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PARTICULATE REMOVAL FROM GAS STREAMS AT HIGH TEMPERATURE/HIGH PRESSURE

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PARTICULATE REMOVAL FROM GAS STREAMS AT HIGH TEMPERATURE/HIGH PRESSURE

by

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ABSTRACT

An evaluation of methods of removing particulate matter from high temperature and/or high pressure gas streams is presented. Available theoretical and experimental information indicates that in many instances the effectiveness of collection and agglomeration mechanisms decreases with increases in temperature and pressure. Control equipment and systems which offer promise for application to particulate cleanup under high temperature and/or high pressure conditions are discussed. All potential systems reviewed require considerable development before they can be reliably used under the conditions of interest.

ACKNOWLEDGEMENTS

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Approved for:

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for H. M. Hubbard, Director
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GLOSSARY OF TERMS, ABBREVIATIONS, AND SYMBOLS

B = magnetic field strength

$\bar{c}$ = mean thermal speed of gas molecules

C = Cunningham correction factor

D = cyclone diameter

D^* = diffusion coefficient

D_c = diameter of collecting body

D_p = particle diameter

E = electric field strength

e = elementary unit of charge

F = force

g = gravitational constant

G = gravitational parameter = v_s/v_o

J = sound intensity

k_g = thermal conductivity of the gas

k_p = thermal conductivity of the gas

K = Boltzmann constant

K_n = Knudsen number

K_o = thermal agglomeration coefficient

m_i = mass of molecules of component i

M = molecular weight

n_i = number of molecules of component i per unit volume

N = ion concentration

P = pressure

P_e = Peclet number

q_p = electrostatic charge on particle

q_f = electrostatic charge on collector per unit area

r_p = particle radius

r = radius of rotation

R = gas constant

R_i = interception parameter

R_e = Reynolds number

T = temperature

t = time

v_{p-g} = particle velocity relative to gas

v_{p-c} = particle velocity relative to collector

v_T = thermophoretic velocity (particle)

v_D = diffusiophoretic velocity (particle)

v_m = particle terminal drift velocity in magnetic field

v_o = particle velocity (freestream)

v_s = particle settling velocity

v_e = particle migration velocity in electric field

v_{tp} = tangetial velocity of particle

v_g = linear gas velocity

z_i = ion mobility

β = coagulation constant

ε = rate of dissipation of turbulent energy

ϵ_p = dielectric constant of particle

ϵ_f = dielectric constant of gas

ϵ_o = permittivity of free space

λ = mean free path of gas

λ_o = internal scale of turbulence

Φ = particle mobility

η = collection efficiency

ν = kinematic viscosity

ρ_p = particle density

ρ = density of gas

μ = gas viscosity

ψ = coagulation rate

ω = angular velocity

SUMMARY

The objective of this task was to critically review and evaluate available literature on methods of removing particulate matter from high temperature and/or high pressure gas streams. The study was subdivided into three major areas of work: (a) literature search; (b) theoretical assessment of the effect of temperature and pressure on particulate collection and agglomeration mechanisms; and (c) identification of promising technology for this application.

The literature survey revealed very little theoretical or experimental work conducted in the past on effects of high temperature and/or high pressure on gas cleaning. Some recent application experiments have been conducted on pilot-scale hardware or components for elevated temperature/pressure systems, but considerable development is required before any system is commercially available.

Since the literature contained such limited information, a review of theoretical models of aerosol collection and agglomeration mechanisms was conducted in order to determine the influence on these mechanisms due to elevated temperature and pressure. Table 1 presents a synopsis of the results of the theoretical assessment. In many instances the effectiveness of collection and agglomeration mechanisms decreases with increases in temperature and pressure. The influence of temperature and pressure is closely related to aerosol particle size for many mechanisms because of the term C/μ ,* which is a fundamental part of many of the equations describing aerosol collection and agglomeration. In general, increases in temperature and pressure will decrease the effectiveness of the operative mechanisms for particles greater than 0.5 μm in diameter.

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* C = Cunningham slip correction factor.
μ = gas viscosity.

Table 1. SUMMARY OF INFLUENCE OF TEMPERATURE AND PRESSURE ON AEROSOL COLLECTION AND AGGLOMERATION MECHANISMS

Aerosol collection or agglomeration mechanism	Characteristic parameter	Temperature and pressure dependence of characteristic parameter	Trend with elevated temperature and/or pressure
A. Aerodynamic capture			
1. Inertial impaction	$STK = \frac{C \rho_p D_p^2 v_o}{9 \mu D_c}$	See Figures 1 and 2	Inertial impaction efficiency is reduced. Decrease can be quite significant for ≤ 1 μm particles.
2. Interception	$R_i = D_p/D_c$	None	Generally unaffected by any variation not a function of particle size.
3. Diffusion	$Pe = \frac{3\pi\mu D_p D_c v_o}{KTC}$	Dependence is dictated by term μ/TC and is somewhat complex.	Principal effect is for small particles with net result being a decrease in efficiency.
4. Electrostatic attraction	$K_I = \frac{2}{3}\left(\frac{\epsilon_p - \epsilon_f}{\epsilon_p + 2\epsilon_f}\right)\left(\frac{C D_p^2 q_f^2}{\epsilon_o \mu v_{p-c} D_c}\right)$	Dependence is dictated by ratio C/μ .	Collection efficiency at high temperature and pressure is reduced for particles larger than 0.05 μm diameter.
	$K_E = \frac{C q_p q_f}{3\pi\mu \epsilon_o D_p v_{p-c}}$	Dependence is dictated by ratio C/μ .	
5. Gravitational settling	$G = v_s/v_o$	$G \sim \frac{1}{T}$	Collection efficiency will decrease with increase in temperature and pressure.
B. Centrifugal forces	$F_s/F_v \simeq C/\mu$	See Figures 4 and 5	Collection efficiency at high temperatures and pressures is reduced for particles larger than 0.1 μm diameter.
C. Flux forces			
1. Electrophoresis	$\psi = \frac{CqE}{3\pi \mu D_p}$	C/μ and q are either temperature and/or pressure dependent. Dependence of migration velocity, ψ , on temperature and pressure is complex.	Particle size has a strong influence on the impact of increases in temperature and pressure--especially in the 0.1 to 1.0 μm diameter.
2. Thermophoresis	$v_T = f[\lambda, \rho, \mu]$	Temperature and pressure dependence associated with gas mean free path, gas viscosity and gas density which influence thermophoretic velocity v_T .	Influence of temperature and pressure is associated with Knudsen number, $K_n = \lambda/r_p$. For $K_n \leq 0.1$, v_T is inversely proportional to pressure and directly proportional to $T^{0.6}$.

Table 1. (concluded)

Aerosol collection or agglomeration mechanism	Characteristic parameter	Temperature and pressure dependence of characteristic parameter	Trend with elevated temperature and/or pressure
3. Diffusiophoresis	$v_D = f[D, n]$	Temperature and pressure dependence is associated with diffusion coefficients which in turn vary directly with temperature and the ratio C/μ .	Influence of temperature and pressure is associated with Knudsen number, $K_n = \lambda/r_p$. For $K_n \leq 0.1$, v_D is directly proportional to temperature and the ratio C/μ .
4. Magnetic force	$v_m = \frac{Cn\ q\ vB}{3\pi\ \mu\ D_p}$	Temperature and pressure dependence associated with ratio of C/μ .	Collection efficiency at high temperature and pressure is reduced for particles larger than 0.1 µm diameter.
D. Particle agglomeration			
1. Thermal agglomeration	$K_o = 4\pi D r_p$.	Temperature and pressure dependence are associated with diffusion coefficient which varies directly with temperature and the ratio C/μ .	Net influence of temperature and pressure dependent upon particle size and relative increases in temperature and pressure.
2. Turbulent agglomeration	None	Temperature and pressure effects are associated with impact on kinematic viscosity and the turbulent microscale.	Net influences of temperature and pressure dependent upon relationship of particle size to interal scale of turbulence.
3. Charged particle agglomeration	k_{em}	Temperature and pressure dependence of correction factor k_{em} is complex. Under simplified conditions, k_{em} is roughly proportional to $T^{1/2}$.	--
4. Sonic agglomeration	$K_a = \frac{1}{\omega} \left(\frac{2J}{\rho C_g}\right)^{1/2}$	Temperature and pressure dependence is associated with gas density.	Agglomeration coefficient will increase with temperature and decrease with pressure.

The most promising approaches which should be explored for particle collection under high temperature and pressure conditions, based on the theoretical review, included: (a) centrifugal forces; (b) aerodynamic capture; and (c) electrostatic forces. Control equipment and systems for particulate collection were identified which utilize the promising mechanisms as a primary capture technique. Cyclones, special types of filter systems (e.g., gravel beds, metallic fibers), scrubbers which do not cool the gas stream (i.e., molten salt), and electrostatic precipitators are included in this category.

A review of the status of the above control devices for high temperature and/or pressure applications was conducted. Table 2 is a summary of these potential particulate removal systems under the conditions of interest. Also included in Table 2 is a relative ranking of the potential for sulfur removal, energy requirements, and potential operating problems.

Cyclones are proven devices for collection of large particles. The technology is well developed and application to high temperatures and pressures, while needing investigation, should pose a relatively simple task. The primary problem will be, as with all devices considered, utilization of materials that maintain structural integrity under elevated temperatures and pressures.

Gravel bed filters such as those under development by Squires and his co-workers as well as the metal fabric filter being developed by the Brunswick Corporation have the best potential for high temperature/pressure applications. Both offer high collection efficiency possibilities with the Squires and similar devices providing additional potential for sulfur removal.

Molten salt scrubbers, while offering potential for desulfurization as well, may have difficulties due to particle reentrainment. Structural problems with this device will probably be minimal, since special materials will be necessary in any event to contain the molten bath.

Electrostatic precipitators require considerable development, although probable low pressure drop is attractive. Materials of construction for precipitators poses the most severe potential problem of all the devices, since alignment of corona wires and plates or pipes, as well as their spatial relationships is unaffected by elevated pressures and high temperatures for uniform high performance.

All of the systems reviewed require considerable development before they can be reliably used. Confirmation by both bench-scale and pilot-scale experiments will be necessary to determine if the collection mechanisms identified actually function in the manner predicted. Proper materials of construction and energy tradeoffs will also need better definition.

Table 2. SUMMARY OF POTENTIAL PARTICULATE REMOVAL SYSTEMS

	System/Developer	Operating conditions Operated (°C/atm)	Operating conditions Projected (°C/atm)	Particulate removal efficiency for < 1 μm	Potential for sulfur removal	Energy penalty/ operating costs	Potential operating problems	Comments
I.	Cyclones	900/high	> 1100/high	Low	None	Low/moderate	Low	Relatively insensitive to variations in temperature and pressure. The cyclone technology is well developed.
	· Aerodyne Torando cyclone/ Aerodyne Development Corporation	500/30	900/30	Moderate	None	Moderate/high	Low/moderate	Secondary air requirements and performance at high temperature and pressure should be investigated.
	· Tan-Jet Cyclone/ Donaldson Company	300/1						
II.	Gravel bed filters	> 500/high	> 1100/20+	High	High	Moderate	Moderate	Relatively insensitive to fluctuations in temperature, pressure, particle size and gas composition. Theoretical and experimental studies are limited. Needs further study in bed material selection and cleanup.
	· Combustion Power	150/1						
	· Ducan	250/1						
	· Lurgi-MB-Filter	350/1						
	· Rexnord	500/1						
	· Squires, CCNY	550/1						
III.	Electrostatic precipitators	400/1	950/5+	High	None	Low	High	Sensitive to changes in temperature, pressure, and gas composition. Needs considerable developmental work before reliable unit can be developed. Materials of construction, alignment, and thermal creep of corona wires may cause problems.
IV.	Molten salt scrubbers	900/1	1100/5+	High	High	Moderate	Moderate	Particulate entrainment poses additional cleanup problems. The potential for particulate removal and desulfurization may be attractive in some applications.
	· Battelle Memorial Institute							
	· Rockwell International Corporation							
V.	Fabric filters	400/1	800/high	High	None	Low	Moderate	Needs considerable developmental work. Casing material, fabric life, removal of collected material and other fabric filtration problems have to be investigated.
	· Silica Fibers, J. P. Stevens Company	800/-						
	· Silica Fibers, 3M Company	1000/-						
	· Metal Fabrics, Brunswick Corporation	800/-						

INTRODUCTION

Concern about the world energy situation has fostered increased interest in the utilization of coal and coal-derived fuels. Research and development activities are underway on a variety of coal gasification and advanced power systems. Gasification systems in early stages of commercialization utilize raw fuel gas cooling followed by purification of the gases at moderate temperatures. Many of the proposed processes now under consideration which produce and/or utilize coal-derived fuels become economically nonviable if conventional low temperature techniques for gas cleaning have to be employed. Rather, the fuel gases must be cleaned at high temperatures and/or high pressures. Typical examples of these systems are:

- Coal gasification processes requiring sulfur and particulate removal at temperatures from 250 to 1250°C and pressures from 1 to 15 atm.

- Gas turbine systems utilizing fuels derived from coal, residual oil-firing, or municipal waste which may require particulate removal at temperatures of 1000 to 1250°C and pressure of 1 atm.

- Magnetohydrodynamic power systems requiring recovery of seeding material and/or removal of ash at temperatures from 500 to 1250°C at pressures around 1 atm.

Advantages which result from gas cleaning under high temperature and pressure include:

- The thermal efficiency of systems is higher.

- Capital costs are reduced by the elimination of gas cooling and reheating steps.

- Removal of primary particulate to meet specifications for gas turbine inlet conditions could minimize need for additional exhaust gas control equipment.*

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* Possible need for exhaust gas control measures to collect secondary particles or remove condensed gases or vapors downstream from the turbine may obviate this potential advantage.

The present study was undertaken for IERL-RTP to: (a) define the state of knowledge regarding the effect of high temperature and pressure on particulate collection and agglomeration mechanisms; (b) identify promising technology for this application; and (c) identify research and development needs.

The following sections of this report present the results of a literature search conducted as part of the study, a discussion of the effects of high temperature and pressure on particle collection and agglomeration mechanisms, a discussion of promising particulate control systems and a delineation of research and development needs.

LITERATURE SEARCH

An extensive literature search was conducted as the initial stage of this task. Various scientific abstracts, e.g., Chemical Abstracts and selected technical journals were surveyed for publications on methods of gas cleaning under high temperature and/or high pressures. Table 3 presents a list of abstracts and journals that were included in the survey.

The literature search revealed very little theoretical or experimental information on high temperature and/or high pressure gas cleaning, indicating a general lack of interest in this field in previous years. With the recent interest in coal gasification and advanced power cycles, there has been a surge of interest in this area and reports and papers are beginning to appear addressing the problem. Two recent reports prepared by Aerotherm Corporation[1/] and Stone and Webster Engineering Corporation[2/] present brief reviews of the state of the art of gas cleaning under high temperatures and pressures.

Since the literature contained limited information on the subject of interest, we next elected to conduct a review of the theoretical aspects of aerosol collection in order to determine the influence of high temperature and pressure on collection and agglomeration mechanisms. The results of the review might then be used to predict possible direction for development of technology for particulate collection under conditions of interest. The next section of the report discusses the review of collection mechanisms.

Table 3. MAJOR LITERATURE SOURCES REVIEWED IN TASK

Abstracts
Chemical Abstracts
Applied Science and Technology Index
Nuclear Science Abstracts
Journals
Environmental Science and Technology
Staub-Reinhalting der Luft (in English)
Aerosol Science
APCA Journal
Atmospheric Environment
Power
Filtration and Separation
Other
Mining Research Contract Reviews
Office of Coal Research Annual Reports

THEORETICAL ANALYSIS OF EFFECT OF TEMPERATURE AND PRESSURE ON PARTICLE COLLECTION AND AGGLOMERATION MECHANISMS

Particulate collection is effected by passing a gas stream through a system where particles are acted on by forces which remove them from the gas stream. To be effective, these forces must be sufficiently large to take the particles out of gas stream during its residence time in the system. If the particulates in the gas stream are submicrometer in size, their removal may be facilitated by agglomerating very small particles and then collecting the agglomerates.

The basic mechanisms or forces that can be used to collect or agglomerate particles are shown in Table 4. A considerable amount of information exists in the technical literature on each of these mechanisms and how they depend upon various parameters.[3,4,41,42] The effectiveness of individual mechanisms is dependent upon various properties of the particles, gas properties, and temperature and flow fields in the system.

High temperatures and pressures primarily influence gas properties such as density and viscosity. Since these gas properties in turn influence particulate collection mechanisms, high temperatures and pressures will exert some impact on particulate collection. In the following subsections, the changes in gas properties caused by high temperature and pressure are highlighted and the influence in changes in gas properties on particle collection mechanisms are delineated.

INFLUENCE OF HIGH TEMPERATURE AND PRESSURE ON GAS PROPERTIES

The main gas properties which are important in particulate collection and which are also influenced by temperature and pressure are density, viscosity, and mean free path of the gas molecules. Each of these properties and their dependence on temperature and pressure are discussed next.

Table 4. PARTICLE COLLECTION OR AGGLOMERATION FORCES (MECHANISMS)

I. Particle collection

   A. Aerodynamic capture

      1. Inertial impaction
      2. Interception
      3. Diffusion
      4. Electrostatic attraction
      5. Gravitational settling

   B. Centrifugal forces
   C. Flux forces

      1. Electrostatic forces
      2. Thermal forces
      3. Diffusion forces
      4. Magnetic forces

II. Agglomeration and/or particle growth

   A. Thermal or Brownian agglomeration
   B. Turbulent agglomeration
   C. Electrostatic agglomeration
   D. Sonic agglomeration
   E. Condensation

Gas Density

The density of a gas at normal temperatures and pressures can be calculated using the ideal gas law,

$$\frac{P}{\rho} = RT \qquad (1)$$

where P = absolute pressure

ρ = gas density

R = gas constant

T = absolute temperature

Under very high temperatures and pressures, real gases deviate from this law. Accurate calculation of gas properties can be made using the charts provided in Appendix A. For air at pressures below 40 atm and 1800°K, only a very small error is incurred in calculating the gas density by using Eq. (1).

Equation (1) can be written as:

$$\frac{\rho}{\rho_o} = \left(\frac{P}{P_o}\right)\left(\frac{T_o}{T}\right) \qquad (2)$$

where ρ_o , P_o and T_o represent base conditions (i.e., 300°K and 1 atm).

Table 5 shows how the quantity ρ/ρ_o for air varies with the temperature and pressure. For example, the density of air at 1300°K temperature and 10 atm pressure is 2.3 times that at room temperature and pressure (base condition).

Gas Viscosity

The viscosity of gases increases as the 0.6 power of the absolute temperature but is very weakly dependent on pressure. For air at pressures less than 20 atm and at temperatures greater than 300°K, dependence of viscosity on pressure can be safely neglected. The charts in Appendix A provide a means of calculating the gas viscosity at various pressures and temperatures. Table 6 gives the values of μ/μ_o for different temperatures. We see from the charts and Table 6 that the viscosity of air at 1300°K and 10 atm is 2.6 times that at 300°K temperature and 1 atm pressure.

Table 5. VARIATION OF GAS DENSITY WITH TEMPERATURE AND PRESSURE (density of air/density of air at 300°K and 1 atm)

Temperature (°K)	1 atm	4 atm	7 atm	10 atm	40 atm
300	1.0000	4.0035	7.0127	10.025	40.343
500	0.5996	2.3961	4.1892	5.978	23.650
700	0.4283	1.7112	2.9912	4.268	16.875
1000	0.2998	1.1981	2.0946	2.990	11.840
1300	0.2306	0.9218	1.6118	2.30	9.128
2000	0.1666	0.6659	1.1646	1.662	6.610

Table 6. VARIATION OF GAS VISCOSITY WITH TEMPERATURE AND PRESSURE (absolute viscosity of air/absolute viscosity of air at 300°K and 1-10 atm pressure)

Temperature (°K)	μ_o	μ/μ_o
300	1.83×10^{-4}	1
500	2.646×10^{-4}	1.4461
700	3.303×10^{-4}	1.8048
1000	4.116×10^{-4}	2.2491
1300	4.803×10^{-4}	2.6245
2000	5.777×10^{-4}	3.1571

Mean Free Path

The mean free path of gas molecules is related to the viscosity and the density of gas as shown in Eq. (3).

$$\lambda = \mu/0.499\ \rho\ \bar{c} \tag{3}$$

where λ = mean free path of the gas molecules

μ = viscosity of the gas

ρ = density of gas

$\bar{c}$ = mean thermal speed of gas molecules

The mean thermal speed of gas molecules is given by

$$\bar{c} = \left(\frac{8KT}{\pi M}\right)^{1/2} \tag{4}$$

where K = the Boltzman constant

M = molecular weight of the gas

Examination of Eqs. (3) and (4) indicates that the mean free path of air molecules is almost inversely proportional to the gas density. At 10 atm pressure and 1300°K temperature, mean free path of air molecules is 0.53 (about half) that at 1 atm pressure and 300°K temperature.

PARTICLE COLLECTION

The gas properties discussed in the preceding paragraphs form a part of several parameters which characterize the effectiveness of various particulate collection and agglomeration mechanisms (e.g., impaction parameter, interception parameter, Reynolds number). The impact of changes in gas properties on these parameters, and thus on particulate collection, is discussed in the next sections.

Aerodynamic Capture

Aerodynamic capture of particles involves the collection of particles by collecting bodies (e.g., fibers, packing, droplets, etc.). In order to utilize aerodynamic capture, the gas stream is brought near the collecting bodies and then a number of short-range mechanisms accomplish the actual collection. The most effective mechanisms are: inertial impaction, interception, diffusion, and electrostatic attraction. The relative importance of each mechanism varies with the size and velocity of the particles and the size of the collecting body.

Inertial impaction - The effectiveness of inertial impaction is a function of Stokes number which arises out of the force balance equation of fluid resistance opposing the motion of particles. The Stokes number is defined as:

$$STK = \frac{C \rho_p D_p^2 v_o}{9 \mu D_c} \tag{5}$$

where C = Cunningham slip correction factor

ρ_p = particle density

μ = fluid viscosity

D_p = particle diameter

D_c = diameter of the collecting body

v_o = particle velocity upstream

The fluid viscosity, μ , and the Cunningham correction factor both are temperature and pressure dependent.

The Cunningham correction factor, C , is given by:

$$C = 1 + \frac{2\lambda}{D_p} \left[1.246 + 0.42 \exp(-0.87 D_p/2\lambda)\right] \tag{6}$$

where the mean free path of gas molecules, λ , is calculated using Eq. (3). The variation of the Cunningham slip correction factor with temperature and pressure is shown in Figure 1. The slip correction factor increases with temperature and decreases with pressure, and this factor becomes increasingly significant for very fine particles at low pressures. For coarser particles and/or for higher pressures the Cunningham factor approaches unity and its variation with temperature and pressure is insignificant.

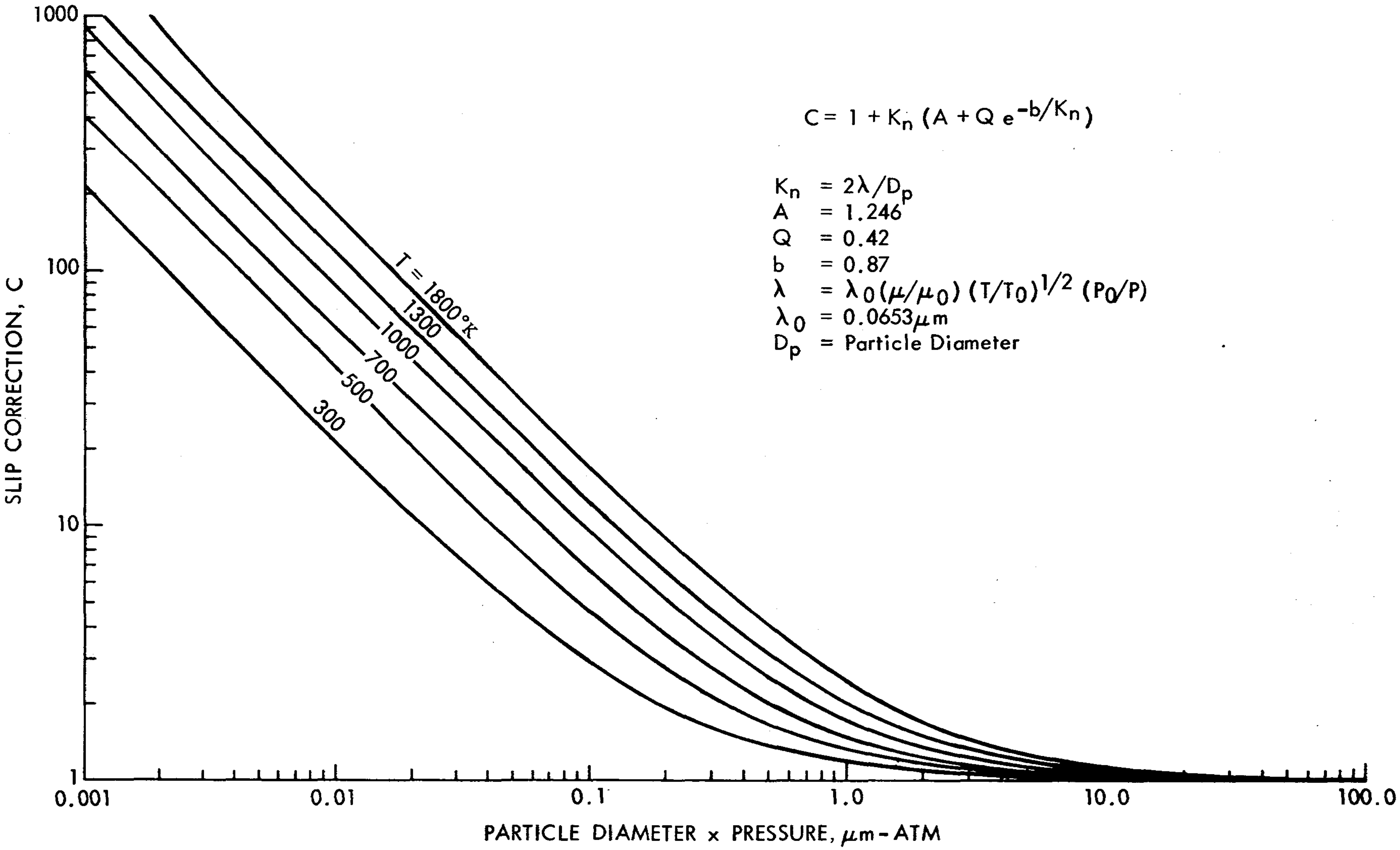


Figure 1. Variation of Cunningham Correction Factor in Air with Temperature and Pressure.

Examination of Tables 5 and 6 and Figure 1 shows that high temperature and pressure reduce the impaction efficiency by decreasing the ratio C/μ in Eq. (5). The variation of impaction efficiency with temperature and pressure for 5 and 1 μm particles of density 2 in air is shown in Figure 2 for a typical case of particles moving past a 10 μm diameter fiber at 25 cm/sec. Figure 2 was developed using the experimental correlation of Wong and Johnstone for the relation between Stokes number and impaction efficiency.[5] Figure 2 shows that the influence of pressure on impaction efficiency is much less for 5 μm particles than for 1 μm particles and that impaction efficiency generally decreases with increasing temperatures. Compensation for this reduction in efficiency can be accomplished by increasing the gas velocity or decreasing the collector body diameter.

Interception - Whenever the streamline, along which a particle approaches a collecting body, passes within a distance of one-half the particle diameter from the body, interception of the particle by the collecting body will occur. This mechanism never occurs alone except as a limiting case for particles of low density. However, it should be taken into account as a boundary condition to be met along with other aerodynamic capture mechanisms.

The dimensionless parameter that describes this mechanism is the ratio:

$$R_i = D_p/D_c \qquad (7)$$

where D_p = particle diameter

D_c = collector body diameter

This parameter is not influenced by changes in external conditions and thus will not vary with temperature and pressure. Ranz[4] has shown that if the particles follow the gas streamlines, the efficiency of interception of a cylindrical target is given by:

$$\eta = A \left[2(1 + R_i) \ln(1 + R_i) \quad \frac{R_i(2 + R_i)}{(1 + R_i)} \right] \qquad (8)$$

where $A = \dfrac{1}{2(2.002 - \ln Re)}$

The temperature and pressure dependent term in this efficiency equation is Re, the Reynolds number, $\rho v_o D_c/\mu$. With increasing pressure, the Reynolds number increases due to increase in gas density whereas with increasing temperature, it decreases due to the increase in gas viscosity and a decrease in gas density.

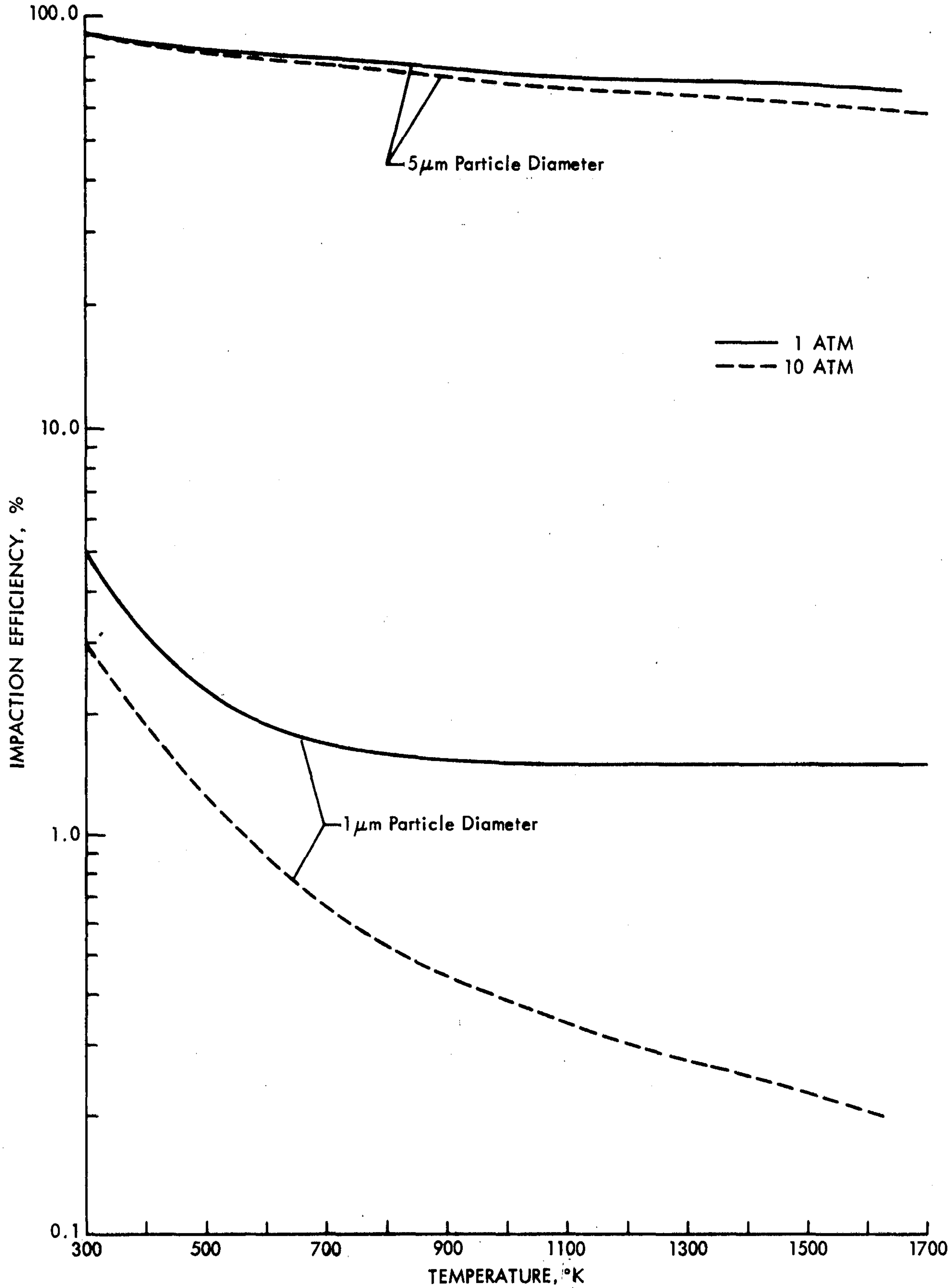


Figure 2. The Effect of Temperature and Pressure on the Calculated Efficiency of Inertial Impaction (particles moving past a 10 μm diameter cylindrical fiber with stream velocity of 25 cm/sec).

Thus, particle collection by interception may increase or decrease depending on the gas temperature and pressure, but this variation is independent of particle size.

Diffusion collection - Very small particles, because of their Brownian motion, do not follow streamlines, but have zig-zag movement around their mean path. This motion can lead to deposition of particles from gas streams close to the collecting body, but it is only of significance for particles smaller than 0.5 µm in diameter. Since Browian motion becomes more pronounced with decreasing particle size, diffusion collection also becomes more significant.

The characteristic parameter for the diffusion process is the Peclet number, which is defined as:

$$P_e = \frac{D_c \ v_o}{D^*} \tag{9}$$

where v_o = freestream particle velocity

D^* = particle diffusion coefficient

D_c = collector body diameter

The diffusivity can be calculated from Eq. (10)

$$D^* = \frac{KTC}{3\pi\mu D_p} \tag{10}$$

where K = Boltzmann constant

T = absolute temperature

C = Cunningham slip correction factor

D_p = particle diameter

Combining Eqs. (9) and (10) one obtains:

$$P_e = \frac{3\pi\mu D_p D_c v_o}{KTC} \tag{11}$$

Based on an analogy between heat and mass transfer, Ranz[4/] gives the following expression for the efficiency of particle collection by diffusion:

$$\eta = \frac{1}{P_e} + 1.727 \frac{Re^{1/6}}{Pe^{2/3}} \tag{12}$$

The temperature and pressure dependent terms in Eq. (12) are the Peclet number (Pe) and the Reynolds number (Re) which involve the parameters C , μ , and ρ .

The collection efficiencies of a single fiber based on Eq. (12) have been calculated for particles moving past a 10 µm fiber at 25 cm/sec and are plotted in Figure 3. These calculations show that for small particles which are primarily collected by diffusion, collection efficiency increases with increasing temperature but decreases with increasing pressure. As the particle size increases, the collection efficiency by diffusion and its dependence on temperature and pressure decreases. Since in most cases the relative changes in efficiency with pressure are much greater than those with temperature, collection by diffusion will also tend to decrease at high temperatures and pressures.

Electrostatic attraction - When an aerosol particle, or a stationary object in a flow stream is electrically charged, or when both the particle and the object carry electric charges, the trajectories of the aerosol particle past the object are affected. This usually results in an increase in the number of particles colliding with the object.

Ranz and Wong[6/] and Kraemer and Johnstone[7/] defined the dimensionless force ratios given by Eqs. (13) and (14) to characterize the forces between an aerosol particle in the absence of a field across a filter.

$$K_E = \frac{Cq_p q_f}{3\pi\mu\epsilon_o D_p v_{p-c}} \tag{13}$$

$$K_I = \frac{2}{3}\left(\frac{\epsilon_p - \epsilon_f}{\epsilon_p + 2\epsilon_f}\right) \frac{CD_p^2 q_f^2}{\epsilon_o \mu v_{p-c} D_C} \tag{14}$$

where ϵ_p and ϵ_f are dielectric constants of the particle and the gas, respectively, q_p is the electrostatic charge on the particle, and q_f is the electrostatic charge on the particle per unit area. The term ϵ_o is the permittivity of free space and μ is viscosity of the air. Equation (13) describes the interaction of a charged particle and collector, and Eq. (14) describes the interaction between a charged collector and a dielectric particle on which the collector induces a charge.

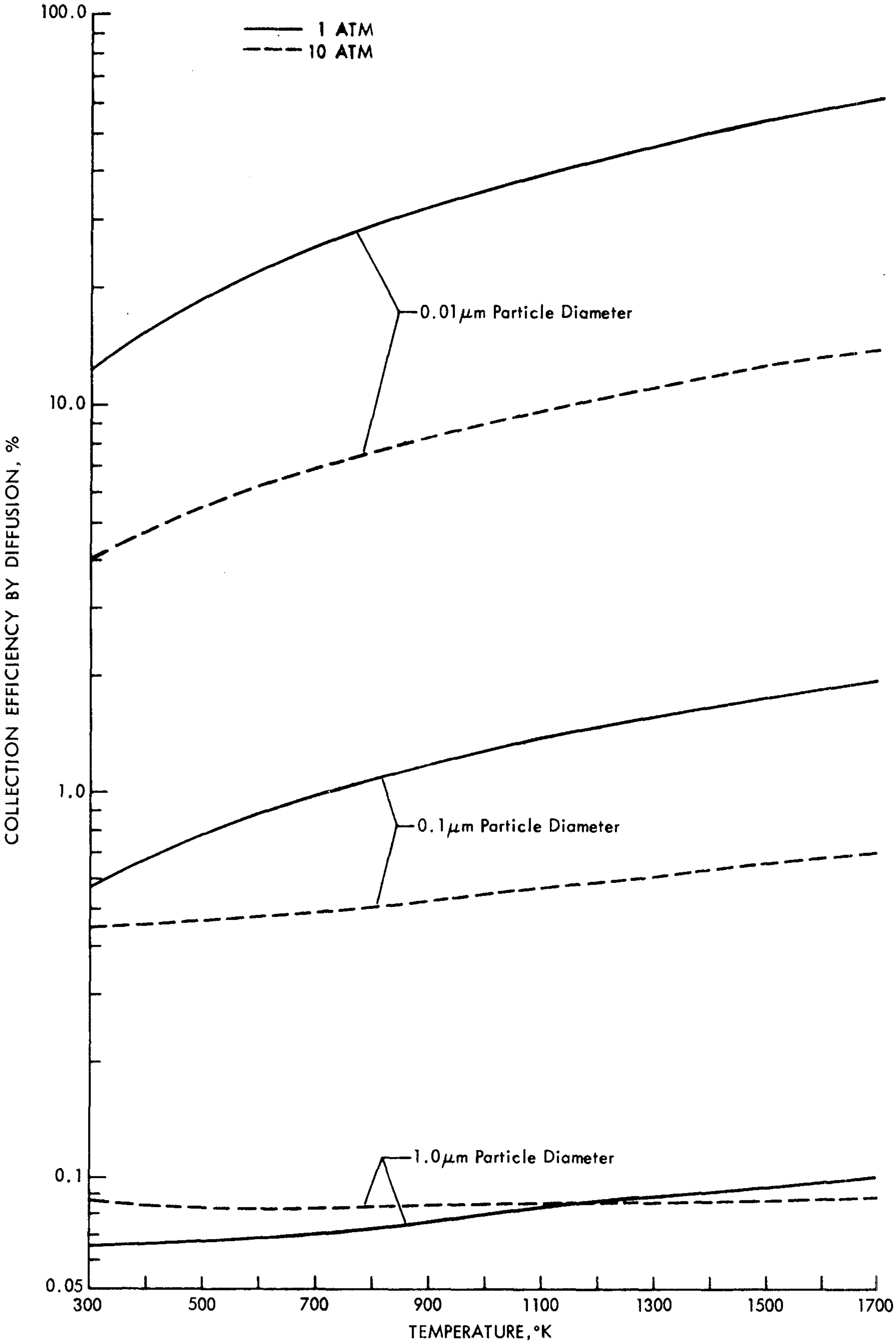


Figure 3. Effect of Temperature and Pressure Changes on Collection Efficiency by Diffusion.

Parameters K_E and K_I may be considered ratios of the electric force at the surface of the collector to the fluid resistance caused by a relative particle velocity of v_{p-c} with respect to the collector. It is noted that when q_p and q_f are of the same sign, K_E is positive and collection efficiency decreases. Target efficiency by these mechanisms is negligible when the corresponding parameter is much less than 10^{-2} and is of the order of unity when the parameter is of the order of unity.

Kramer and Johnstone[7] suggest that target efficiencies can be calculated for induced electrostatic attraction by:

$$\eta \approx \left(\frac{3\pi}{4} K_I\right)^{0.33} \tag{15}$$

and for charge particles and collector electrostatic attraction by:

$$\eta \approx - \pi K_E \tag{16}$$

based upon experimental data for a cylindrical collector.

The temperature and pressure dependency of the target efficiences in Eqs. (15) and (16) can be seen from Eqs. (13) and (14) to be the parameter C/μ . Since the Cunningham correction factor, C , depends also upon the particle size, the factor C/μ depends upon temperature, pressure and particle size. Using Figure 1 and Table 6, ratios of $\left[C/\mu / (C/\mu)_o\right]$ were calculated and plotted in Figures 4 and 5. The subscript zero refers to the ambient condition (i.e., 300°K temperature and 1 atm pressure). Calculated target efficiences for particles with diameters of 1.0 to 0.01 µm at elevated temperatures and pressures are shown in Figures 6A and 6B. Values of 0.1 were assumed for both K_E and K_I .[7] Examination of Figures 4, 5, 6A and 6B and Eqs. (13), (14), (15) and (16) shows that under conditions of both high temperature and pressure the effectiveness of electrostatic attraction is reduced for particles above 0.01 µm diameter.

Gravitational settling - Individual particles have a certain sedimentation velocity due to gravity. As a consequence of this, the trajectory of the particles deviates from the streamlines of the gas and particles may touch the collection surfaces and be removed.

The intensity of gravitational deposition is described by the gravitational parameter, G , which is:

$$G = \frac{v_s}{v_o} \tag{17}$$

where v_s is the settling velocity of the particle in the fluid. The settling velocity is determined from:

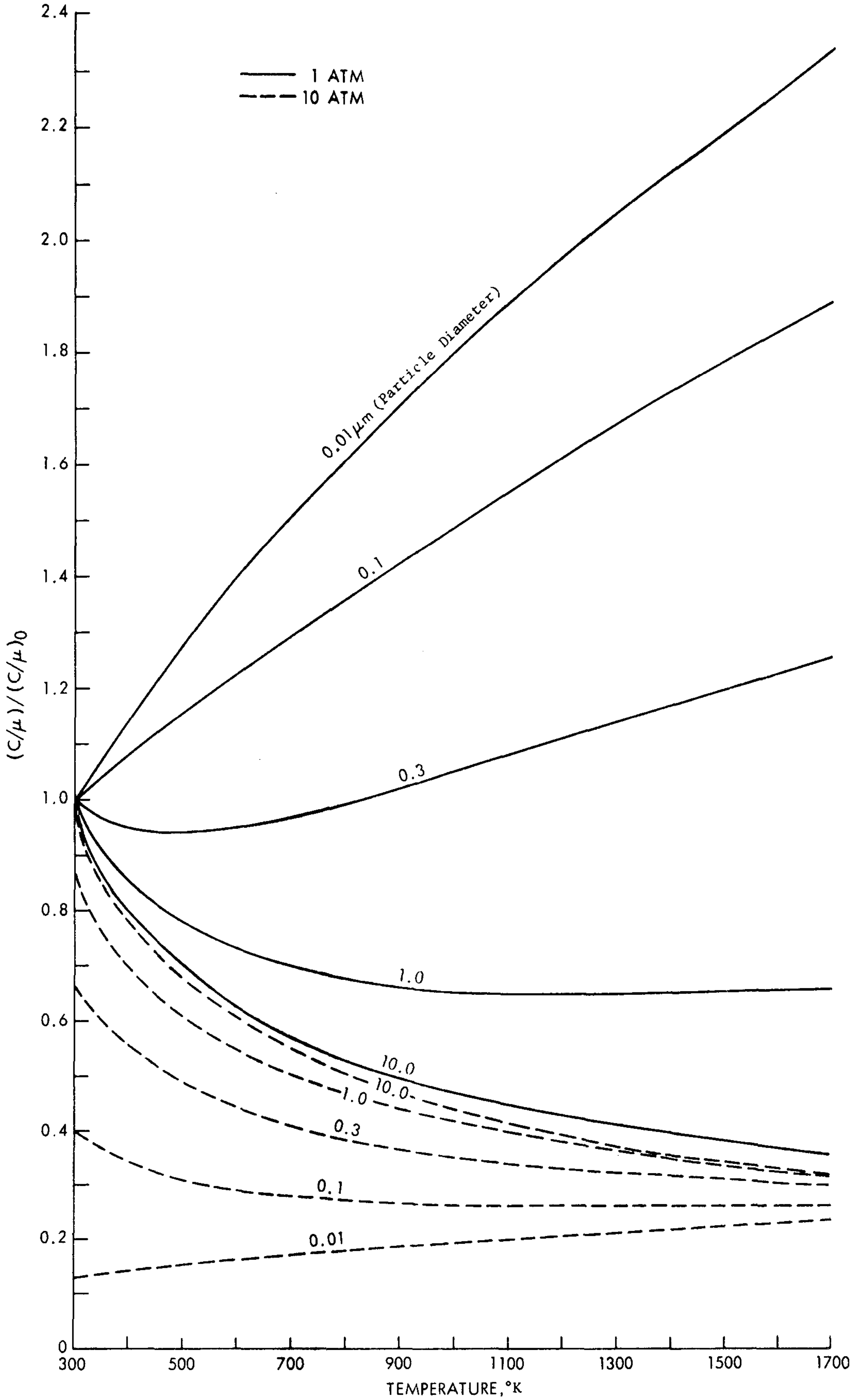


Figure 4. Variation of Ratio C/μ with Temperature, Pressure and Particle Diameter.

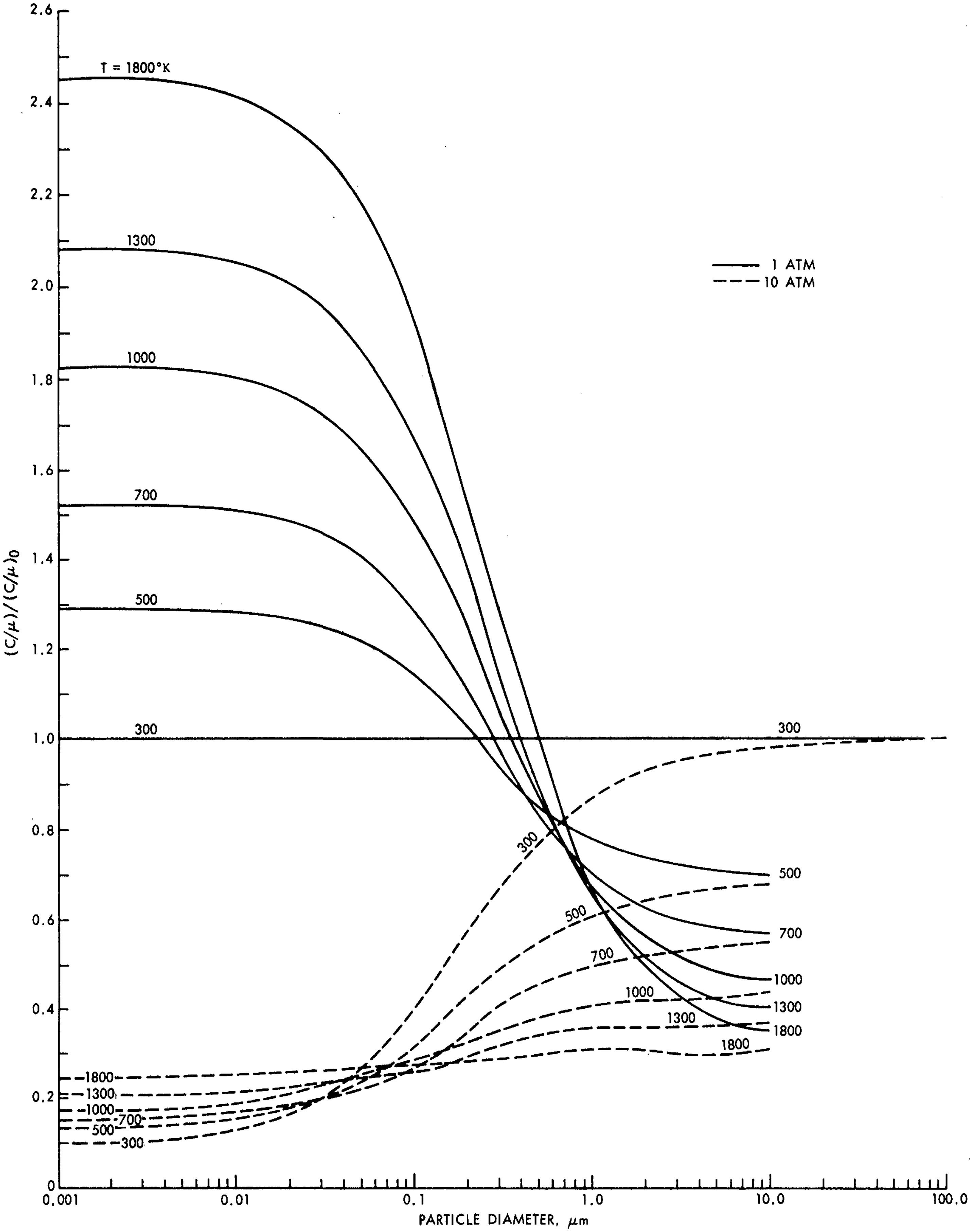
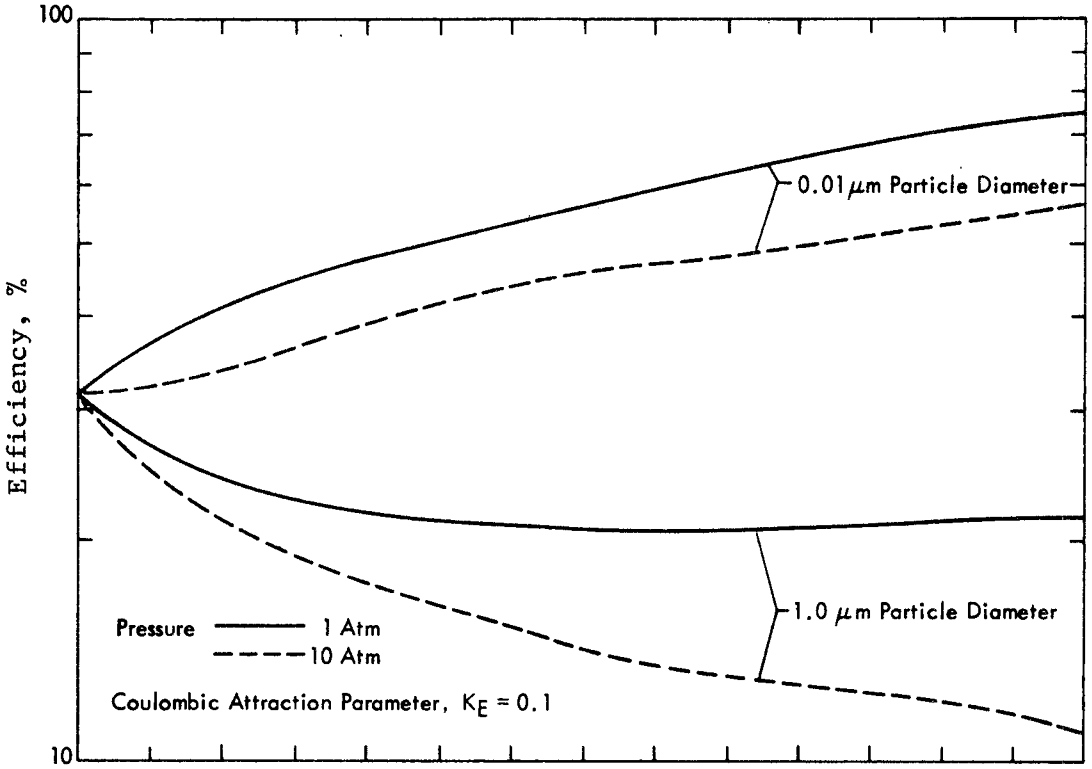
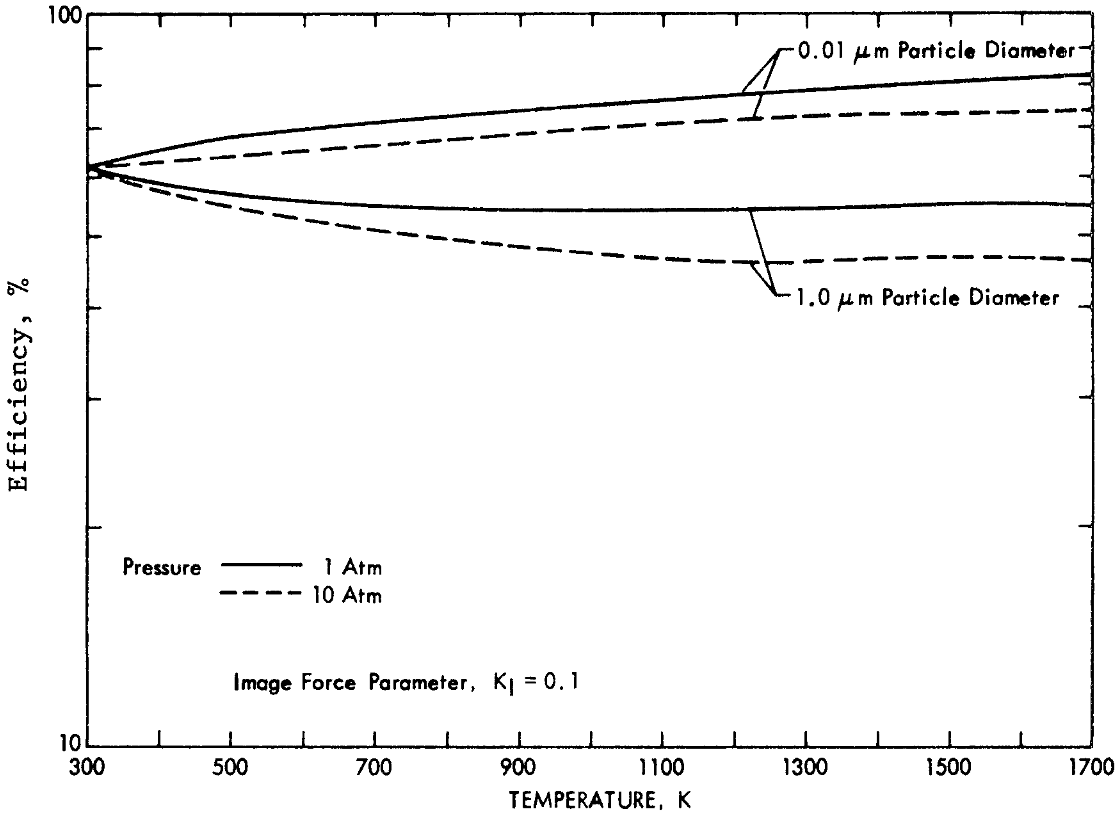


Figure 5. Variation of Ratio C/μ with Particle Diameter, Pressure, and Temperature.



A. Effect of Temperature and Pressure on Target Efficiency Due to Coulombic Attraction.



B. Effect of Temperature and Pressure on Target Efficiency Due to Image Forces.

Figure 6. Effect of Temperature and Pressure on Target Efficiencies Due to Electrical Forces for 0.01 and 1.0 μm Particle Diameters.

$$v_s = \frac{C\left(\rho_p - \rho\right)}{18\ \mu}\ g\ D_p^2 \qquad (18)$$

For gases, since ρ is negligible compared to ρ_p , and since only large particles are removed with this mechanism for which C is close to unity, gravitational settling is primarily influenced by temperature.

The ratio of settling velocity, v_s at a given temperature and pressure to the settling velocity, v_o at ambient conditions is very nearly equal to the ratio $(C/\mu)/(C/\mu)_o$ so, Figures 4 and 5 can be used to estimate impact of temperature and pressure on settling velocity. The settling velocity of large particles is little effected by pressure and decreases with increasing temperature.

<u>Centrifugal Forces</u>

Particulate matter is separated from gas in a cyclone by centrifugal force, or radial force, tending to drive the particles (against the resistance of motion by the gas) to the cyclone wall. The radial force imparted to the particle is:

$$F_s = \frac{\pi\left(\rho_p - \rho\right)\ D_p^3\ v_{tp}^2}{6 \cdot g \cdot r} \qquad (19)$$

where F_s = radial separating force

ρ_p = particle density

ρ = gas density

D_p = particle diameter

g = gravitational constant

r = radius of rotation

v_{tp} = tangential velocity of particle

The force resisting the particle is given by Stokes' Law:

$$F_r = \frac{3\pi\mu D_p v_{p-g}}{C} \qquad (20)$$

where F_r = frictional resistance to flow

μ = gas viscosity

v_{p-g} = particle velocity with respect to gas

C = Cunningham correction factor

The ratio of the separating force to the resisting force:

$$F_s/F_r = \frac{(\rho_p - \rho)\, D_p^2 v_{tp}^2 C}{18\ \mu\ gr\ v_{p-g}} \tag{21}$$

provides an indication of the relative ability to remove various size particles in a cyclone.

Since ρ is negligible compared to ρ_p even at very high pressures, the temperature and pressure dependent factor in this force ratio is C/μ . The variation of C/μ with temperature and pressure for various particle sizes is shown in Figures 4 and 5 and all the comments made in connection with inertial impaction or gravitational settling apply.

Flux Forces

Particles can be collected by forces which result from electrical, temperature and concentration gradients, from a magnetic field and from flux of matter or energy. This group of forces are especially attractive for the collection of fine particles because the magnitude of the flux forces does not approach zero as the size of the particles to be collected approaches the submicrometer range. Individual flux forces are discussed in the following sections.

Electrical forces (electrophoresis) - If charged particles are subjected to an unidirectional electric field, they move towards the electrodes and are deposited. The motion or migration of the particles in the field is termed electrophoresis. In the absence of turbulence or other aerodynamic effects, the migration velocity, v_e resulting from the electrostatic force can be obtained from Stokes' Law and is given by:

$$v_e = \frac{Cq_pE}{3\pi\mu D_p} \quad (22)$$

where q_p = charge on the particle

E = strength of electric field

This expression neglects second order electrostatic effects such as polarizability of the particle, and assumes a spherical particle is moving in laminar flow (Re < 1). Both of these assumptions are normally adequate.[8] It is clear from Eq. (22) that temperature and pressure influences migration velocity through the variables C , μ , and q_p . For a given particle size, electric field strength and electric charge on the particles, the factor v_e/v_{e_o} is a function only of $\left[(C/\mu)/(C/\mu)_o\right]$.

The charge on the particle q_p can be predicted using the equations developed for two idealized charging conditions, viz, the diffusion charging and the field charging. In diffusion charging, a suspended aerosol particle in an ionized gas acquires a charge by virtue of the random thermal motion of the ions and their consequent collision with and attachment to the particle.

According to White,[9] the charge on the particle is given by:

$$q = \frac{D_pKT}{2e} \ln \left(\frac{1 + D_p\bar{c}\pi e^2Nt}{2KT}\right) \quad (23)$$

where K = Boltzmann constant

T = absolute temperature

$\bar{c}$ = mean thermal speed of air molecules

e = elementary unit of charge

N = ion concentration

t = exposure time

In field charging, the particles are charged by the bombardment of ions moving under the influence of the applied electric field. Assuming the motion of the ions to be confined along the electric line of force, White has derived the following field charging equation:[9]

$$q = \left(1 + 2 \frac{\epsilon_p - 1}{\epsilon_p + 2}\right) \frac{ED_p^2}{4} \left[\frac{\pi Nez_i t}{\pi Nez_i t + 1}\right] \quad (24)$$

where ϵ_p = dielectric constant

z_i = ion mobility

E = field strength

Equations (23) and (24) suggest that the charging of particles by diffusion charging and field charging is favored by high temperature. The effect of pressure is negligible in both the mechanisms.

Analysis of Figures 4 and 5 in conjunction with Eqs. (22), (23), and (24) indicates that the dependence of migration velocity on temperature and pressure is quite complex. The particle size of the aerosol has a strong influence on the impact by increase in temperature and pressure--especially in the 0.1 to 1.0 µm diameter range. Figure 7 presents an illustration of the effect of temperature on the calculated migration velocity.

Thermal forces (thermophoresis) - Particles can be removed from a gas stream by the use of a temperature gradient. The force which causes particle motion results from momentum differences imparted to the particle on opposite sides. The hotter (and thus faster) molecules colliding with the particle will impart a higher momentum to the particle than the cooler (slower) molecules. Aerosol particles will then drift in the thermal gradient toward the cold surface. The motion of aerosol particles associated with a temperature gradient is called thermophoresis.

The theory of thermophoresis of aerosol particles was recently reviewed by Derjaguin and Yalamov[10] who showed that thermal forces, like other interactions between gas molecules, and particles, depend on the Knudsen number, K_n, where

$$K_n = \lambda / r_p$$

where λ = mean free path of gas molecules

r_p = particle radius

For very small particles (i.e., large Knudsen numbers) the authors have developed Eq. (25) for calculating the drift velocity due to thermophoretic force:

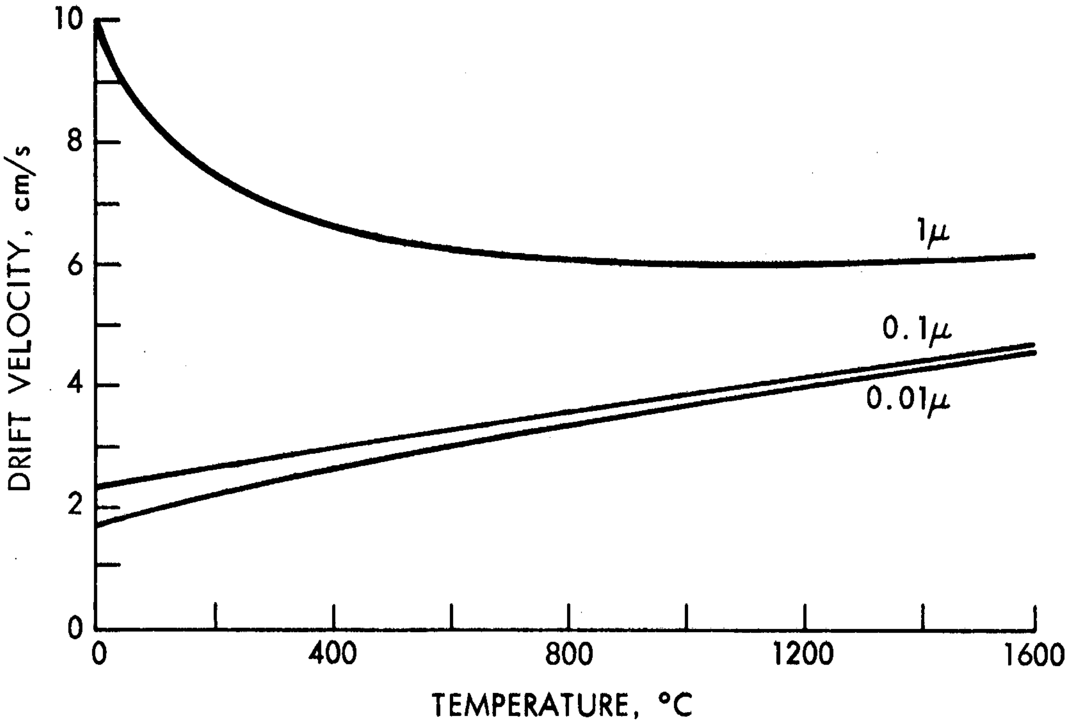


Figure 7. The Effect of Temperature on the Relative Migration Velocity of 1 Micron Diameter, 0.1 Micron Diameter, and 0.01 Micron Diameter Particles in Air for an Electrostatic Precipitator Where the Migration Velocity of a 1 Micron Diameter Particle at Ambient Conditions is 10 cm/sec.

$$v_T \approx - 0.37\ \lambda/T\ \bar{c}\ (\text{grad } T) \quad (25)$$

where grad T = dT/dx

$\bar{c}$ = mean thermal speed of gas molecules

For large Knudsen numbers, the drift velocity is independent of the particle size and inversely proportional to the square root of temperature and to the first power of the pressure. Thus, the thermophoretic velocity would be expected to decrease with increases in either temperature or pressure.

For moderately large particles ($0.01 \leq K_n \leq 0.1$), Brock has developed the following expression:[11]

$$v_T = - \frac{3\mu}{\rho T} \frac{\left[k_g/k_p + C_t \cdot K_n\right] \text{grad } T}{\left[1 + 2k_g/k_p + C_t\ K_n\right] \left[1 + C_m\ K_n\right]} \quad (26)$$

where k_g/k_p is the ratio of thermal conductivity of the gas to that of the particle, C_t and C_m are constants and are associated with the temperature jump and the velocity slip at the particle surface. Brock suggests that C_t ranges from 1.875 to 2.48 and C_m from 1.0 to 1.27. Thus, this equation shows that the thermophoretic velocity of moderately large particles is slightly dependent on particle size and is inversely proportional to the pressure and directly proportional to $T^{0.6}$.

For large particles ($K_n \longrightarrow o$) Eq. (26) reduces to:

$$v_T = - \frac{3\mu}{\rho T} \left[\frac{k_g/k_p}{1 + 2\ k_g/k_p}\right] \text{grad } T \quad (27)$$

The temperature and pressure dependence for this case is the same as that for Eq. (26). Figure 8 illustrates predicted effect of temperature on thermophoretic velocity of carbon particles in a unit thermal gradient.

Diffusion forces (diffusiophoresis) - In a concentration gradient, which is accompanied by diffusion but not necessarily by net motion of the gas phase, the heavier molecules will impart a higher momentum than the lighter molecules. If there is a net motion of the gas phase (Stefan flow), additional force is applied to the particles. The combination of forces due to Stefan flow and the concentration gradient is referred to as the diffusiophoretic force. Particle movement by this force is called diffusiophoresis.

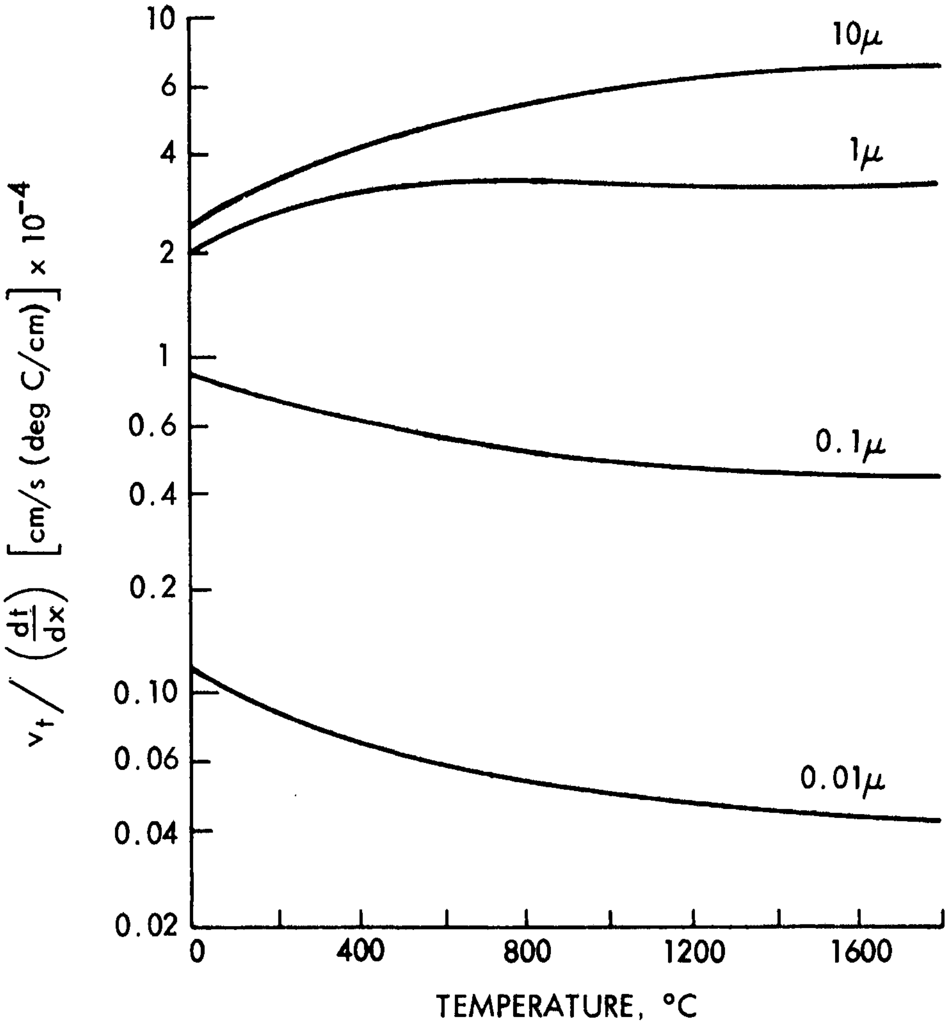


Figure 8. The Effect of Temperature on the Thermophoretic Velocity of Carbon Particles with Unit Thermal Gradient.

Several theoretical models of diffusiophoresis have been developed. Derjaguin and Yalamov[10] provide a theory for diffusiophoretic force acting on spheres in the range from free molecule (large K_n) to continuum ($K_n \longrightarrow o$) behavior. The analysis of these investigators substantially differs from the analysis of Hidy and Brock.[12] For binary gas mixtures, in the case of equimolar counter diffusion and small particles:

$$v_D = -\left[\left(\frac{\sqrt{m_1} - \sqrt{m_2}}{n_1\sqrt{m_1} + n_2\sqrt{m_2}}\right) - \left(\frac{n}{n_1 n_2} \quad \frac{(n_1 d_1 + n_2 d_2)}{(1 + \pi/8)d_o[n_1\sqrt{m_1} + n_2\sqrt{m_2}]}\right)\right] D_{12} \text{ grad } n_1 \tag{28}$$

where m_1 and m_2 = masses of the molecules of the first and second components of the mixture

n_1 and n_2 = concentration of gas molecules

d_o, d_1 and d_2 = coefficients in the expansion of the Boltzmann kinetic equation

D_{12} = mutual diffusion coefficients for two components

For large particles, Eq. (29) is applicable.

$$v_D = -\frac{n_o\ (m_2 - m_1)}{\rho_o} D_{12} \text{ grad } C_1 \tag{29}$$

where $N_o = n_1 + n_2$

$\rho_o = \rho_1 + \rho_2$

$C_1 = n_1/n$

Equations (28) and (29) show that the diffusiophoretic velocity is a function of density and the diffusion coefficient. Therefore, the exact dependence of the diffusiophoretic velocity on increases in temperature and pressure will depend upon particle size and the relative changes in temperature, pressure, and the ratio C/μ .

Magnetic forces - A force (Lorentz force) is generated when an electrical charge or an electrically charged particle moves in a magnetic field transverse to the field lines. If a dust particle carrying "n" elementary charges "e" moves with a speed v , the direction of the force will be at right angles to both the direction of the field and the direction of motion of the particles so that the particles will be diverted from its original path. As a result of the change in direction of the particle, the possibility of particle precipitation exists.

The potential for particle precipitation using the Lorentz force can be assessed by determining the terminal drift velocity of a particle in a magnetic field. The terminal velocity can be obtained by equating the Lorentz force to the resistance of the gas, calculated from the Stokes-Cunningham Law:

$$nevB = \frac{3\pi\mu D_p v_m}{C} \tag{30}$$

where n = number of charges on particle

e = elementary charge

v = velocity of particle in field

B = magnetic field strength

μ = gas viscosity

D_p = particle diameter

v_m = terminal drift velocity of particle

C = Cunningham factor

The left-hand term in Eq. (30) represents the Lorentz force and the right-hand term is the gas resistance. Equation (30) can be rearranged to yield the following expression for the terminal drift velocity:

$$v_m = \frac{CnqvB}{3\pi\mu D_p} \tag{31}$$

Equation (31) indicates that terminal drift velocity due to Lorentz forces is effected by temperature and pressure primarily through the factor C/μ .

PARTICLE AGGLOMERATION AND/OR PARTICLE GROWTH

Submicrometer particles can grow to larger, i.e., micrometer-sized particles by agglomeration and condensation. Therefore, it may be possible to utilize devices which cause particle agglomeration or growth in conjunction with conventional control systems to collect fine particles.

Thermal Agglomeration

A variety of forces may cause particles to come in contact with each other and agglomerate. If agglomeration is strictly as a result of Brownian motion (diffusion) it is termed thermal agglomeration.

The basic equation of change with time of the size distribution of an aerosol due to thermal coagulation is given by:[3/]

$$\frac{\partial n(v,t)}{\partial t} = \frac{1}{2} \int_0^{v} K(v-\bar{v}, \bar{v})\, n(v-\bar{v},t)\, n(\bar{v},t)\, d\bar{n} - \int_0^{\infty} K(v,\bar{v})\, n(v,t)\, n(\bar{v},t)\, d\bar{v} \qquad (32)$$

where $n(v,t)dv$ is the number concentration of aerosol at time t whose volume lies between v and dv and $K(v,v)$ is the coagulation coefficient between the particles of volume v and particles of volume $\bar{v}$. Equation (32) is a partial intergo-differential equation for which there does not exist an analytical solution.

For the simple case of a narrow size distribution aerosol in which the coagulation coefficient K can be considered constant, Smoluchowski gives the rate of particle agglomeration as:[3/]

$$\frac{dN}{dt} = -K_o N^2 \qquad (33)$$

where N = total number of particles per cubic centimeter

$K_o = 4\pi D r_p$

D = diffusion coefficient

r_p = particle mean radius

The diffusion coefficient D^* can be calculated using Eq. (10)

$$D^* = \frac{KTC}{3\pi\mu D_p}$$

Thus, the rate of agglomeration, as a function of diffusivity D^*, is affected by both temperature and pressure. The variation can be seen to depend upon the factor C/μ whose variation with temperature and pressure was discussed earlier.

Turbulent Agglomeration

Turbulence increases the relative velocities among particultes which in turn increases the chance of particulate collision. Theoretical studies on the coagulation of aerosols in turbulent flow have been conducted by Levich,[13] East and Marshall,[14] Tunitskii,[15] Obukhov and Yaglon,[16] and Beal.[17]

Levich discusses agglomeration effected by fluctuations having a scale of the same order as the particle size, which is appreciably less than the internal scale of turbulence, λ_o. Levich derived the following equation for the coagulation rate:

$$\psi = 32\pi r_p^3 \beta n_o \approx 25 \left(\frac{\epsilon}{\gamma}\right)^{1/2} r_p^3 n_o \qquad (34)$$

where β = coagulation constant

γ = kinematic viscosity

ϵ = rate of dissipation of turbulent energy per gram of medium

Beal has studied the case where the sink particle is larger than the turbulent microscale ($r_p > \lambda_o$) and has derived the following equation for the collision rate per unit area of sink particle:[10]

$$j = \frac{7}{3} \beta_1 \lambda_o^{2/3} \left(\frac{\epsilon}{\gamma}\right)^{1/2} r_p^{1/3} n_o \qquad (35)$$

where $\lambda_o \approx \left[\frac{\gamma^3}{\epsilon}\right]^{1/4}$

For the case described by Eq. (34), the temperature and pressure influence on the coagulation rate results from their influence on the kinematic viscosity, μ/ρ. Thus

$$\psi \approx \left(\frac{\rho}{\mu} \right)^{1/2}$$

and since $\rho \sim \frac{P}{T}$ and $\mu \sim T^{0.6}$

$$\psi \approx \frac{P^{1/2}}{T^{0.8}} \tag{36}$$

As a result, increasing the pressure will increase the coagulation rate while increasing the temperature will decrease the rate.

In the situation where Eq. (35) is applicable, temperature and pressure influence λ_o and γ. The dependence of the coagulation rate on temperature and pressure is given by:

$$j \approx \gamma^{1/4} \approx \left(\frac{\mu}{\rho} \right)^{1/4} \approx \frac{T^{0.4}}{P^{0.25}} \tag{37}$$

In this case, the coagulation rate increases with increasing temperature and decreasing pressure.

Agglomeration of Charged Particles

One method of increasing the rate of agglomeration of fine particulates is to add a bipolar charge, either with or without an externally imposed field. With proper conditions large electrostatic forces between particulates can produce a large increase in the rate of agglomeration of submicron particulates.

Fuchs[3] and Zebel[18] have derived the following equation for the rate of agglomeration for charged particles:

$$- \frac{dn}{dt} = k_{em} K_o n^2 \tag{38}$$

where K_o = agglomeration coefficient in the absence of charge

k_{em} = correction factor to allow for both particle charge and particle mean free path

The correction factor, k_{em} is given by:

$$k_{em} = \frac{N_q}{e^{N_q - 1} + N_{me}} \tag{39}$$

where $N_q = \dfrac{q_{p1} \; q_{p2}}{2\pi\epsilon_o \epsilon_f KT(D_{p_1} + D_{p_2})}$

$N_{me} = N_m N_q e^{N_q}$

$$N_m = \left[\frac{4(D_1^* + D_2^*)}{(D_{p_1} + D_{p_2})}\right]\left[\frac{4}{3KT}\left(\frac{m_1 m_2}{m_1 + m_2}\right)\right]^{1/2}$$

The temperature and pressure dependence of the correction factor k_{em} is complex. However, if the exponential term e^{N_q} is neglected in the above expressions, and assuming a constant $(q_{p1} \; q_{p2})$, the correction factor k_{em} is roughly proportional to $T^{1/2}$.

Sonic Agglomeration

Mednikov has proposed the following equation to describe sonic agglomeration:[19]

$$n = n_o e^{-K_a t} \tag{40}$$

where n = particle count concentration at time t

n_o = particle count concentration at time $t = o$

K_a = acoustic coagulation constant

The acoustic coagulation constant can be written as:

$$K_a \approx \frac{1}{\omega}\left(\frac{2 \bar{J}}{\rho \; C_g}\right)^{1/2} \tag{41}$$

where ω = angular velocity

J = sound intensity

C_g = speed of sound

ρ = gas density

Thus, $K_a \sim \frac{T^{1/2}}{P^{1/2}}$ and the rate of acoustic agglomeration will increase with temperature and decrease with pressure.

POTENTIAL PARTICULATE REMOVAL SYSTEMS FOR HIGH TEMPERATURE AND PRESSURE APPLICATIONS

The preceding theoretical analysis indicated that centrifugal forces, aerodynamic capture, and electrostatic forces are promising avenues for collection of particles under high temperature and pressure conditions. Since cooling of the gas stream is not considered a viable approach in this study, scrubbing systems using water are not suitable. Cyclones, electrostatic precipitators, and special types of filter systems (e.g., gravel beds, metallic fibers) and scrubbers which do not cool the gas stream (i.e., molten salt) are likely systems for use in these applications. Available information on the performance of these systems is presented next.

CYCLONES

Cyclones are generally good for removing large particles (> 5 µm), although some of the multiple-tube parallel units attain up to 90% efficiencies on particles of 3 µm diameter. Cyclones are commonly used as precleaners for a more efficient collector such as an electrostatic precipitator, wet scrubber or a fabric filter. In high temperature and pressure applications, cyclones are being used to remove large particulates in gases from a variety of gas streams and as precleaners for gravel bed filters.

Cyclones vary widely in physical size, flow capacity, and pressure drop. To permit comparison between different cyclones, the dimensions of the cyclone are specified by diameter, D, and seven dimensions ratios a/D, b/D, De/D, S/D, h/D, and B/D (see Figure 9). A number of cyclone "standard designs" or sets of dimension ratios have been suggested in the literature. Several are listed in Table 7. No single cyclone design will perform best for all dust collection problems.

The theoretical prediction of cyclone pressure drop and collection efficiency is still not possible because of complexities of flow fields. Based on simplifying assumptions of the flow fields and on experimental correlations, a number of equations have been developed for pressure

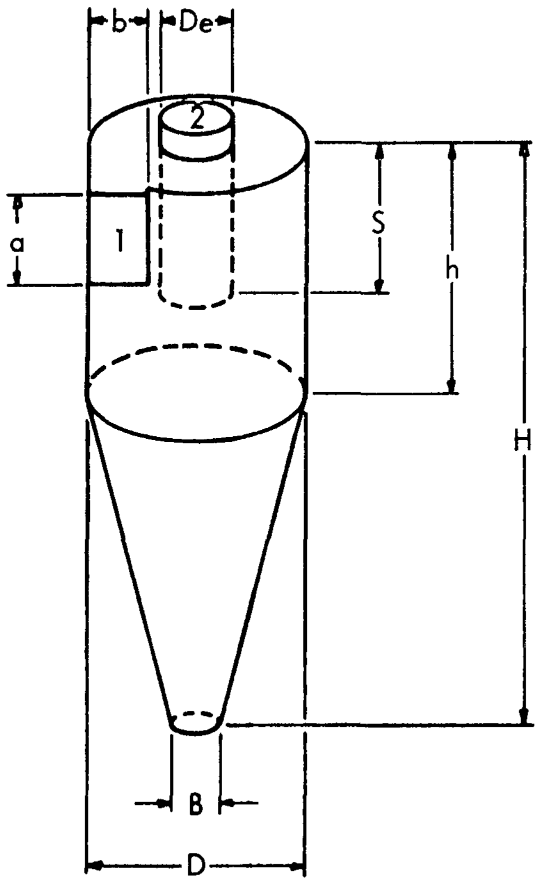


Figure 9. Cyclone with Typical Design Parameters.

Table 7. CYCLONE STANDARD DESIGNS

Recommended duty	D	a/D	b/D	De/D	S/D	h/D	H/D	B/D
High efficiency	1	0.5	0.2	0.5	0.5	1.5	4.0	0.375
High efficiency	1	0.44	0.21	0.4	0.5	1.4	3.9	0.4
General purpose	1	0.5	0.25	0.5	0.625	2.0	4.0	0.25
General purpose	1	0.5	0.25	0.5	0.6	1.75	3.75	0.4
High throughput[a/]	1	0.75	0.375	0.75	0.875	1.5	4.0	0.375
High throughput	1	0.8	0.35	0.75	0.85	1.7	3.7	0.4

a/ Scroll type gas entry used.

drop and collection efficiency. However, current design practice emphasizes past experience rather than an analytical design procedure. Recently Leith and Mehta[43] have evaluated five pressure drop theories and four efficiency theories against experimental data taken from the literature. The following equations are considered to be simple and to best fit the experimental data.

(a) Shepherd and Lapple pressure drop equation:[20,21]

$$\Delta P = \left(\frac{v_g^2\ \rho}{2g\rho_L}\right)\left(K\,\frac{ab}{D_e^2}\right) \tag{42}$$

where ΔP = pressure drop in length units of liquid with density ρ_L

ρ_g = gas density

a, b, D_e = are defined in Figure 9

K = 16 for a cyclone with standard tangetial inlet and 7.5 for a cyclone with an inlet vane, i.e., where the inner wall of the tangential entry extends past the cyclone inner wall to a point halfway to the opposite wall

(b) Leith and Licht efficiency equation:[22]

$$n = 1 - \exp\left[-2\left[G(stk/2)\right]^{1/(2n+2)}\right] \tag{43}$$

where G is a function of the cyclone's dimension ratios only:

$$G = \frac{\pi D^2}{ab}\left[2\left(1 - \left(\frac{De^2}{D}\right)\right)\left(s/D - a/2D\right) + \frac{1}{3}\left(\frac{s + \ell - h}{D}\right)\left(1 + \frac{d}{D} + d/D^2\right) + h/D - \left(\frac{De^2}{D}\right)\frac{\ell}{D} - S/D\right] \tag{44}$$

where

$$\ell/D = 2.3\,\frac{De}{D}\left((D^2/ab)\right)^{1/3} \tag{45}$$

$$d/D = \frac{D - (D-B)\left[(S + \ell - h)/(H - h)\right]}{D} \tag{46}$$

Here, ℓ is the farthest distance the vortex extends below the gas exit duct as given by Alexander,[23] and d is the diameter of the conical section at that point. The parameter stk is a modified Stokes number, reflecting the nature of the gas/particle system to be treated:

$$\bar{stk} = \frac{C \rho_p D_p^2 v_g}{9 \mu D_c} (n + 1) \qquad (47)$$

where C = Cunningham slip correction factor

ρ_p = particle density

D_p = particle diameter

μ = gas viscosity

v_g = gas velocity

The value of the vortex exponent, n, can be calculated from Eq. (48):

$$n = 1 - \left(1 - \frac{(0.394\ \bar{D})^{0.14}}{2.5}\right)\left(\frac{T}{283}\right)^{0.3} \qquad (48)$$

where $\bar{D}$ = cyclone diameter in centimeters

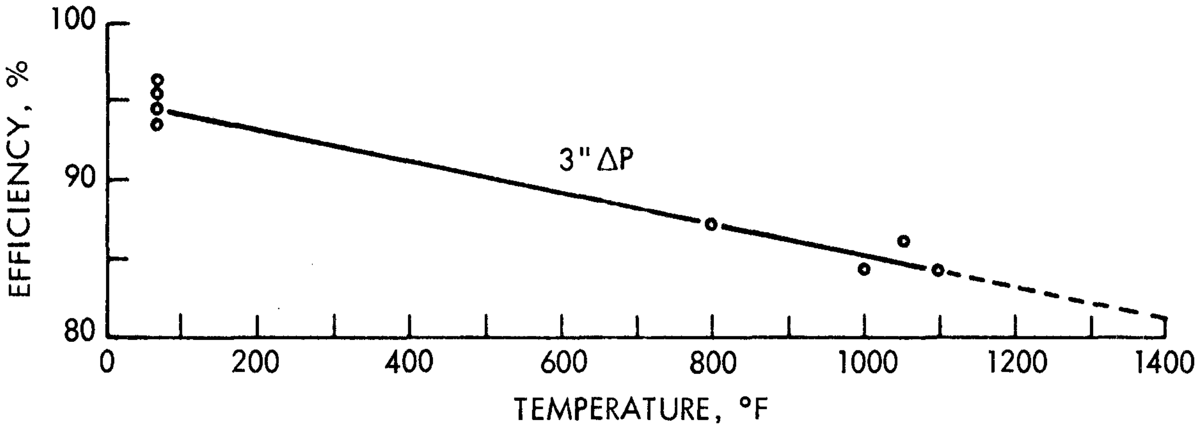
T = absolute temperature in degree Kelvin

The equations given above for pressure drop and collection efficiency predict numbers close to the experimental data. However, the equations do not take into account all the factors known to influence cyclone performance. Furthermore, since the experimental data with which these equations (in fact, all the cyclone theories) are correlated are taken at ambient conditions, it is not known whether these equations apply satisfactorily under high temperatures and high pressures.

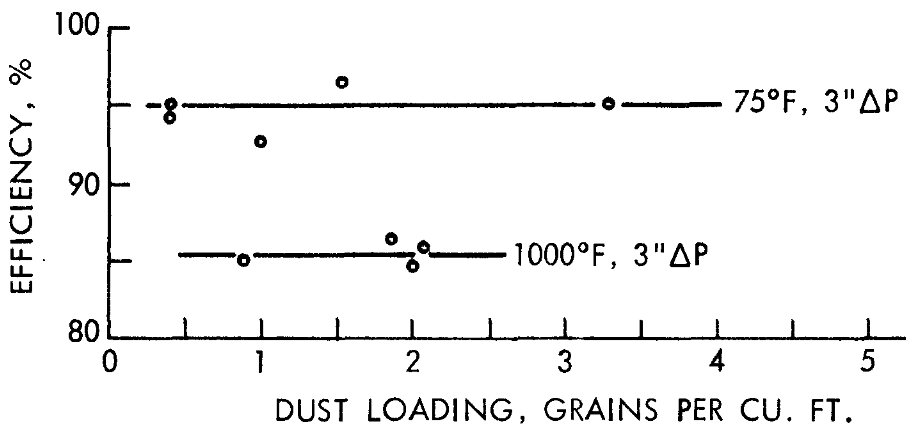
Experimental data on the performance of cyclones at high temperatures and pressures are meager. Yellott and Broadley, working with the Locomotive Development Committee Program, have experimentally evaluated several different cyclones.[24/] Data on the pressure drop and efficiency as a function of temperature and gas throughput at ambient pressure are shown in Figure 10. No fractional efficiency data were obtained. As expected, the mass efficiency of cyclones decreases with temperature.

Current Cyclone Research and Development

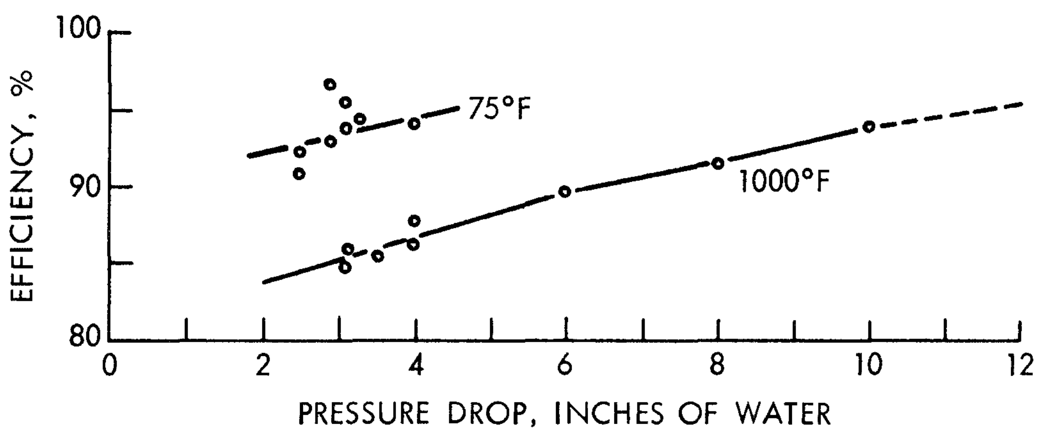
Babcock and Wilcox is in the process of developing a proprietary particulate collection system which may be regarded as an extension of cyclone collector art. The system has been tested on a paraffin



A. Effect of Temperature on Efficiency



B. Effect of Loading on Efficiency



C. Effect of Pressure Drop on Efficiency

Figure 10. Efficiency Test Results of Aerotec Separators.[24/]

hydrocarbon mist at ambient temperature with encouraging initial results on a large laboratory model. Babcock and Wilcox has proposed that this concept be utilized as an option in a hot fuel gas clean-up system experimental evaluation. Further tests on fly ash are required to demonstrate the principle.

Westinghouse has tested an Aerodyne Tornado Cyclone (Figure 11) which employs the interaction of two counter current high velocities to increase the collection efficiency for the fine particles. Laboratory data suggests that the design is capable of removing 1 μm particles with 80 to 90% efficiency, which is a significant improvement over the conventional cyclones. Reliable field test data on this system are not available.

Energy requirements of the secondary flow are also not known. Combustion Power Company studied the use of Aerodyne Cyclones for the CPU-400 system and concluded that secondary air flow requirements would result in higher power cycle loss penalties than the pressure drops from conventional cyclones with similar cleaning efficiencies.

Donaldson Company, Inc., has recently developed a Tan-Jet cyclone system (Figure 12) for high temperature and pressure work. The company claims that the system is significantly more efficient than conventional cyclones in collecting the particles in the < 5 μm diameter range. However, it should be noted that in this case too, secondary air power requirements were not thoroughly investigated.

GRANULAR BED FILTERS

Granular bed filters are a promising technique for high temperature and pressure gas cleaning. Its attractiveness is enhanced by the possibility of a single device being capable of removing both particulate matter and sulfur. In the past, granular beds have found practical application in atomic energy facilities and the filtering of small volume gas streams. Their application to industrial sources of particulate pollution has been limited--especially in the United States. Most recently, granular beds hav_ received increased attention and a number of research projects are underway to develop these systems.

State of the Art

The gravel bed filter often uses sand, gravel, coke or sintered material as the filtering media. Several designs are reported in the technical literature and they fall into one of three categories depending upon the movement of the bed material. In the crossflow shaft-falling solid

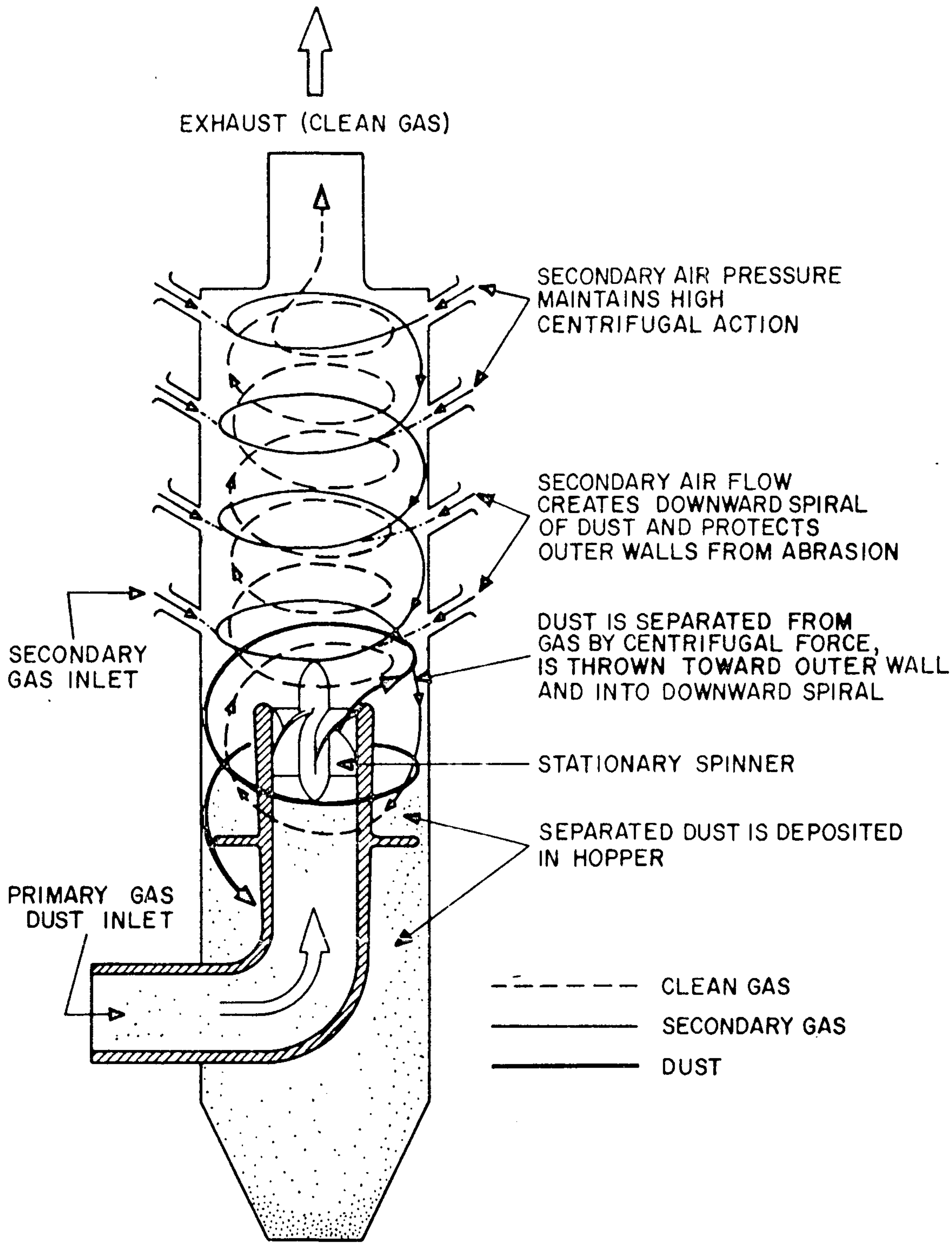


Figure 11. Aerodyne Tornado Cyclone.

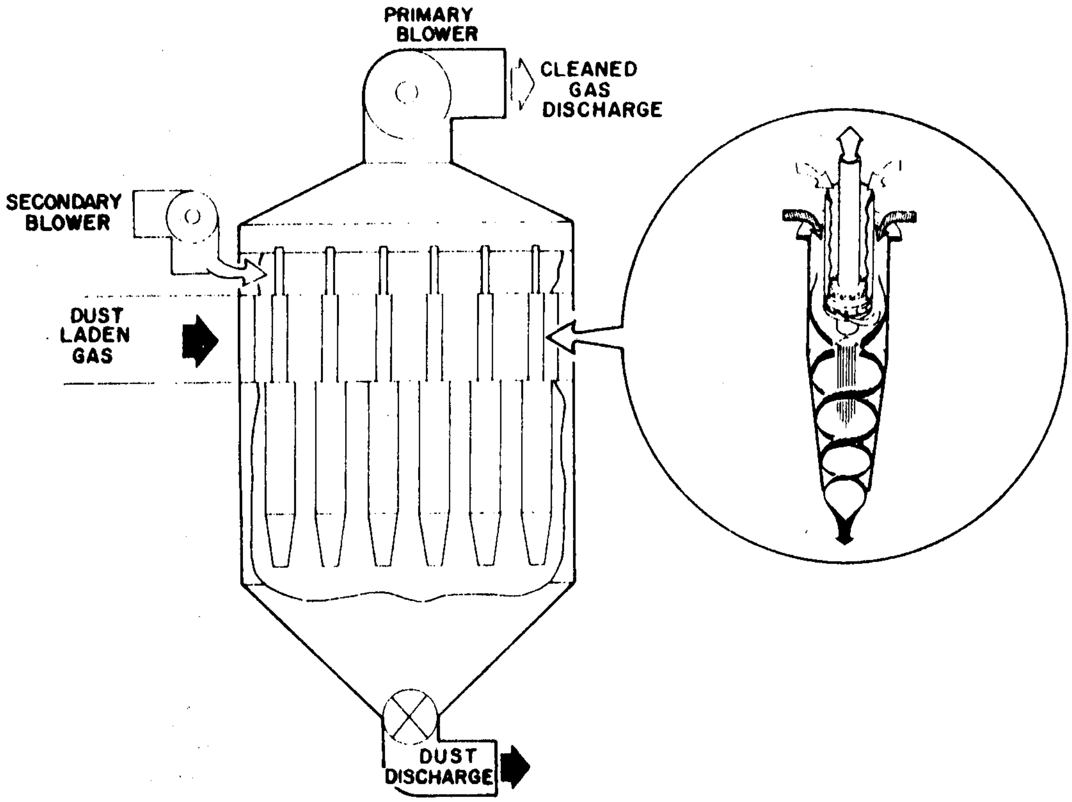


Figure 12. Donaldson Company Tan-Jet System.

design, the collecting particles continuously fall through a shaft while the gas flows across the shaft. This group includes the Dorfan Impingo filter, the Consolidation Coal Company filter, the Carnegie-Mellon cross-flow filter, and the Combustion Power Company dry scrubber.

In the intermittent moving-bed type of design, a fixed bed held between vertical panels moves intermittently. The original Squires panel bed filter is representative of this type.[25]

In the fixed-bed granular filter, the bed material is not moved or replaced. Rejuvenation of the bed material is achieved by a back flow of clean gas or mechanical shaking. The Ducon filter,[26] the Lurgi-MB-filter[27] and the Rexnord filter[28] are examples of this type. Figures 13 through 16 illustrate some of the available granular bed systems.

Currently available theoretical and experimental information on granular bed filters was recently reviewed by Shannon.[29] At present, there are no useful models for describing aerosol filtration in granular beds. Our knowledge of the performance of granular beds has been obtained essentially from experimental studies at both the laboratory and pilot-scale level. Most experimental work has been at room temperature and pressures with the exception of a few high temperature studies. Although the general conclusions reached from these studies are expected to be valid under conditions of high temperature and pressure, tests are needed to confirm these conclusions.

Current Granular Bed Research and Development

Work on granular bed filters is underway at several laboratories. Tests were recently conducted at Morgantown Energy Research Center on a panel bed filter developed by Squires. Collection efficiencies of 99% were reported when the filter was handling coal combustion flue gas at 1000°C.[1]

Tests on the Ducon filter have been conducted by Westinghouse, Bureau of Mines, and IGT with efficiencies of 99% reported. Combustion Power Company is currently testing their pebble bed filter on a bark boiler at a pulp mill. Laboratory tests have indicated collection efficiencies of the order of 80%.

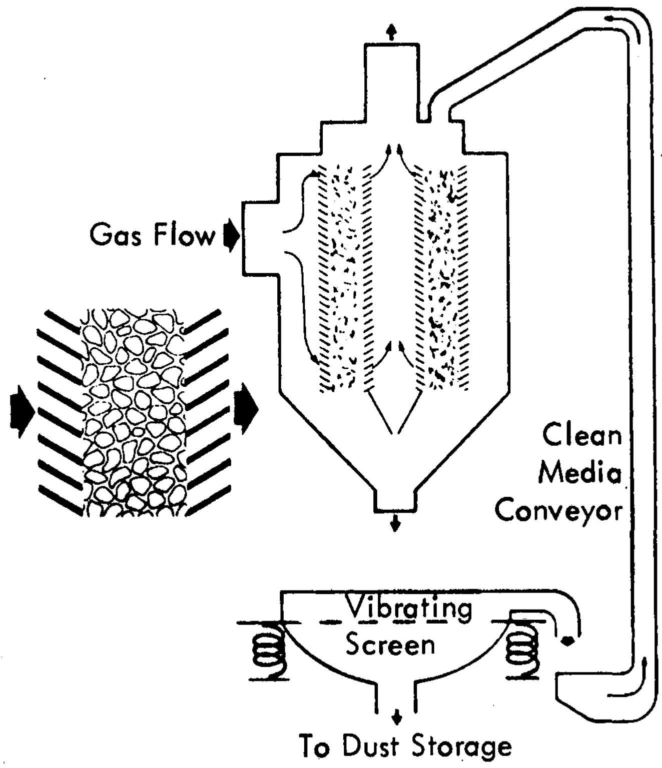


Figure 13. Combustion Power Company Dry Scrubber.

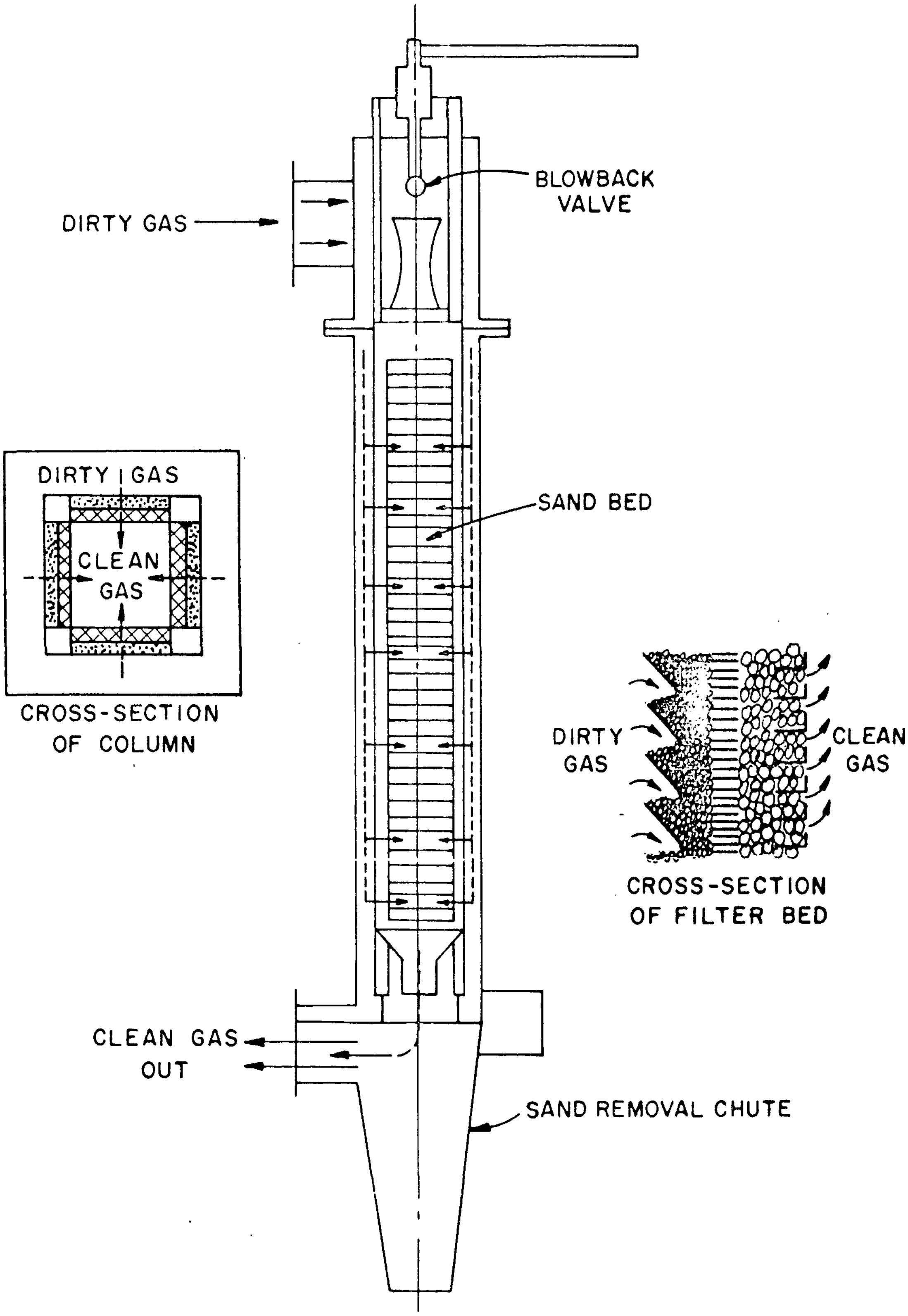


Figure 14. Possible Design for Squires Panel Bed Filter.

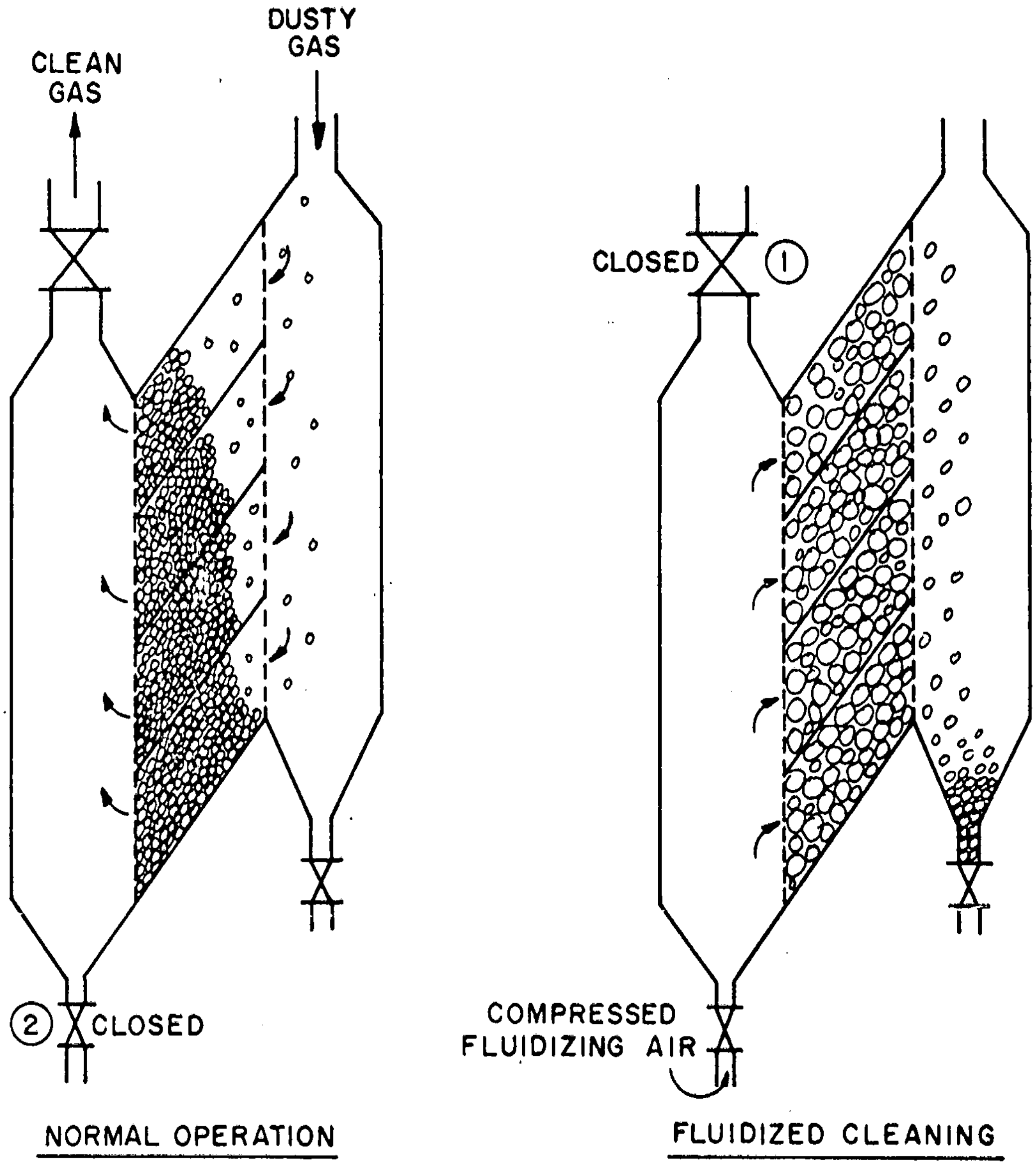


Figure 15. Ducon Fixed Bed Fluidizable Filter.

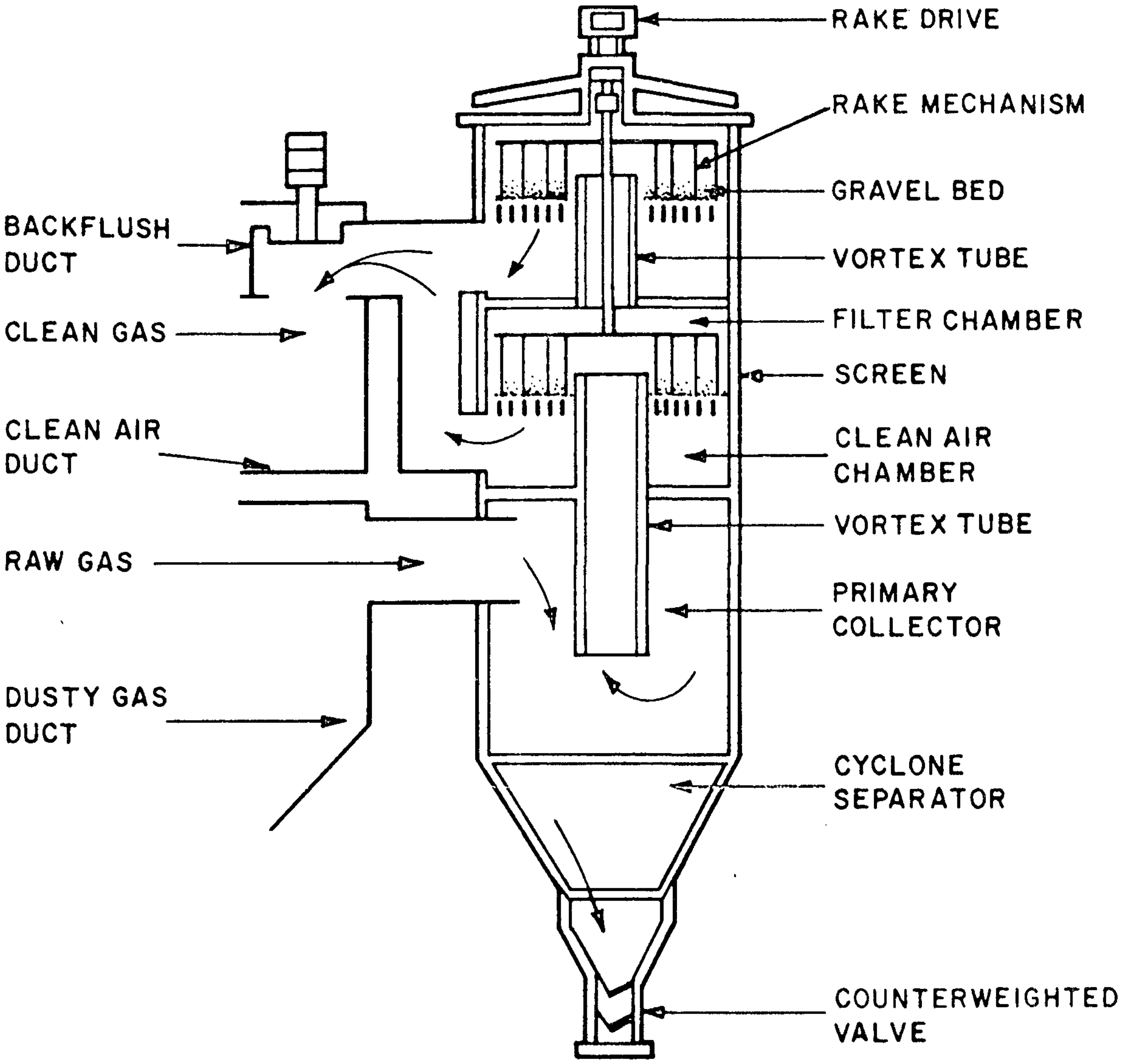


Figure 16. Rexnord Gravel Bed Filter.

ELECTROSTATIC PRECIPITATORS

State of the Art

In recent years, electrostatic precipitators have been used in chemical processing, power generation, and mass-transport application involving temperatures and pressures well in excess of conventionally accepted limits. Walker,[30] Robinson[8] and more recently Hall[31] have reviewed the application of electrostatic precipitation to extreme conditions of pressure and temperature. It is reported that successful pilot or full scale trials have been run at pressures up to 55 atm and temperatures (not simultaneous) to 800°C.

The understanding of corona discharge phenomenon at elevated temperatures and pressures is essential to the design of a high temperature/high pressure precipitator. Over the past decade or so, considerable research work has been done in this area. Important contributions were made by Robinson,[8] Brown and Walker,[32] and by Shale et al.[33,34]

Robinson[8] reported that both the corona starting and spark-over voltages increased with gas density. However, at a critical density the two voltages coincide. This critical density value depends on the precipitator electrode configuration. Positive polarity has a lower value of the critical density than negative, all other conditions being equal.

Shale reported that at moderate pressure ($\approx$ 6 atm), negative polarity spark-over potential decreased with increasing temperature and became unstable above about 700°C while positive polarity corona remained stable up to the investigation limit of 800°C.[35] In addition, Shale has reported that negative corona is more effective than positive in removing entrained solids at 800°C and 6.4 atm, even though the negative voltage was limited by sparking and was less than that attainable by positive corona.

Brown and Walker have concluded that the use of the electrostatic precipitation process up to temperatures of 900°C+ is entirely feasible and practical.[32] Both positive and negative corona were electrically stable provided a minimum gas pressure of at least 6.4 atm existed. Their data also indicated that the migration velocity of particles decreases with temperature, which is in agreement with the theoretical predictions.

Current Electrostatic Precipitator Research and Development

Currently development of electrostatic precipitators for use under conditions of high temperature and pressure is not being pursued. Development work of an electrostatic precipitator at the Bureau of Mines for operation with a coal fired gas turbine has been discontinued and the experimental study performed in the course of the CPU-400 program by Combustion Power Company has given way to the development of alternative techniques.

MOLTEN SALT SCRUBBERS

Over the past few years scrubbers have found considerable application in gas cleaning processes. These are efficient for particle collection and have the capability of removing particulate and gaseous pollutants simultaneously. The main disadvantage of conventional scrubbers for use in high temperature and high pressure gas cleaning applications is that the particle collection media is liquid (water) which evaporates at high temperatures and cools the gas. More recently, molten salts are being used as scrubbing liquids--playing the role, in effect, of high temperature analogs of aqueous solutions.

The main application of the molten salt scrubbers has been scrubbing SO_2 from stack gases. Atomics International has used a molten eutectic mixture of lithium, sodium and potassium carbonate to scrub a power plant gas stream.[36/] The sulfur is recovered from the molten salt through additional processing.

Battelle Memorial Institute's molten carbonate scrubber is being developed under contract to the Office of Coal Research.[37/] The device is essentially a horizontal venturi scrubber, which utilizes a molten salt mixture of sodium, potassium and lithium carbonates as a solvent for the calcium carbonate which acts as the reactant for sulfur removal. The Battelle scrubber has achieved both sulfur compound and particulate removal to below the turbine inlet specifications given Battelle by Westinghouse.

A major potential limitation of the molten salt scrubber for use in advanced power systems is entrainment of a salt mist into the turbine.

Current Molten Salt Scrubber Research and Development

Battelle Memorial Institute is developing a molten alkali carbonate scrubber system under contract to the Office of Coal Research. A pilot plant scrubber capable of treating 100 cu ft/min of gas is being installed on a Battelle fixed bed pilot plant gasifier. Provision for particulate removal upstream of the scrubbers will be provided. Downstream salt deentrainment is to be accomplished by a demister constructed of sapphire fibers and manufactured by Alcoa.

FABRIC FILTER SYSTEMS

State of the Art

Currently one of the most widely used techniques for gas cleaning is the use of fabric filters. However, conventional fabric filters are not recommended for use above about 250°C.

A number of particle collection mechanisms cause dust collection in a fabric filter system. These mechanisms include interception, impingement, diffusion and to some extent electrostatic forces. These forces and their effect on particle collection have been the subject of considerable study. Theoretical equations have been developed to predict pressure drop across the filter and the filter cake, but they are not adequate for design purposes. Thus, the design of fabric filters depends largely upon the experience gained from previous installations and observations of existing systems.

Only limited investigation of the performance of fabric filter systems at elevated temperatures or pressures has been conducted. The use of fabric filters in high temperature applications and innovations in filter fabrics for high temperature usage have been recently reviewed by Bergamann[38] and First.[39] It is reported that high temperature (350 to 400°C) needled fabrics woven from yarns prepared by twisting fiber frax fibers around fine stainless steel monofilaments were prepared by the Carborundum Corporation 20 years ago. Kane, Chidester, and Shale have tested the efficiency of fly ash collection to 980°C with an aluminum silicate fiber ("fiber frax") which melts at 1750°C.[40] They reported that the temperature limit was not imposed by the fiber, but by the fiber support.

Figure 17 depicts the calculated effect of temperature on the efficiency of collection of the major mechanisms operating in fabric filters. At higher temperatures, with rapidly decreasing values of inertial impaction efficiencies and moderately increasing diffusion collection efficiences, overall collection efficiency would probably decrease.

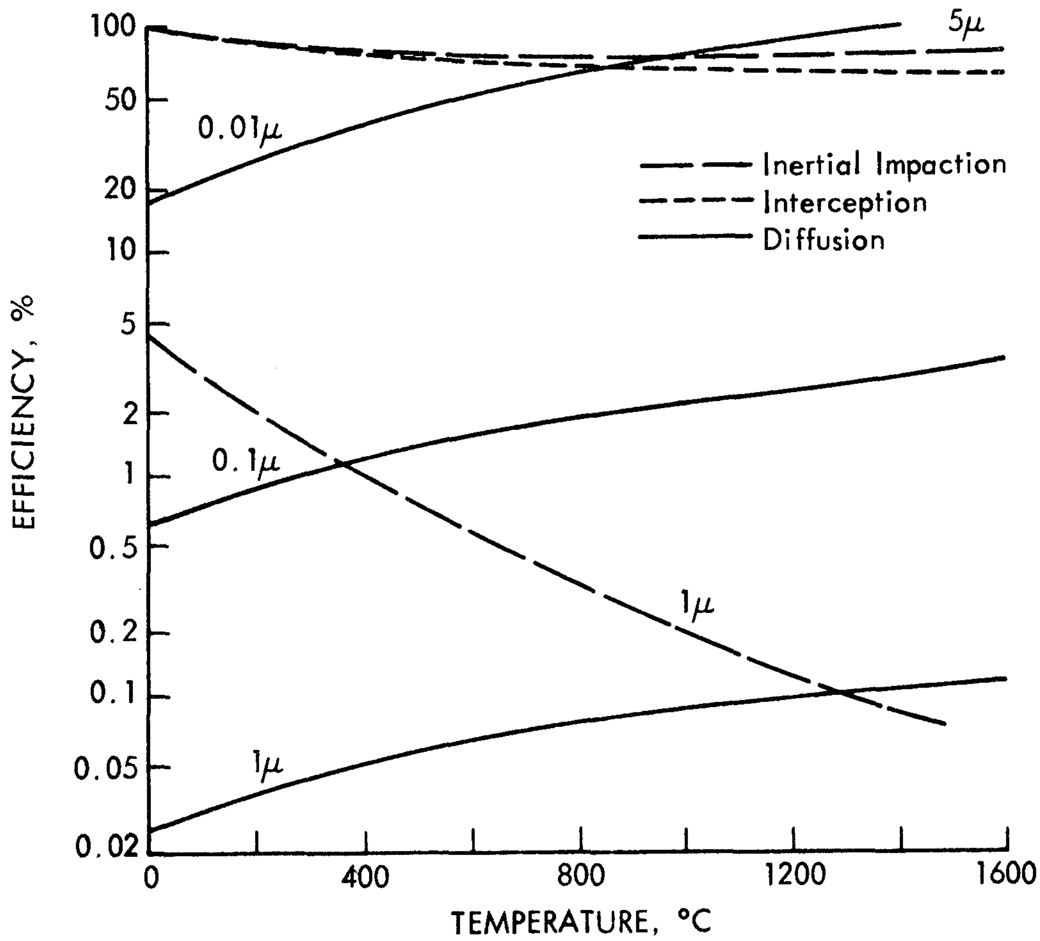


Figure 17. The Effect of Temperature on the Calculated Efficiency of Collection in Fiber Filtration (particles moving past a 10 micron diameter cylindrical fiber with a stream velocity of 25 cm/sec).

Current Fabric Filter Research and Development

Presently, the J. P. Stevens Company has a silica fiber filter material under development which is reportedly capable of operating at temperatures of 800°C. Similarly, Owens Corning has developed an inorganic bonding material for fiberglass fabrics which they suggest is adaptable to 500°C gas streams.

The 3M Company has developed filter material of alumina-boria-silica and zirconia-silica which have maximum operating temperatures of 1200 and 1000°C, respectively.

One of the most promising fabric filter materials for high temperature applications is under development by the Brunswick Corporation. The Brunsmet filter uses metal fibers fabricated from materials used by Pratt and Whitney for turbine seals at temperatures above 1200°C. Initial laboratory tests on the Brunswick material have shown a 99% efficiency for 0.5 μm diameter particles with an air-to-cloth ratio of 120. Brunswick has constructed a 220 cu m pilot plant for general tests to establish the filter's operating characteristics.

RESEARCH AND DEVELOPMENT NEEDS

Technology for particulate removal from gases under high temperatures and/or high pressures is at a very early stage of development. Well-conceived research and development programs are needed to improve and develop equipment for systems and processes which require high temperature and pressure gas cleaning. The analysis of particulate collection and agglomeration mechanisms has shown that the effectiveness of most mechanisms decreases with increasing temperature and pressure. However, experimental tests are needed to confirm these predictions and to establish the prominence of those parameters identified as the governing factors under the conditions of interest.

FUNDAMENTAL STUDIES

One of the reasons for the lack of experimental data has been the lack of suitable aerosol generation and sampling techniques for high temperature and pressure conditions. Therefore, considerable effort should be invested in developing sampling systems and sampling methodology. Impactors should be valuable sampling systems in high temperature work, so development of *in situ* impactors and their collection surfaces is highly recommended.

Specific experiments on the effect of elevated temperature and pressure on particle collection should include the study of the factor C/μ which enters in many equations describing the key parameters. The factor C/μ is influenced by temperature, pressure, particle size, and gas properties. The variation of C/μ with temperature and pressure can be obtained directly from mobility experiments or indirectly using a simple impaction system such as a jet impacting on a plate.

CONTROL EQUIPMENT STUDIES

Two of the most important parameters of any particulate removal system are the fractional efficiency and the pressure drop. Theoretical models and experimental correlations developed using laboratory or pilot-scale test units are useful in predicting these two parameters. It is recommended that research be conducted on all the promising particulate removal systems using carefully designed test units. The correlations developed from these experimental investigations can then be used as a guide for design of pilot-scale and full-scale models.

The existing pressure drop and fractional efficiency equations for cyclones are based on experimental data obtained at ambient conditions. It is not known whether these relations are valid at elevated temperature and pressure. It is recommended that the validity of existing equations be investigated.

The study of corona and particle charging at high temperatures and pressures is necessary for understanding the operation of electrostatic precipitators under these conditions. Investigations of charging phenomena at high temperature and pressure along with the selection of materials of construction are recommended.

At present there are no useful models for aerosol filtration in either granular beds or fabric filters. The potentially high collection efficiency offered by these devices, especially for fine particles, suggests that substantial efforts should be made to develop these systems for high temperature and pressure applications. The effect of parameters such as the particle size of the bed material or fiber diameter, face velocity, bed or filter thickness, etc., on total mass efficiency, fractional efficiency, and pressure drop should be thoroughly investigated. Efforts should also be focused on the selection of bed or filter material, expected life of bed of fiber material, and materials of construction for housings and associated equipment. Methods of cleaning or bed regeneration need to be developed and, for granular beds, bed material attrition and entrainment should be studied. Finally, studies of combined desulfurization and particulate removal efficiency and the associated problems are recommended.

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APPENDIX A

DATA ON GAS PROPERTIES

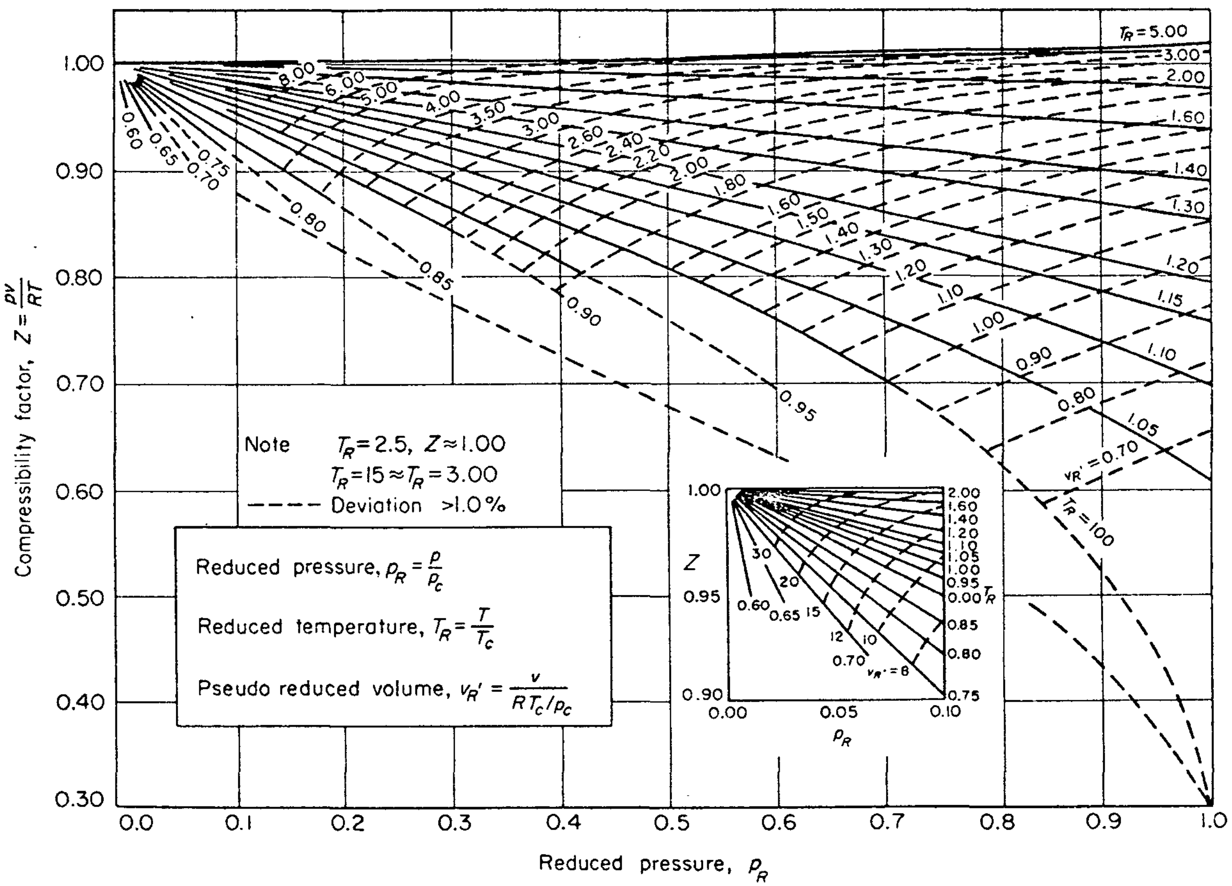

Figure A-1. *Generalized compressibility chart.* SOURCE: L. C. Nelson and E. F. Obert, "Generalized p-v-T Properties of Gases," trans. A.S.M.E., 76, 1057 (1954).

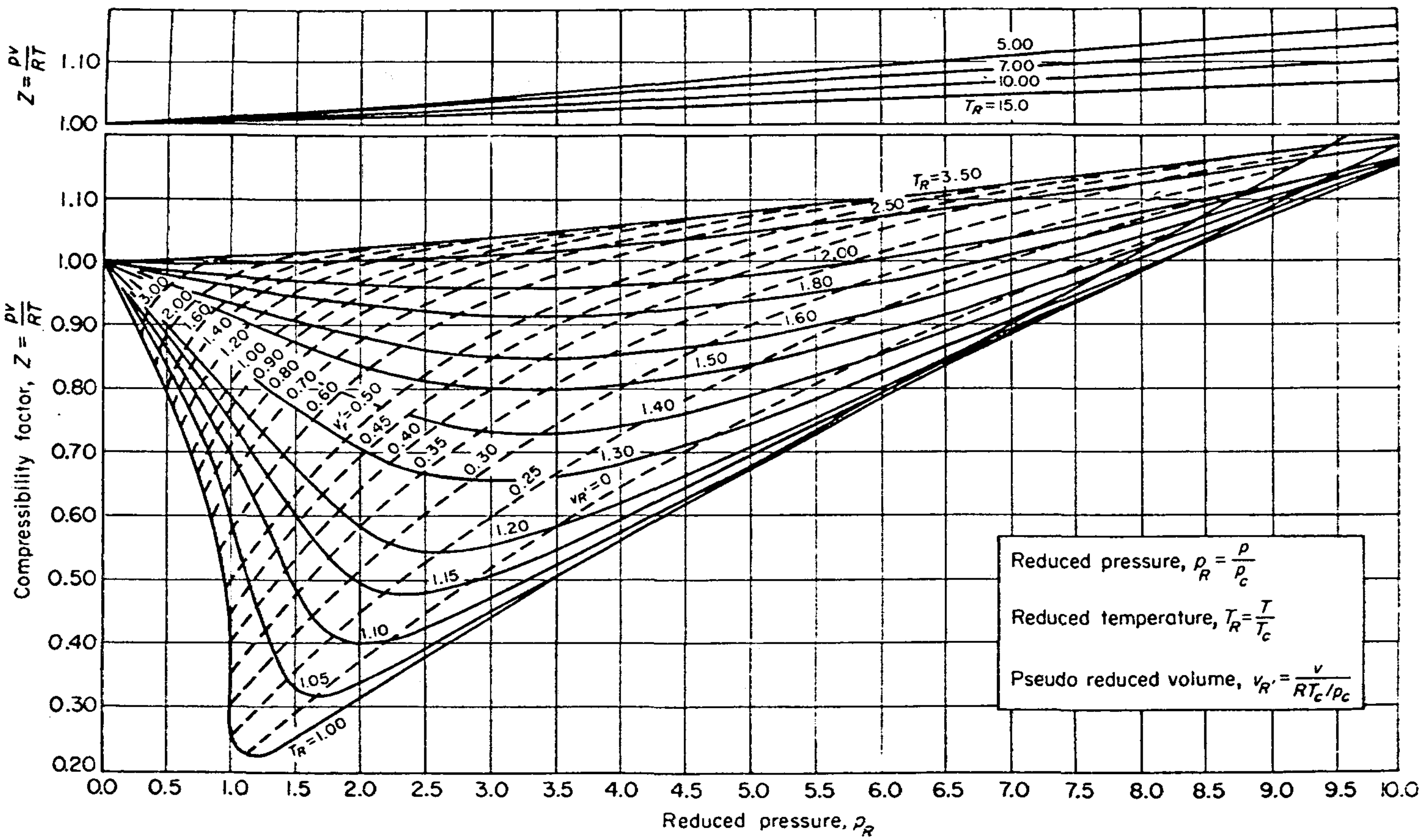

Figure A-2. *Generalized compressibility chart.* SOURCE: L. C. Nelson and E. F. Obert, "Generalized p-v-T Properties of Gases," trans. A.S.M.E., 76, 1057 (1954).

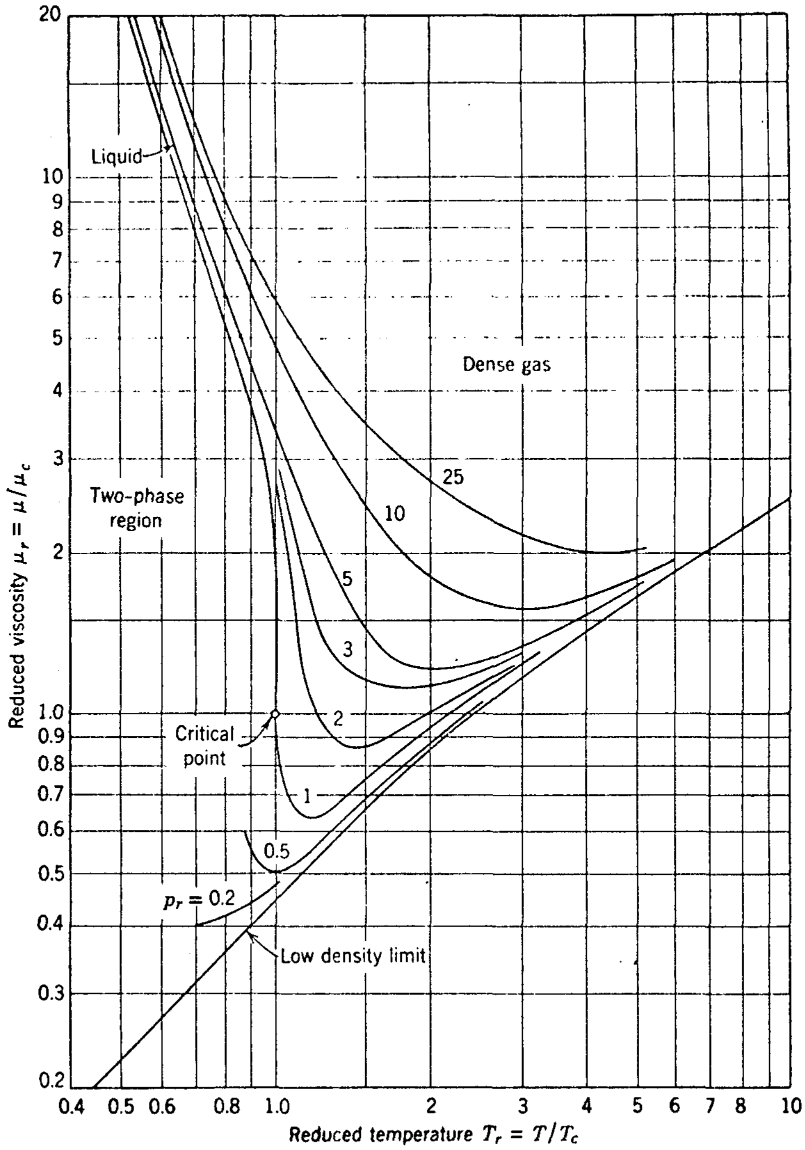

Figure A-3. Reduced Viscosity $\mu_r = \mu/\mu_c$ as a Function of Temperature for Several Values of the Reduced Pressure $p_r = p/p_c$. SOURCE: Bird, Stewart, and Lightfoot, "Transport Phenomena," John Wiley and Sons, Inc. (1960).

TABLE A-1

INTERMOLECULAR FORCE PARAMETERS AND CRITICAL PROPERTIES

Substance	Molecular Weight M	Lennard-Jones Parameters[a]		Critical Constants[b,c,d]				
		σ (Å)	ϵ/κ (°K)	T_c (°K)	p_c (atm)	$\tilde{V}_c$ (cm^3 $g\text{-}mole^{-1}$)	μ_c ($g\ cm^{-1}\ sec^{-1}$) $\times 10^6$	k_c ($cal\ sec^{-1}\ cm^{-1}\ °K^{-1}$) $\times 10^6$
Light elements:								
H_2	2.016	2.915	38.0	33.3	12.80	65.0	34.7	—
He	4.003	2.576	10.2	5.26	2.26	57.8	25.4	—
Noble gases:								
Ne	20.183	2.789	35.7	44.5	26.9	41.7	156.	79.2
Ar	39.944	3.418	124.	151.	48.0	75.2	264.	71.0
Kr	83.80	3.498	225.	209.4	54.3	92.2	396.	49.4
Xe	131.3	4.055	229.	289.8	58.0	118.8	490.	40.2
Simple polyatomic substances:								
Air	28.97[e]	3.617	97.0	132.[e]	36.4[e]	86.6[e]	193.	90.8
N_2	28.02	3.681	91.5	126.2	33.5	90.1	180.	86.8
O_2	32.00	3.433	113.	154.4	49.7	74.4	250.	105.3
O_3	48.00	—	—	268.	67.	89.4	—	—
CO	28.01	3.590	110.	133.	34.5	93.1	190.	86.5
CO_2	44.01	3.996	190.	304.2	72.9	94.0	343.	122.
NO	30.01	3.470	119.	180.	64.	57.	258.	118.2
N_2O	44.02	3.879	220.	309.7	71.7	96.3	332.	131.
SO_2	64.07	4.290	252.	430.7	77.8	122.	411.	98.6
F_2	38.00	3.653	112.	—	—	—	—	—
Cl_2	70.91	4.115	357.	417.	76.1	124.	420.	97.0
Br_2	159.83	4.268	520.	584.	102.	144.	—	—
I_2	253.82	4.982	550.	800.	—	—	—	—
Hydrocarbons:								
CH_4	16.04	3.822	137.	190.7	45.8	99.3	159.	158.0
C_2H_2	26.04	4.221	185.	309.5	61.6	113.	237.	—
C_2H_4	28.05	4.232	205.	282.4	50.0	124.	215.	—
C_2H_6	30.07	4.418	230.	305.4	48.2	148.	210.	203.0
C_3H_6	42.08	—	—	365.0	45.5	181.	233.	—
C_3H_8	44.09	5.061	254.	370.0	42.0	200.	228.	—
$n\text{-}C_4H_{10}$	58.12	—	—	425.2	37.5	255.	239.	—
$i\text{-}C_4H_{10}$	58.12	5.341	313.	408.1	36.0	263.	239.	—
$n\text{-}C_5H_{12}$	72.15	5.769	345.	469.8	33.3	311.	238.	—
$n\text{-}C_6H_{14}$	86.17	5.909	413.	507.9	29.9	368.	248.	—
$n\text{-}C_7H_{16}$	100.20	—	—	540.2	27.0	426.	254.	—
$n\text{-}C_8H_{18}$	114.22	7.451	320.	569.4	24.6	485.	259.	—
$n\text{-}C_9H_{20}$	128.25	—	—	595.0	22.5	543.	265.	—
Cyclohexane	84.16	6.093	324.	553.	40.0	308.	284.	—
C_6H_6	78.11	5.270	440.	562.6	48.6	260.	312.	—
Other organic compounds:								
CH_4	16.04	3.822	137.	190.7	45.8	99.3	159.	158.0
CH_3Cl	50.49	3.375	855.	416.3	65.9	143.	338.	—
CH_2Cl_2	84.94	4.759	406.	510.	60.	—	—	—
$CHCl_3$	119.39	5.430	327.	536.6	54.	240.	410.	—
CCl_4	153.84	5.881	327.	556.4	45.0	276.	413.	—
C_2N_2	52.04	4.38	339.	400.	59.	—	—	—
COS	60.08	4.13	335.	378.	61.	—	—	—
CS_2	76.14	4.438	488.	552.	78.	170.	404.	—

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16. ABSTRACT

The report gives results of an evaluation of methods of removing particulate matter from high temperature and/or high pressure gas streams. Theoretical and experimental information indicates that in many instances the effectiveness of collection and agglomeration mechanisms decreases with increases in temperature and pressure. Control equipment and systems which offer promise for application to particulate cleanup under high temperature and/or high pressure conditions are discussed. All potential systems reviewed require considerable development before they can be used reliably under the conditions of interest.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Exhaust Gases			21B
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