 of particulates with mean diameter d_{50}= 100 μm, a geometric standard deviation $\sigma_g = 3.5$, and tar contamination of 1000 mg/Nm^3.

The solids can be quite abrasive, and the tar mist can cause the inlet valves, rings, throttle shafts, and other moving parts to stick. Therefore, both contaminants must be thoroughly removed for reliable engine operation. Successful gasifier-engine systems have required gas cleanliness standards from 10 mg/Nm^3 to less than 1 mg/Nm^3.

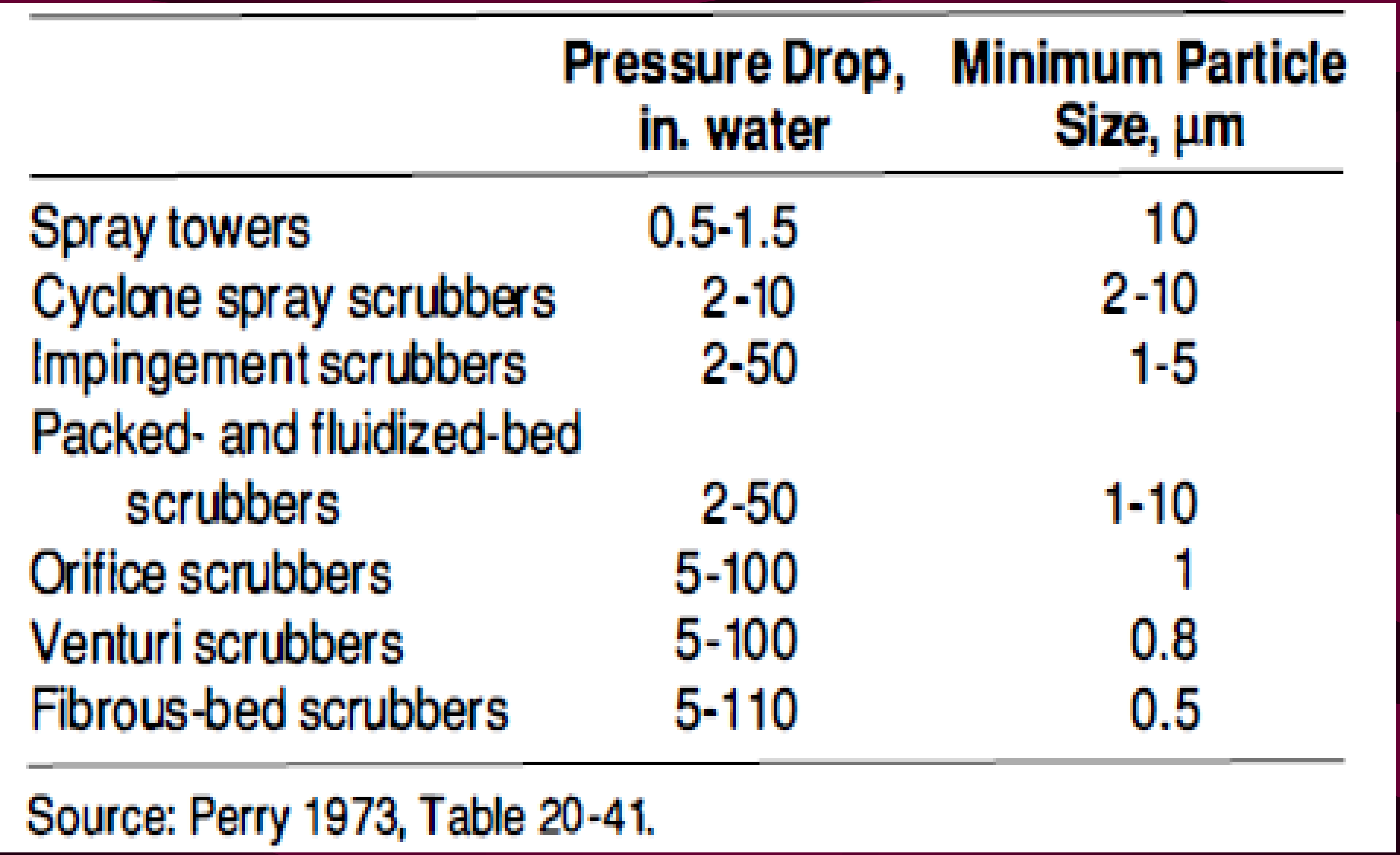
Many gasifiers can produce very clean tar-free gas under certain conditions. However, it is best to design the gas cleanup system with adequate capability for the very dirty gas that is occasionally produced by every gasifier, especially during startup, idling, and when wet fuel is used.

- Cleanup Design Target

  Requirements for solid-particle removal jIlay be determined from knowledge of average particle diameter $d_{p'}$and the worst-case char-ash dust content (C_d)' This information can be gathered using isokinetic sampling techuiques to collect a representative sample of all particle sizes. If celmax represents the maximum permissible dust level for engine use, then the maximum permissible dust penetration α is given by

$$\alpha = C_{dmax} \times 100\% / C_{dmeasured}$$

Minimum Particle Size for Various Types of Scrubbers



	Pressure Drop, in. water	Minimum Particle Size, µm
Spray towers	0.5-1.5	10
Cyclone spray scrubbers	2-10	2-10
Impingement scrubbers	2-50	1-5
Packed- and fluidized-bed scrubbers	2-50	1-10
Orifice scrubbers	5-100	1
Venturi scrubbers	5-100	0.8
Fibrous-bed scrubbers	5-110	0.5

Source: Perry 1973, Table 20-41.

Classification of Particles

- Solid particles with diameters greater than 1 μm are called **dust**, and those with diameters below 1 μm are referred to as **fume**. Liquid droplets over 10 μm in diameter are called **spray**, and droplets with diameters below 10 μm are called **mist**. **Aerosols** are solids or liquids suspended in a gas (Calvert 1972).
- **Dispersion aerosols** are materials that begin as large particles and subsequently are broken into smaller sizes. They tend to be coarse with a wide size-range, composed of irregular particles and aggregates (i.e., char-ash dust). **Condensation aerosols** are formed from supersaturated vapors, such as tar and water mist from chemical reactions, and soot formed from cracked hydrocarbon molecules. They tend to be very fine and of uniform size.

Dry Collectors

Gravity Settling Chambers

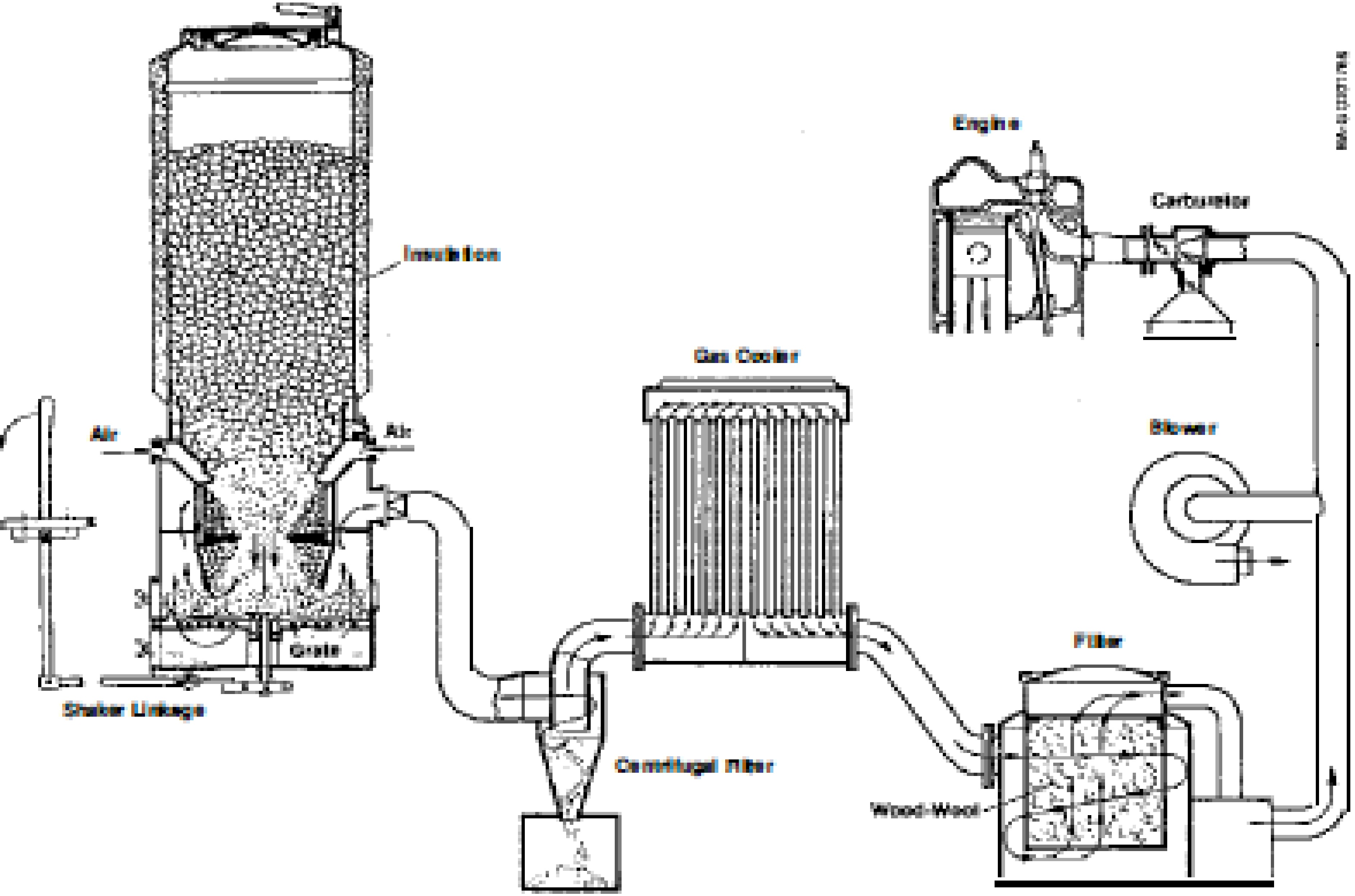
As long as unlimited space and materials are provided, a gravity settling chamber theoretically can achieve any level of particle separation down to the Stokes' limit of about 1 µm. In fact, many of the earliest gasworks used gigantic settling chambers. However, even though it is effective, this method tends to be a bit cumbersome.

Cyclone Separators

Cyclones are simple and inexpensive dust and droplet separators; they are widely used on gasifiers and will be discussed in extra detail in this section.

Hot gas cyclone separators are well suited to remove solid particles larger than 10 µm as a prefilter for the gas cooler and fine particle removal, as shown in Fig. below, for a vehicle gasifier of the 1939-1945 era.

Typical vehicle gasifier system showing cyclone and gas cooler



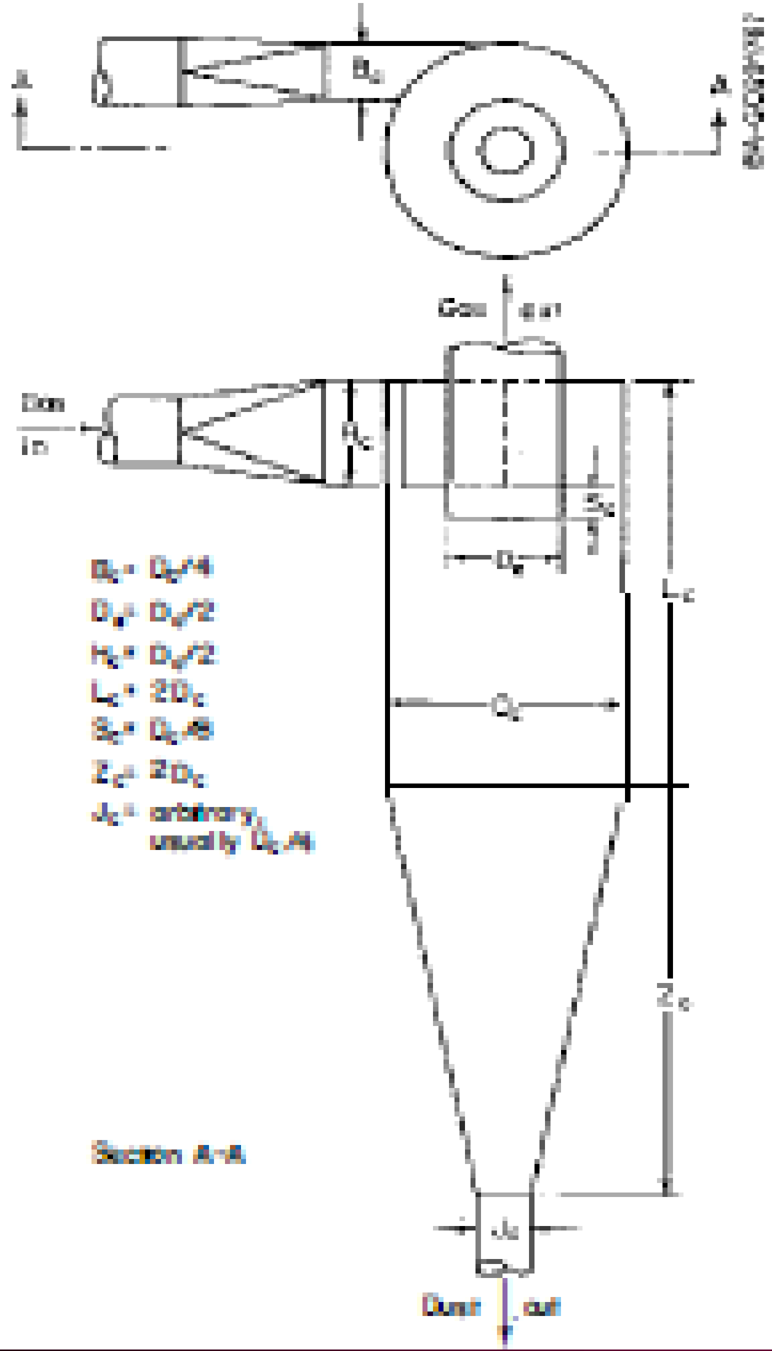
Cyclone Operating Principles

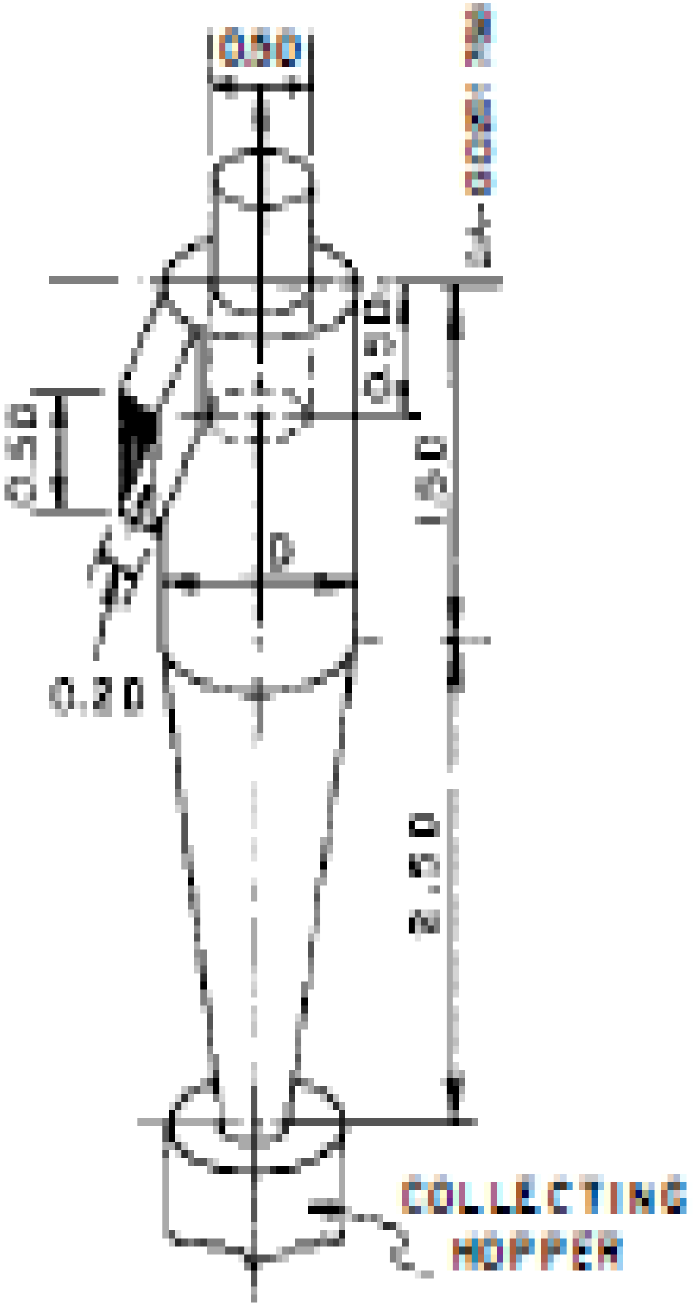
A cyclone separator imparts a rotary motion to the gases and thereby enhances the settling rate to many times that induced by gravity alone. A cyclone separator is essentially a gravitational separator that has been enhanced by a centrifugal force component. The cyclone separator grade efficiency curve, applies to all cyclone separators, as well as to inertial and gravitational collectors.

Cyclone performance is rated in terms of particle cut diameter or cut size. The cut size, dp50, is the particle size which is captured 50%.

The relationship between particle cut diameters for this type separator is given by below, where is the particle diameter and the numerical subscript the collection efficiency of that size particle.

$$d_{p50} = (1/2)\ d_{p80} = (1/3)\ d_{p90} = (1/4)\ d_{p95}$$


A
A
B_c
Gas out
Gas in
H_c
S_c
D_e
L_c
D_c
Z_c
J_c
Dust out
$B_c = D_c/4$
$D_e = D_c/2$
$H_c = D_c/2$
$L_c = 2D_c$
$S_c = D_c/8$
$Z_c = 2D_c$
J_c = arbitrary, usually $D_c/4$
Section A-A


0.5D
0.5D
0.5D
1.5D
D
0.2D
2.5D
COLLECTING HOPPER

Baghouse Filter

Principle of Baghouse Filters

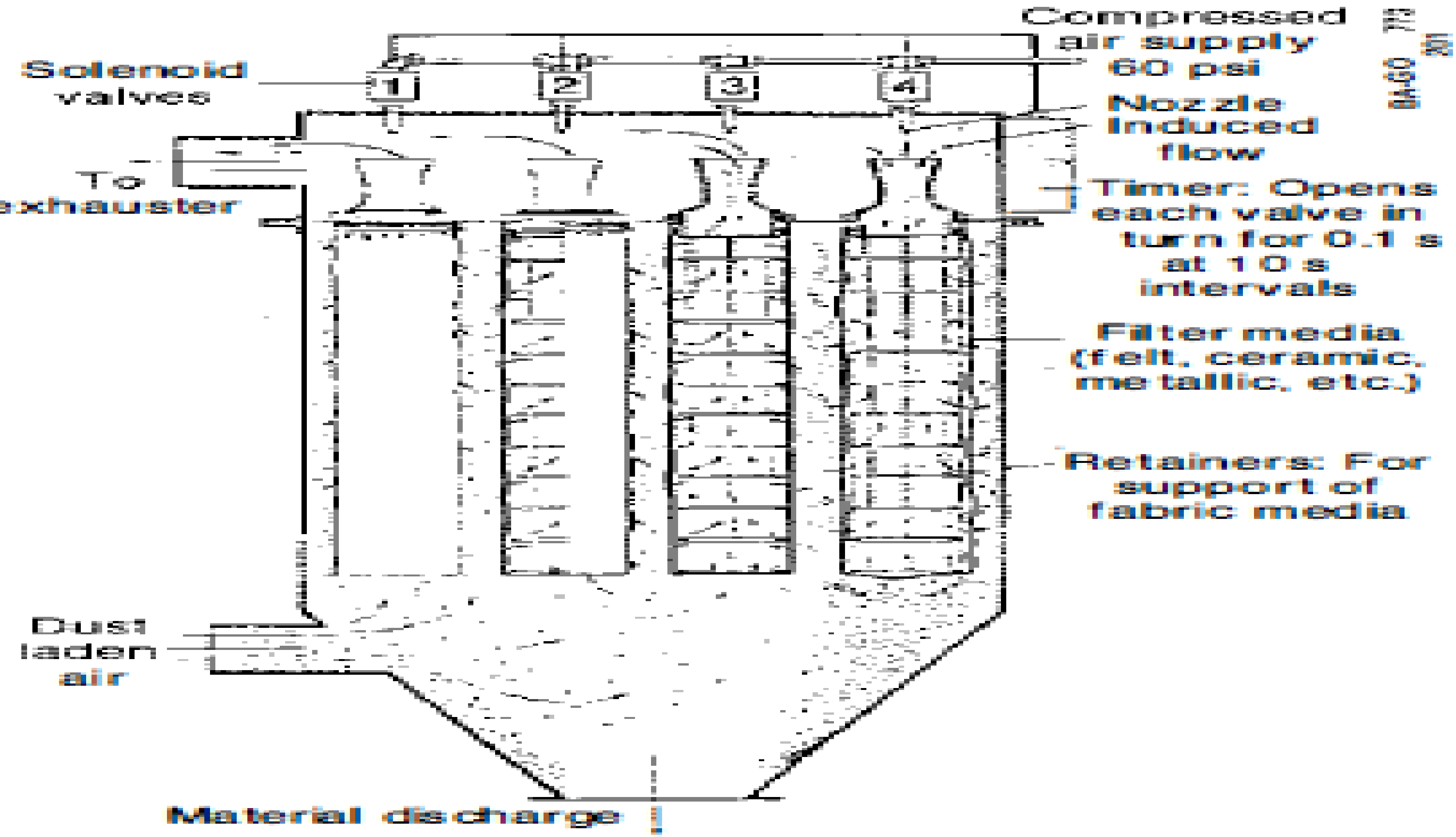
Baghouse filters are used widely today to capture fine dust particles and to separate flyash from combustion gases. A baghouse filter consists of one or more fibrous filter bags supported on metal cages enclosed in a chamber through which the gases must pass, A deposit of the separated particles soon builds up on the bag and establishes a dust cake of appropriate pore size through which additional particles cannot pass. As more dust is accumulated, the pressure drop increases. When the cake is an optimal thickness for removal, the bag is agitated either by gas pressure or by mechanical means, causing the excess cake to drop to the bottom of the housing where it is eventually removed.

Action of the Filter Cake in the Operation of Fabric Filters

Fibrous bag filters have been found to be outstanding in the removal of particles down to submicron sizes. High-efficiency capture of small particles is surprisingly independent of the size of openings in the filter weave, The reason for this is that the primary capture element is the dynamic cake that forms on the filter surface. This cake, which consists of captured particles, presents a circuitous path that effectively captures fine particles, while coarser captured particles maintain an open cake structure to promote high gas permeability, When a new filter fabric is inserted, the main mechanism of particle collection is physical sizing as determined by the openings in the weave. At first, small particles may pass uncaptured until some buildup accumulates on the filter. From this point on, the gas must effectively pass through a packed bed of micrometer-sized particles. Interception and impaction then emerge as significant collection mechanisms

Application of Baghouse Filters

- Baghouse filters have been used with good success in many of the more successful and reliable engine gasifier systems . The use of fabric filters has virtually eliminated the corrosive ash that otherwise was present in condensate or scrub water. The fabric filter is no doubt the most efficient device for fine cleaning; but for wood gas. extensive precautions against condensation of tar or water are necessary.
- During operation. the previously described filter cake grows steadily in thickness. collection efficiency climbs. and the pressure drop across the filter rises. When the filter cake has reached optimal thickness for removal. the filter cake must be removed by one of the following methods: momentary flow reversal to collapse the bag and dislodge the cake as shown in Fig. Below. a pulse jet of compressed gas or air to create the momentary bag collapse. or dismantling and manually shaking the bag (Breag 1982).



Note: This schematic is intended to describe function and is not necessarily typical of actual construction

Cloth bag filter with intermittent reverse pulse cleaning

Electrostatic (Cottrell) Precipitators

Electrostatic precipitators have a long history of industrial use to produce exceptionally clean gas. During operation. the gas passes through a chamber containing a central high-voltage (1030 kV) negative electrode. A corona discharge forms around the central electrode. which imparts a negative charge to all particles and droplets. The negatively charged particles then migrate to the positive electrode. which may be washed by a continuous water stream to remove these particles. The electrostatic precipitator is effective for all drop and particle sizes.

A small precipitator (20 cm in diameter and 1 m in length) was operated at SERI to clean gas produced by a 75-hp Hesselman gas generator powering a 15-kW electric generator. The initial results were very dramatic. and the tar mist at the flare could be seen to disappear instantaneously when the voltage was applied. However. the electrodes and insulators soon became coated with soot and tar. and formed a short-circuit path that supported an arc. A means for cleaning the electrodes must be provided. along with a means to warm the insulators to prevent a water-condensation short-circuit. These problems are being investigated.

The precipitator tube diameter should be small enough to allow the corona discharge to be established at a reasonable voltage and large enough so that its volume will provide the necessary residence time with a reasonable length. Low flow rates result in a higher residence time and higher collection efficiency.

Wet Scrubbers

Principles of Wet Scrubbers

As we have previously stated, particles with diameters larger than 1 µm settle by gravity and inertia. They follow Stokes' law and can be captured by impaction, gravitational. or centrifugal means. For particles smaller than 0.1 µm, motion is dominated by molecular collisions. They follow Brownian motion principles, behave more like a gas, and may be collected by diffusion onto a liquid surface. In this section we will look at the basic mechanisms of particle movement and capture for wet scrubber systems.

Particles with diameters between 0.1 and 1 /µm fall within the so-called "open window." They are the most difficult particles to capture, either by diffusion or inertial mechanisms. They are too large to diffuse well but too small to settle. However, they can be made to grow in size, since small particles collide naturally and agglomerate into larger particles that are easier to capture.

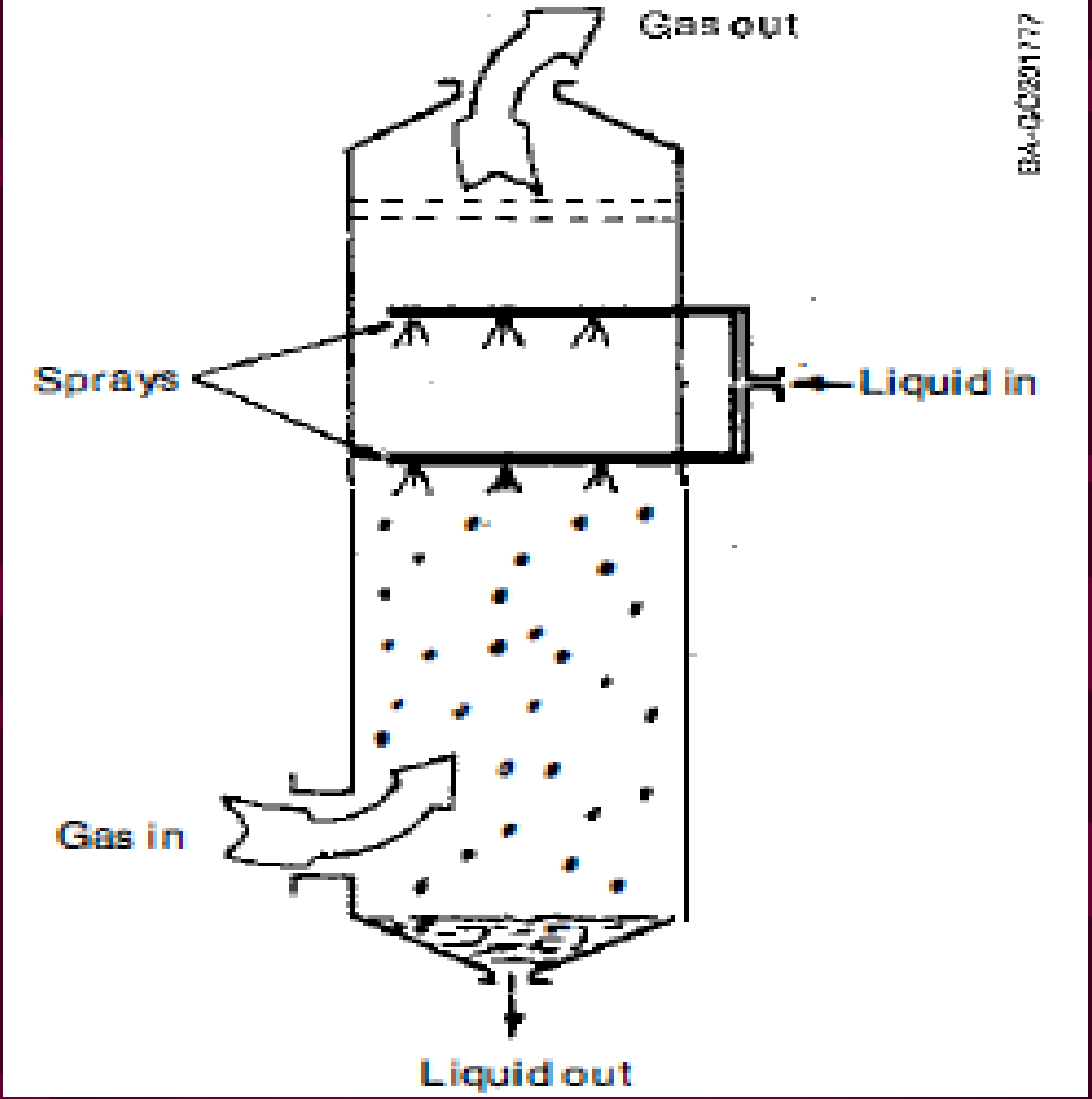
One method of high-efficiency collection uses primary collection of large particles by inertia and diffusion, followed by an increase in fine particle size by agglomeration, and finally by collection and entrainment separation. The rate of agglomeration is proportional to the total number of particles present. Agglomeration is also assisted by the presence of droplets that act as nuclei.

Particles tend to move toward a surface on which condensation is taking place. This phenomenon is referred to as "Stefan motion." Particles tend to migrate away from a hot surface and toward a cold surface. This phenomenon is called "thermophoresis."

Wetted particles tend to stick together better when they collide. thereby assisting agglomeration. Wet scrubbers have been used widely. especially in stationary applications for cleaning and cooling the gas. A scrubber operates by creating conditions for maximum contact between the gas to be cleaned and a scrubbing liquid medium.

Scrubber Equipment

- Spray Towers
- The simplest type of scrubber is the spray tower , which is composed of an empty cylinder with spray nozzles. The optimum spray droplet size is 500 to 1000 µm. Typical upward superficial gas velocity for a gravity spray tower is 2 to 4 ft/s, and particle collection is accomplished when particles rising with the gas stream impact with droplets falling through the chamber at their terminal settling velocity. The spray tower is especially well-suited as a prefilter for extremely heavy dust loads (over 50 g/Nm^3), which would plug other less-open types of scrubbers. Fullcone spray nozzles produce 500 to 1000 µm droplets, which fall with a settling velocity of13 ft/s. For a spray tower 53 ft high, the value of d_{50} is 5 µm.



Spray tower scrubber

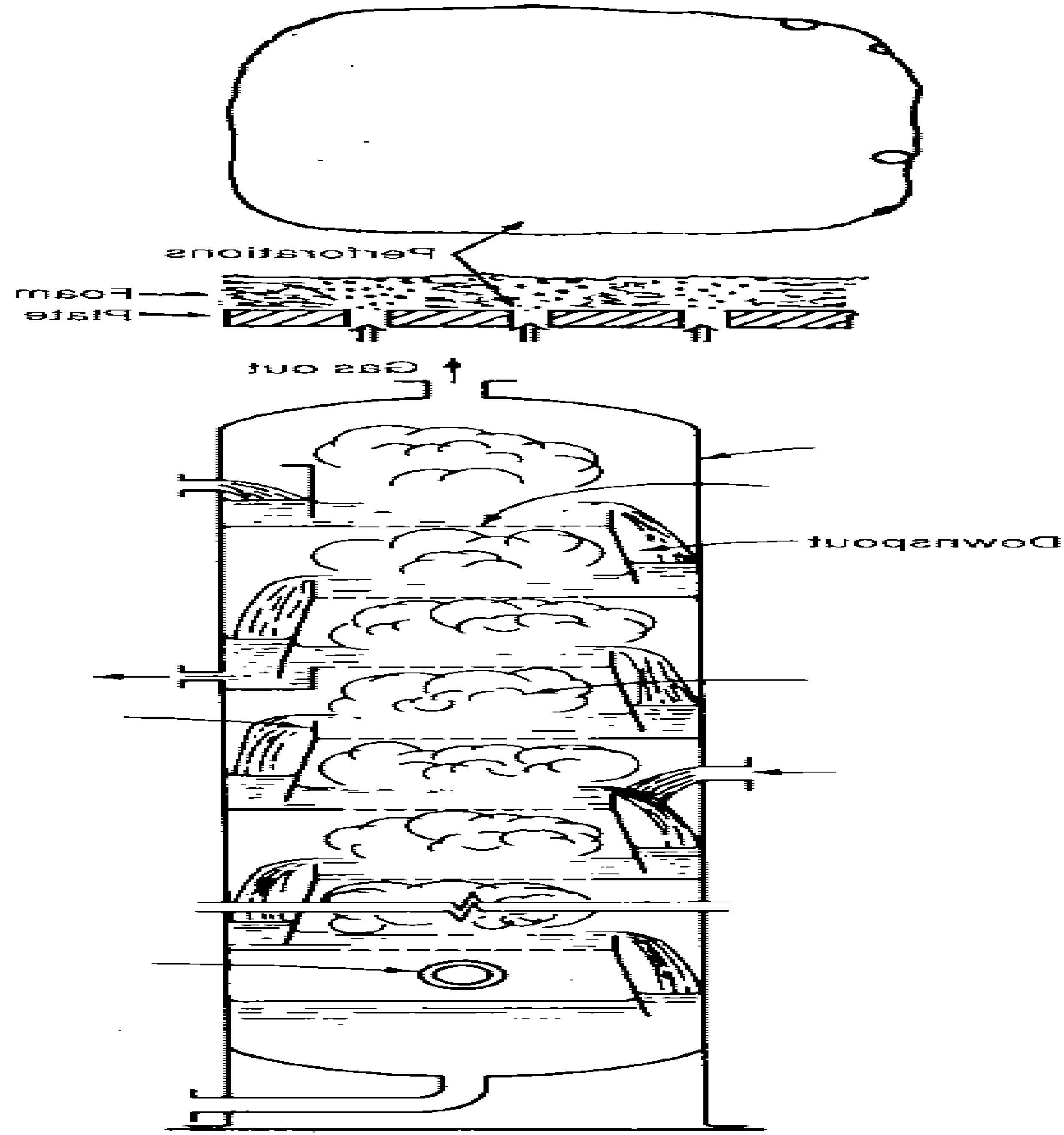
Cyclone Spray Scrubbers

The cyclone spray scrubber combines the virtues of the spray tower and dry cyclone separator. It improves the particle-capture efficiency of the spray droplets in ordinary spray scrubbers by increasing spray-droplet impact. The cyclone spray scrubber also has the advantage, compared with the spray scrubber, of being self cleaning, of collecting more particles regardless of size, and operating at smaller pressure drops. Commercial cyclone scrubbers are better than 97% efficient at removing particles with diameters greater than 1 μm. The cut diameter for a cyclone spray scrubber is about an order of magnitude less than that for either a dry cyclone or spray scrubber.

Sieve-Plate Scrubbers

A sieve-plate scrubber consists of a vertical tower with a series of horizontal perforated sieve plates. The scrubbing liquid is fed into the top of the column and flows downward via down comers from plate to plate; the gas to be scrubbed is introduced at the bottom of the column and passes upward through the sieve holes counter to the liquid. Contact between the liquid and gas is enhanced by using plates with bubble caps, impingement plates, or sieve plates.

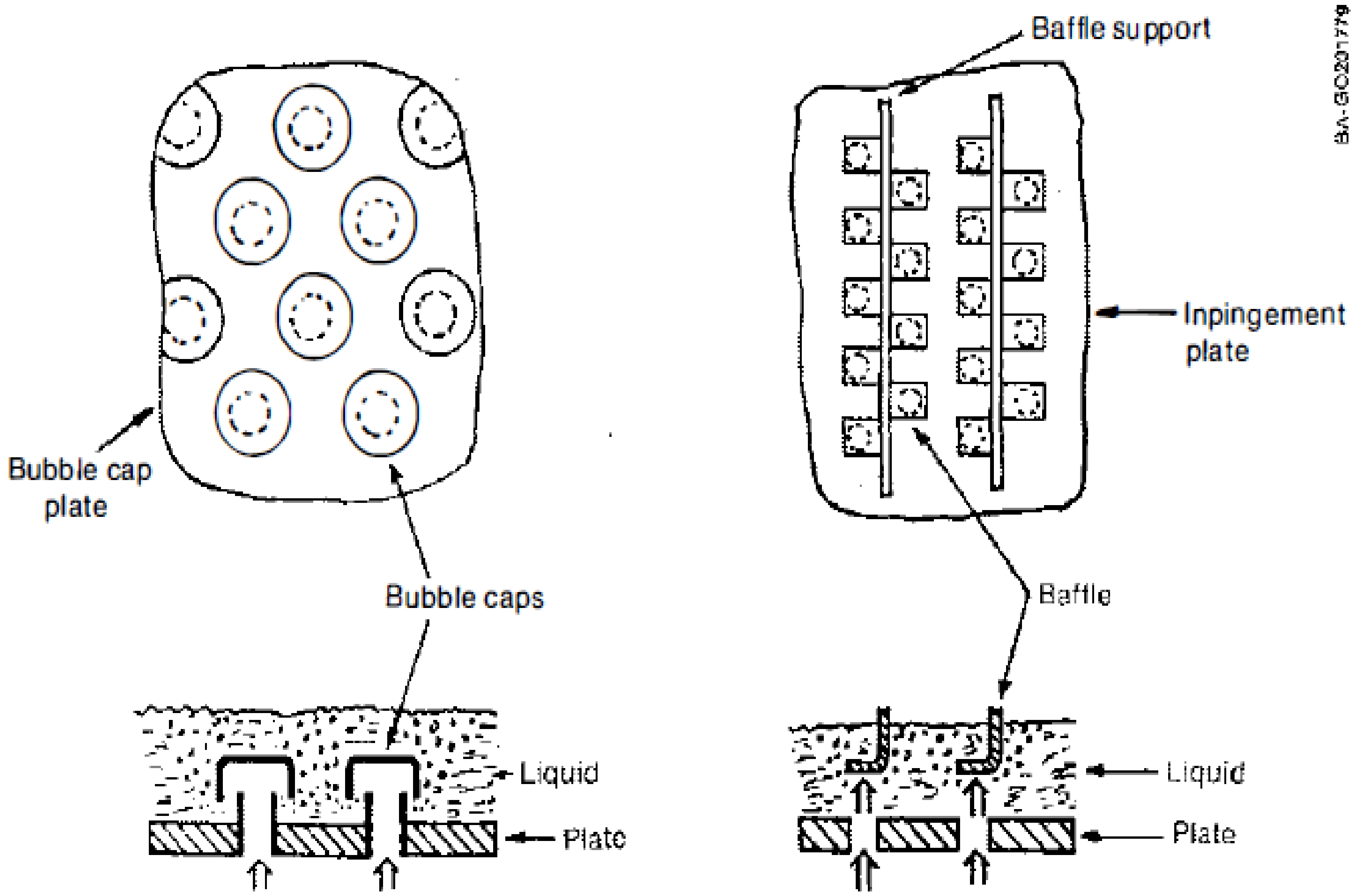
The sieve-plate scrubber captures large particles by impingement and impaction, and small particles by diffusion. Gas passes upward into the water layer through holes in the sieve plate. The high gas velocity through the sieve holes atomizes the scrubber liquid into fine droplets, and most inertial particle collection takes place just as the bubble is being formed, by impaction on the inner surface of the bubble. Diffusive particle collection dominates as the bubble rises. Here, surface active agents can reduce the collection efficiency because of Stefan motion. but a cold water scrubbing liquid receiving a hot aerosol increases the collection efficiency. A deeper foam reduces inertial effects and increases collection by diffusion. Inertial collection is only slightly increased by adding plates or increasing the pressure drop. A typical sieve-plate scrubber can attain 90% efficiency for 1μm particles using 3/16-in. sieve holes, at a specific velocity of 15 m/s (50 ft/s). Typical performance characteristics of sieve-plate scrubbers are discussed in Kaupp (1984a).



Sieve plate scrubber

Impingement Plate Scrubbers

The impingement-plate scrubber shown in Fig. below is similar to a sieve-plate scrubber, except impingement plates are arranged so that each hole has an impingement target one hole diameter away from the hole. Gas flow past the edge of the orifice produces spray droplets that, when formed, are at rest, resulting in a large relative velocity between dust particles and these droplets. The gas velocity usually is above 15 m/s (50 ft/s), and the typical operating pressure drop is 1.5 in. water gauge (4 mbar) per plate. An increased pressure drop raises the collection efficiency. The required water flow rate is 1 to 2 gpm per 1000 cfm of gas flow.



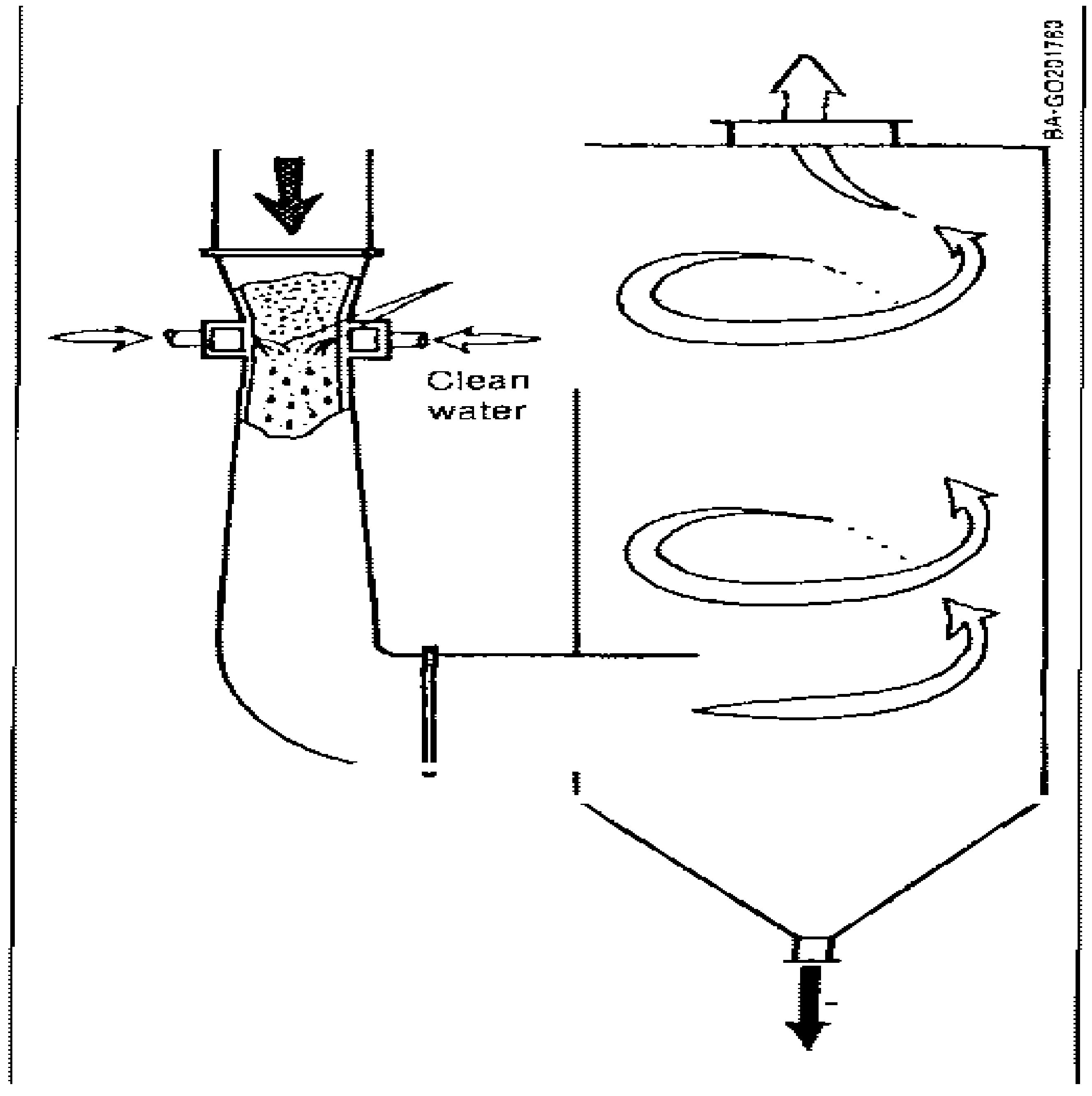
Impingement plate scrubber

Venturi Scrubbers

The Venturi scrubber captures largeparticles by impaction and impingement, and also rinses away any deposits that might otherwise form. Some fine particles are also captured here by diffusion. High-velocity flow through the low-pressure throat area atomizes the droplets. The low pressure at the throat causes condensation, and the high relative velocity of the droplets with respect to the gas captures most larger particles by impaction.

The atomized droplets present a considerable surface area for fine particles to be captured by diffusion. Furthermore, condensation in the throat improves capture through diffusion because ofthe phenomenon ofStefan motion. The atomized droplets rapidly agglomerate in the diffuser section, where collection through diffusion continues, Entrained droplets containing captured contaminants are separated inertially from the cleaned gas. Liquid recycle requires cooling and removal of captured materials, or disposal and replenishment.

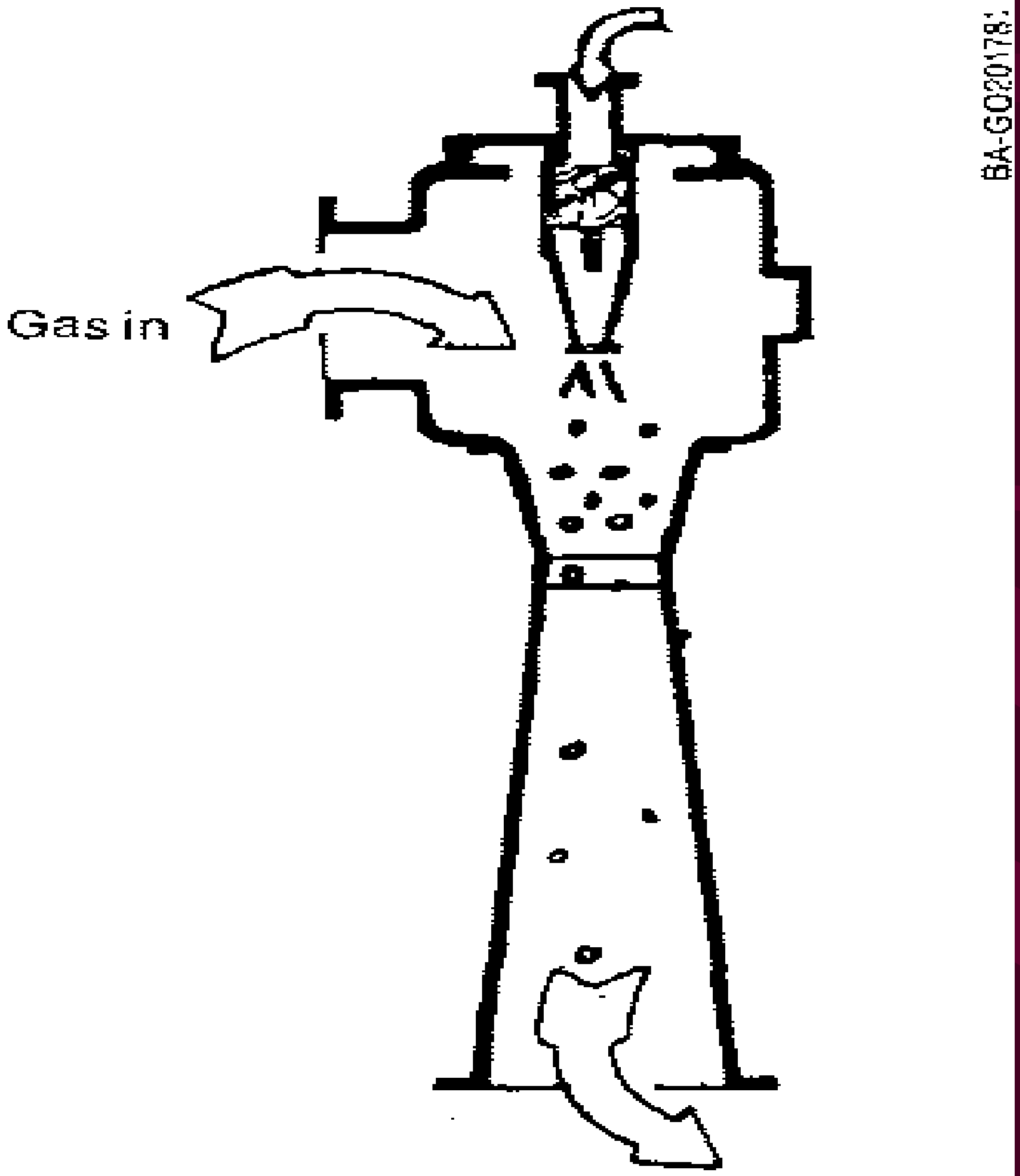
The collection efficiency and droplet size are determined by the pressure drop: efficiencies may be increasedby reducing the throat area to raise the pressure drop. The efficiencies of Venturi scrubbers are discussed in Calvert (1972).



Venturi scrubber with centrifugal entrainment separator

Ejector Venturi Scrubbers

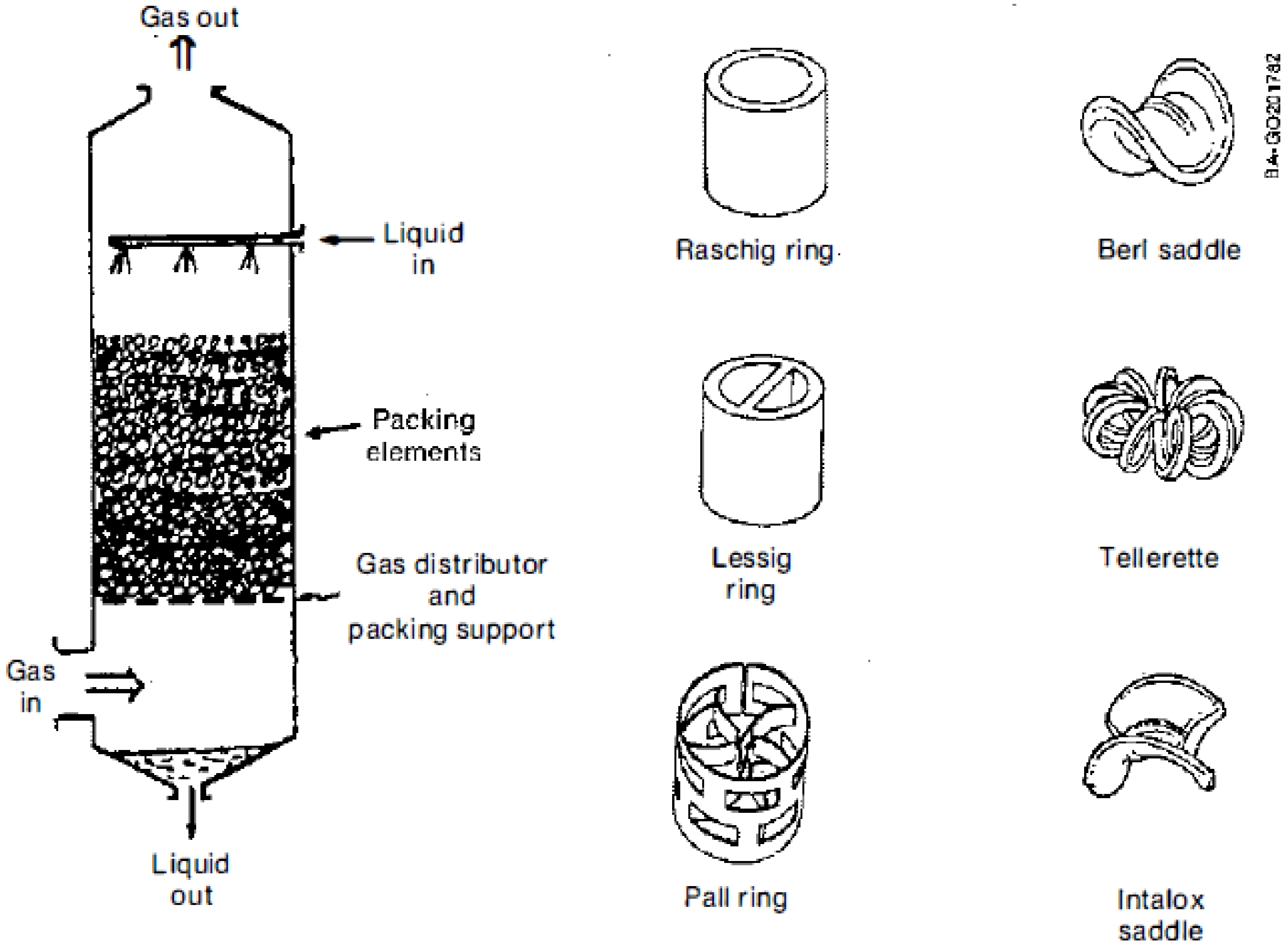
The velocity of the contacting liquid both pumps and scrubs the entrained gas in an ejector Venturi scrubber, as shown in below. Spiral spray nozzles impart axial and tangential velocities to the liquid jet. The contacting liquid must be removed after the scrubber by a suitable entrainment separator. Compared to a Venturi scrubber, the ejector Venturi scrubber requires both more liquid and more power to achieve the same particle collection and gas movement. Ejector Venturi scrubbers have no moving parts and are especially well-suited for very dirty, corrosive, or abrasive materials that might otherwise damage a blower impeller



Ejector Venturi Scrubbers

Packed-Bed Scrubbers

The packed-bed scrubber is simple and open in design, and uses spheres, rings, or saddles as random packings to enhance the gas-liquid contact area. Packed beds are more effective for both gas absorption and liquid-gas heat exchange than they are for particle collection. However, packed beds are excellent for capturing entrained liquids. For entrainment separation, the optimum superficial gas velocity for packed-bed scrubbers using 1/2-in. spheres is 10 to 12 ft/s. Flooding and re-entrainment occur above a gas velocity of 12 ft/s. The pressure drop is 7.5 to 8.5 in. water gauge for a 6-in.-deep bed. Packed beds are free-draining; they may be irrigated to remove accumulations with a water flow (Calvert 1972).



Packed tower and packings

Entrainment Separators

Entrained liquids from the wet scrubber must be thoroughly removed from the gas stream because they carry a slurry of captured materials. Entrainment droplets are typically greater than 10 μm and may be captured using a variety of techniques, including a packed bed, a packed fiber bed, a cyclone separator, an impingement separator, a spray tower, or a settling chamber. Poor entrainment separation has been a corn- man problem for wet scrubbers in gasifier systems. Gas contaminant testing is advisable for all unproven designs.

THANK YOU