Aerosol Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713656376

Impaction of Solid Aerosol Particles on Fine Wires

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First published on: 01 January 1987

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The results of an initial study of the collection of 3-μm-diameter latex microspheres, dispersed in a laminar jet stream, on wires with diameters ranging from 0.001 and 0.010 in. (25.4 to 254 μm) are presented. The measured total collection efficiency based on the Stokes and Reynolds numbers and the interception parameter in regions on the wire where particles were collected are compared with previous experimental and theoretical results. For all cases examined, this efficiency is found to be significantly less than that predicted by theory. This difference is correlated with the particle's incident velocity. Particles below a critical velocity do not reach the wire's surface, and particles above another critical velocity always rebound from it. The probability of adhesion for these cases is assessed in terms of particle incident kinetic energy and is found to agree with the results of other similar experiments.

NOMENCLATURE

C	Cunningham slip correction factor
D_c	cylinder (wire) diameter
D_p	particle diameter
I	interception parameter $= D_p/D_c$
r	radial coordinate measured from centerline of housing unit
Re	Reynolds number $= \rho U_0 D_c/\mu$
Stk	Stokes number $= C\rho_p U_0 D^2{}_p/9\mu D_c$
U_o	gas velocity
μ	gas absolute viscosity
η	collection efficiency
ρ	gas density
ρ_p	particle density

INTRODUCTION

The collection of aerosol particles onto cylindrical surfaces has been studied extensively both experimentally and theoretically for over 50 years. Most of these studies have been motivated by their application to the filtration of particles from a carrier gas. In recent years, these studies have been used conversely to determine the size distribution of particles in a moving gas from the number of particles collected on either stationary or rotating cylinders, wires, or fibers. This particle collection technique has proven to be particularly suited for sampling in environments that preclude extractive sampling systems.

Self and Keating (1980) have applied this in situ particle collection technique to sample ash droplets in the demanding environment of a coal-fired magnetohydrodynamic plasma flow at a velocity of 350 m/s and a temperature of 2800°K. The size distribution of droplets collected on stationary iridium wires (76-μm diameter) was determined from subsequent particle counting using electron micrographs. Dunn et al. (1983) have extended their technique to capture radioactive nuclear fuel fission-product aerosols (solid and liquid) on fine wire impactors (12.7- to 254-μm diameter) for subsequent size distribution analysis and chemical identification. Velocities, temperatures, and pressures in

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these experiments ranged from 0.01 to 30 cm/s, 300 to 650°K, and 85 to 780 kPa, respectively. Fog droplets have been collected by inertial impaction on screens consisting of 300-μm-diameter Teflon monofilaments by Jacob et al. (1984) to determine the droplet size distribution. Wilson (1984) has referenced the use of a 75-μm-diameter wire impaction system used on NASA high-altitude aircraft to determine the size distribution of stratospheric particles. The commercially available "Rotorod" (Metronics Assoc. Inc., Palo Alto, CA) exploits the same technique for particle sampling in more quiescent environments by rotating a pair of collector rods at high velocities (nominally 10 m/s).

The theoretical models of particle impaction on an isolated cylinder have been developed for a variety of flow and particle-to-cylinder size conditions. The nondimensional parameters that characterize particle collision with the cylinder's surface under the aforementioned conditions are the Stokes (Stk) and Reynolds (Re) numbers and the interception parameter or particle-to-cylinder diameter ratio, I. The regimes of flow about the cylinder include the viscous ($Re < 1$), transition ($1 \leq Re \leq 1000$), and potential ($Re \geq 1000$) flow regimes. Most of the early theoretical analyses performed (Albrecht, 1931; Sell, 1931; Langmuir and Blodgett, 1945; Brun et al., 1955) were for potential flow assuming particle diameters much smaller than the cylinder diameter, i.e., $I \ll 1$. A model with $Re = 10$ and $I \ll 1$ was developed by Landahl and Herrmann (1949). Models that have considered the effect of particle collision by interception where I is of order one include the potential flow models of Davies and Peetz (1956) with $Re = 2000$, Householder and Goldschmidt (1969), and Steumpfle (1973); the transition flow models of Davies and Peetz (1956) with $Re = 10$; Subramanyam and Kuloor (1969) with $Re = 1$, 10, and 60; and Suneja and Lee (1974) with $1 \leq Re \leq 100$; and the viscous flow models of Davies and Peetz (1956) and Householder and Goldschmidt (1969), both with $Re = 0.2$.

The most recently developed particle collection models have also considered the effect on collection efficiency of particle rebound after impact from the cylinder's surface. Here, particle collection efficiency is expressed as the product of the particle collision efficiency and an adhesion probability. Hiller and Löffler (1980) have developed a model for viscous flow. For potential flow, Paw U (1984) has arrived at a model for the total collection efficiency. Wang (1986) has produced an extensive model for potential flow. Development of a model applicable for transition flow has been reported verbally by Dahneke et al. (1986).

Experiments on particle impaction on an isolated cylinder have been performed for all three flow regimes over a wide range of I, with both liquid and solid particles. The conditions of these experiments are summarized in Table 1. Experiments conducted in the viscous flow regime are those of Billings (1966) and of Hiller and Löffler (1980). The experiments of Ranz and Wong (1952), Wong and Johnstone (1953), Gillespie (1955), Subramanyam and Kuloor (1969), Bürkholz (1978), and Ellenbecker et al. (1980) were performed in the transition flow regime. Those of Renken (1984) spanned both the viscous and transition regimes. Gregory (1951), May and Clifford (1967), and Starr (1967) conducted experiments in both the transition and potential regimes. In the majority of all these experiments either liquid, spherical droplets or solid, nonspherical particles have been used. Only those of Billings (1966), Hiller and Löffler (1980), and Renken (1984) have employed the type of hard, spherical particles that rebound after impact and are readily ameanable to modeling. Of these, only Renken's experiments (1984) were in the transition flow regime. His data are the basis of the subject paper.

The present study originated out of the need to determine the collection efficiency of solid particles on the fine wire impactors

TABLE 1. Experiments on Particle Impaction

Author	Particle type	Particle diameter (μm)	Cylinder diameter (μm)	Velocity (m/s)	*Re*	*I*
Gregory (1951)	Spores	32	180–29,000	1.1–3.3	59–4400	.001–.181
Ranz and Wong (1952)	Sulfuric acid	.36–1.30	77	12–97	55–450	.005–.17
Wong and Johnstone (1953)	Sulfuric acid	.56–1.40	29–105.7	3.99–50.9	13–330	.005–.050
Gillespie (1955)	Stearic acid, paraffin	1.1, 1.8	300	.058–.263	11.3–51.2	.0037–.0060
Billings (1966)	Latex microspheres	1.30	8.5–11.0	.138–.580	.76–.414	.118–.150
May and Clifford (1967)	Dibutyl phthalate	20–40	1,250–19,700	2.2–6.2	165–8500	.001–.032
Starr (1967)	Spores, pollen	4.5–12.8	1,500–2,000	.4–6.0	10–1000	.0023–.0085
Subramanyam and Kuloor (1969)	Spores	35	345–1,500	.2–2.5	4–60	.023–.100
Bürkholz (1978)	Surfuric acid	1–20	250–500	2.5–15	83–500	.002–.080
Ellenbecker et al. (1980)	Fly ash, DOP	0.14, 0.7	8	1–8	5.19–41.5	.0175–.0875
Hiller and Löffler (1980)	Quartz, paraffin	5, 10	20, 50	.05–.91	.16–5.5	.1–.5
Renken (1984)	Latex microspheres	3.0	25.4–254	.02–3.55	.03–58.6	.012–.118

used in the experiments of Dunn et al. (1983). The flow about the wires in these experiments was in the transition regime. This paper specifically addresses the use of micrometer-sized wires in this flow regime to collect solid micrometer-sized particles for subsequent size distribution analysis. The experimental results are compared where appropriate with existing experimental and theoretical results. Although the results of this study apply directly to the chosen wire-housing configuration, they also apply more generally to particle collection by impaction on an isolated cylinder. The experimental results presented herein are the first reported for solid, spherical particle collection on an isolated cylinder in the transition flow regime.

EXPERIMENTAL APPARATUS

In these experiments, 3-μm-diameter latex microspheres were entrained in a laminar jet stream flowing past a single wire contained inside a circular commercial filter housing. Particles were collected on the wire over a given period of time and then counted directly using a scanning electron microscope. With this configuration, a wide range of velocities along the wire's axis over which particle collection could occur were produced in a single experimental trial. A schematic of the experimental apparatus used for this investigation is shown in Figure 1. The main components of the system were an aerosol generation system, a housing unit containing a single wire, and a particle counting system.

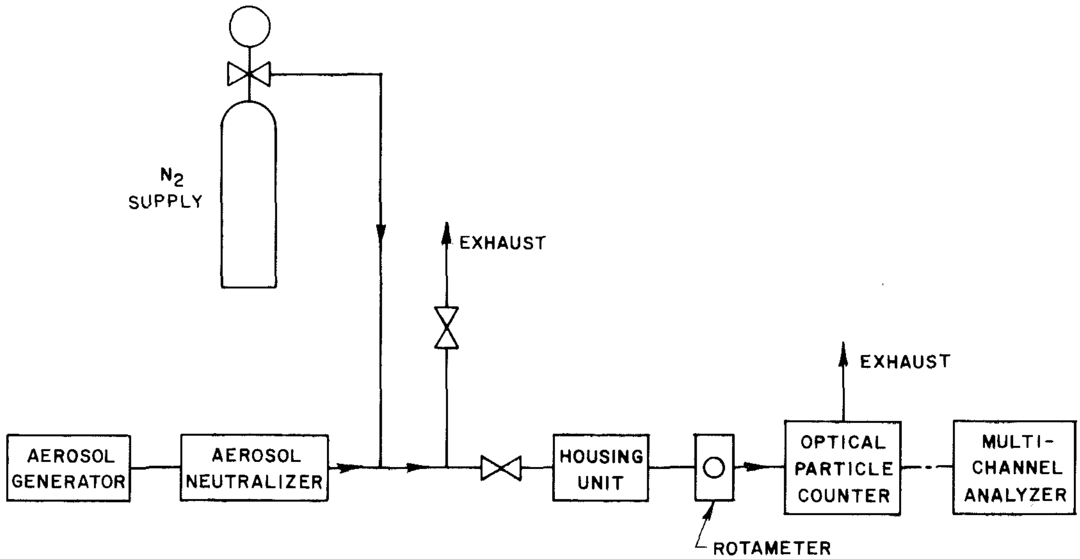


FIGURE 1. Schematic of the experimental apparatus.

The aerosol was generated from a 125-ml solution of distilled, deionized water and approximately 0.1 ml of liquid containing 3-μm-diameter styrene-vinyltoluene latex microspheres (Duke Scientific Corp., Palo Alto, CA) having a density of 1045 kg/m^3 and a Cunningham slip correction factor of 1.054. The aerosol was produced using a Model 3460 Tri-Jet Aerosol Generator (TSI Inc., St. Paul, MN). This yielded a solid aerosol by removing residual liquid from the microspheres with both a heater and a diffusional dryer. A Model 3054 Aerosol Neutralizer was used between the aerosol generator and housing unit to produce a net neutral charge on the particles. The resulting charge-neutralized aerosol of microspheres in filtered air at a flow rate of 5.0 liters/min was then mixed with 2.1 liters/min of filtered, dry N_2 by injection of the N_2 perpendicular to the flow using a standard tee-fitting. This method gave a uniformly mixed aerosol at a flow rate of 7.1 liters/min that entered the housing unit and subsequently the particle counting system.

The housing unit that contained the suspended wire is shown in Figure 2. The unit itself was a Model 1209 filter holder (Gelman Sciences, Inc., Ann Arbor, MI). The wire was suspended across the center of a stainless-steel washer [outer diameter = 0.873 in. (2.22 cm), inner diameter = 0.750 in. (1.91 cm)], which was inserted between the two halves of the housing unit. This size was chosen so that the washer containing the wire with collected particles could be placed directly into the scanning electron microscope chamber for examination and particle counting. The wire was affixed to the washer by laser microwelding [see Renken (1984) for procedure]. Wire diameters of 0.001, 0.002, 0.003, 0.004, 0.005, 0.008, and 0.010 in. (25.4, 50.8, 76.2, 102, 127, 203, and 254 μm) were used in these experiments.

The number of particles in the gas was measured by a Model CI-225 Particle Analyzer (Climet Instruments, Redlands, CA). Its signal was displayed on a TN-7200 Multichannel Analyzer (Tracor Northern, Middleton, WI). Particle concentration was determined from the sample flow rate and the number of signal counts in the voltage range corresponding to the monodisperse particle diameter.

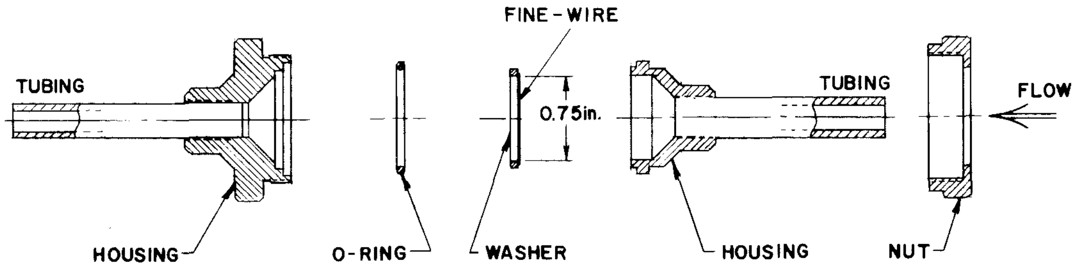
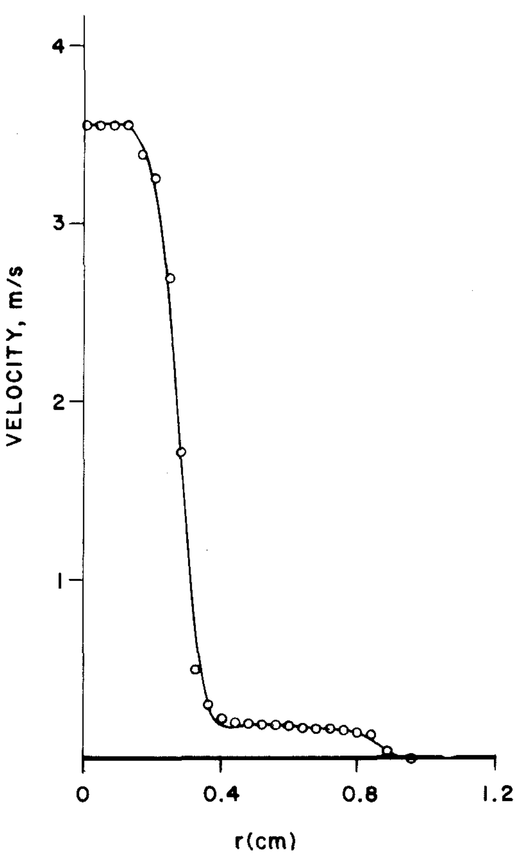


FIGURE 2. Wire impactor housing unit.

The velocity profile within the housing was determined using a Thermo-Systems, Inc. Model 1050 Series Anemometer and Model 1462 conical hot-film probe. Measurements were taken at 1/64-in. (0.0397-cm) intervals across the housing unit along a direction corresponding to the wire's axis. The measured jet velocity achieved at the 7.1 liters/min volumetric flow rate ranged from 0 m/s at the housing wall to 3.5 m/s at its centerline, as shown in Figure 3.

The estimated most probable errors of the nondimensional parameters determined from measured quantities were 5.8, 7.5, 11.9, and 12.4% for I, Re, η, and Stk, respectively.

FIGURE 3. Housing unit velocity profile.



EXPERIMENTAL PROCEDURE

Prior to preparing the aerosol solution, the vial containing the microspheres in solution was suspended and agitated in an ultrasonic bath (Bransonic Inc., Shelton, CN) for 1 min. Then, several drops of this solution were added to a beaker containing distilled, deionized water. This final solution was agitated ultrasonically just prior to the experiment. This method was found to assure uniform dispersion of the microspheres in solution.

Prior to testing, each washer-wire unit was cleaned in the ultrasonic bath. These units were stored in petri dishes before and after testing to prevent contamination.

The operating procedure for each test run basically consisted of bringing the aerosol generator to a steady operating condition, which was achieved after approximately 1/2 hr of operation, inserting the washer-wire unit into the housing unit, measuring the total number of test particles that passed through the housing unit over a given period of time, and then removing the washer.

After the experiment, a scanning electron microscope (Jeol, Peabody, MA) was used to count directly the number of particles that were collected on the wire. Positions of the particles along the wire's axis were noted also. These positions corresponded to radial positions in the housing unit. In this manner, particle position could be correlated directly with the local jet velocity.

Concerns about particle loss during the transfer of the impacted wires to the electron microscope were allayed by the results of control tests. Several washer-wire units with collected particles were dropped approximately 30 cm onto a flat surface and then reexamined for particle count. In each test the particle count did not change.

RESULTS AND DISCUSSION

Inspection of each wire using the scanning electron microscope yielded distinct regions of collected particles along its axis. These regions are depicted in Figure 4 as shaded areas on the wires. All the 0.008- and 0.010-in.- (203- and 254-μm)-diameter wires tested were observed to have one region of collected particles that was centered about the flow centerline of the wire. For all of the wires tested having diameters less than 0.008 in., regions void of particles about the centerline of the wire were observed, with smaller regions of collected particles on either side. The extent of the center void region was found to increase with decreasing wire diameter. For all wires tested, there was also a region void of particles at both ends of the wire.

The factors influencing the boundaries of the regions of collected particles were assessed first. The existence of void regions along the wire's axis was attributed to the particles having either insufficient inertia to reach the wire's surface (at the wire's end) or sufficiently high inertia to impact the wire, bounce off its surface, and return to the flow (along the wire's axial centerline). It was assumed that the particles were dispersed uniformly in the incident jet stream. This assertion was not supported by direct measurement, but indirectly by several facts. The particles, which were mixed uniformly in the tubing prior to entering the filter housing unit, did not have sufficient inertia to depart from their laminar flow streamlines in the housing unit (the particle Stokes number referred to the housing diameter was less than 10^{-5}). Also, they had sufficient velocity to travel through the tubing without any downward displacement because of gravitational settling (transit velocity/housing settling velocity $\cong 10^2$ to 10^3). Further, no indication flow recirculation or separation within the housing was noted from examination of the output of the anemometer's bridge circuit as displayed on an oscilloscope during velocity profile measurements.

The absence of particles in the regions at the ends of the wire was attributed to the particles having an insufficient incident velocity, hence inertia, to reach the wire. The boundary of this region was found to occur where the particles exceeded a critical value of the Stokes number. No particles were collected below this critical value. This value was found to be inversely proportional to the Reynolds number, as predicted by Davies and Peetz (1956). The experimental critical values of the Stokes numbers were 1.2, 0.60, 0.39, 0.29, 0.24, 0.15, and 0.12 for the 1-, 2-, 3-, 4-, 5-, 8-, and 10-mil-diameter wires, respectively. These critical Stokes numbers agreed closely with those predicted by the appropriate flow regime theory of Davies and Peetz (1956), which ranged from 0.899 to 0.125 for viscous to potential flow.

The absence of particle collection in the center region of wires with diameters less than 0.008 in. (203 μm) was attributed to all the particles in the projected flow area of that region having sufficiently high incident velocity, hence inertia, to bounce off the wire's surface and return to the flow. Several authors (Gillespie, 1955; Dahneke, 1971, 1973, 1975; Dahneke et al., 1986; Esmen et al., 1978; Ellenbecker et al., 1980; Hiller and

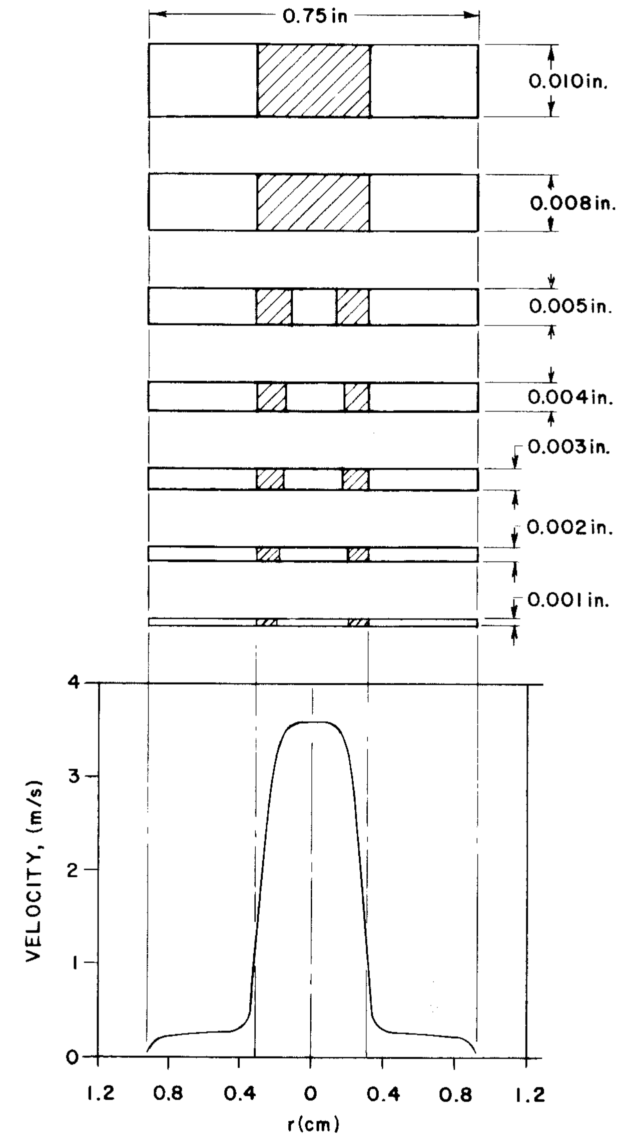


FIGURE 4. Regions of particle collection versus wire diameter.

Löffler, 1980; Paw U, 1984; Wang, 1986) have studied the bounce of solid particles off of surfaces. Their collective experimental data and theoretical analyses support the premise that the impaction efficiency of particles on a cylinder decreases when the particle velocity increases beyond a certain critical value.

Billings (1966) investigated the effect of incident velocity on impaction of latex microspheres onto glass fibers for the viscous flow regime. He found a decrease in collection efficiency with an increase in velocity beyond a certain magnitude. Hiller and Löffler (1980) verified their theoretical analysis for the viscous flow regime by experiments. They showed that the cylinder's collection efficiency was governed by the particle's probability of adhesion to the cylinder's surface, which decreased with increasing incident particle velocity. Paw U (1984) formulated theoretically for the potential flow regime a semi-empirical "critical rebound speed," above which the particle will bounce off of, but below which the particle will remain adherent to, the cylinder's surface. The theory of Paw U suggests that impaction efficiency at first increases with an increase in Stokes number, but then decreases above a particular Stokes number as the solid particles begin to bounce off of the cylinder's surface.

The recently proposed collection efficiency models of Wang (1986) for the potential flow regime and of Dahneke et al. (1986) for the transition flow regime both incorporate the effect of particle bounce. Wang (1986) models both single and multiple particle collision and rebound from the cylinder's surface and predicts surface collection efficiencies as a function of the angular orientation from the cylinder's forward stagnation point. The probability of particle adhesion is related directly to the ratio of the incident velocity component normal to the surface divided by the stagnation point velocity.

The present experimental results agree with the hypothesis of a decrease in collection efficiency above a particular Stokes number and, further, that this is the result of the particle exceeding a "critical rebound speed." Here, the flow velocity normal to the cylinder's forward stagnation point at the boundary of the center region of zero particle collection was 325, 328, 333, 343, and 355 cm/s for the 1-, 2-, 3-, 4-, and 5-mil wires, respectively.

Within the region(s) of particle collection, an experimental collection efficiency was determined. The experimental collection efficiency for the subject experiments was defined as the total number of counted particles within the region of collection divided by the total number of particles that passed through the region's upstream projected area. For the cases in which two regions of particle collection were observed for each wire, the total number of particles collected and the total projected area combined for both regions were used to determine the experimental collection efficiency. The corresponding average values of Stk, Re, and I were determined using the linearly averaged velocity of the region of particle collection.

A theoretical model of particle collection incorporating the effect of particle bounce is not currently available for comparison with the present experimental results. The present experiments were conducted in the transition flow regime, based upon the average Reynolds number range of 3.5 to 49, corresponding to wire diameters from 0.001 to 0.010 in. (25.4 to 254 μm), respectively. The theory of Suneja and Lee (1974) of particle collection by impaction and interception in the transition flow regime is the most appropriate for comparison with the present results. This theory, however, does not consider the effect of particle bounce. They proposed the following approximate analytical expression of the cylinder's collection efficiency for $1 < Re \leq 500$ that best fits their numerical results:

$$\eta = \frac{1}{\left[1 + \dfrac{\left(1.53 - 0.23\ln Re + 0.0167(\ln Re)^2\right)}{Stk}\right]^2} + \frac{2}{3}\frac{I}{Stk}. \quad (1)$$

Substitution of the maximum experimental value of $I = 0.118$ at constant Stokes and Reynolds numbers into this expression yields a total collection efficiency only 2% greater than that for $I = 0$. This implies that particle collection in the present experiments would be almost all by impaction. Additional particle collection by the process of collision, rebound, and then adhesion upon secondary and further collisions cannot be assessed by these experiments.

The collection efficiencies for all of the experimental cases examined are listed in Table 2 along with their corresponding average Stokes and Reynolds numbers and interception parameter values. Also listed in Table 2 are the corresponding theoretical

TABLE 2. Comparison of the Present Experiment with the Theory of Suneja and Lee (1974)

Trial No.	*Stk*	*Re*	*I*	η_{exp}	η_{theory}
1	0.71	49	0.012	0.097	0.207
2	0.71	49	0.012	0.087	0.207
3	0.71	49	0.012	0.078	0.207
4	0.71	49	0.012	0.101	0.207
5	0.88	39	0.015	0.107	0.253
6	0.88	39	0.015	0.082	0.253
7	1.25	22	0.024	0.101	0.326
8	1.25	22	0.024	0.089	0.326
9	1.25	22	0.024	0.116	0.326
10	1.25	22	0.024	0.057	0.326
11	1.55	17	0.030	0.105	0.379
12	1.55	17	0.030	0.107	0.379
13	1.91	12	0.039	0.122	0.426
14	1.91	12	0.039	0.226	0.426
15	1.91	12	0.039	0.144	0.426
16	1.91	12	0.039	0.105	0.426
17	1.91	12	0.039	0.097	0.426
18	1.91	12	0.039	0.218	0.426
19	2.86	7.9	0.059	0.134	0.528
20	2.86	7.9	0.059	0.099	0.528
21	5.02	3.5	0.118	0.415	0.653
22	5.02	3.5	0.118	0.202	0.653
23	5.02	3.5	0.118	0.068	0.653
24	5.02	3.5	0.118	0.367	0.653

results of Suneja and Lee (1974) computed using Eq. (1). Over all of the cases examined, the experimental collection efficiencies are significantly less than the predicted efficiencies, by approximately 50 to 80%. Here, theory predicts that the collection efficiency increases with decreasing wire diameter because of an increase in the interception parameter, in spite of an increase in the Stokes number. The trend of the experimental results is similar. The average difference between theory and experiment also increases with decreasing wire diameter.

This apparent discrepancy between theory and experiment can be reconciled qualitatively by postulating that solid particle bounce occurred in the region of particle collection and that it increased with decreasing wire diameter. In this region of particle collection, some but not all of the impacting particles bounced off of the wire's surface and returned to the flow. As shown by Dahneke (1971), for the capture of spherical particles by cylindrical surfaces, the energy required by an incident particle to escape the particle–surface potential well and subsequently rebound decreases, and the thickness of the laminar boundary on its frontal surface decreases with the cylinder's diameter. In addition, as the diameter of the wire decreases, the thickness of the laminar boundary layer on its frontal surface decreases. Hence, a particle with a fixed velocity incident upon a smaller wire will have a thinner boundary layer to penetrate and a smaller particle–surface potential to overcome, and, therefore, a greater probability to rebound and return into the flow. The premise that some solid particle bounce occurred in the present experiments is also supported indirectly by comparable experiments in the transition flow regime using liquid droplets that do not bounce and thereby yield a higher collection efficiency. The liquid droplet experiments of Wong and Johnstone (1953), May and Clifford (1967), Starr (1967), and

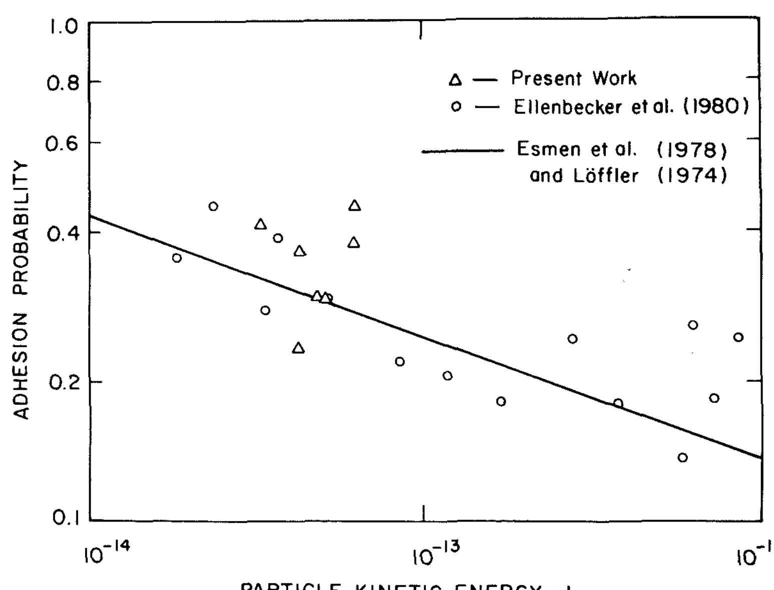
Subramanyam and Kuloor (1969) all agree well with their appropriate theoretical predictions. The experiments of Hiller and Löffler (1980) also have shown that under similar viscous flow conditions, solid quartz spheres yield a lower adhesion probability, hence collection efficiency, than do sticky paraffin droplets.

Additional indirect evidence that particle bounce occurred in the present experiments and that it solely produced the resultant difference between experiment and theory can be found by comparing the particle's adhesion probability with its incident kinetic energy. Here, adhesion is determined as the experimental collection efficiency averaged over all cases for a given wire diameter divided by the theoretical collection efficiency predicted by Eq. (1). The incident kinetic energy equals one-half of the product of the particle mass (1.48×10^{-14}) and the square of the incident velocity averaged linearly over the region of particle collection. These results are compared with those reported by Ellenbecker et al. (1980) for other solid particles. As shown in Figure 5, there is very reasonable agreement between the present experimental results, the data of Ellenbecker et al. (1980), and the linear regression fit of the data, as reported by Ellenbecker et al. (1980), Esmen et al. (1978), and Löffler (1974).

CONCLUSIONS

The present work has shown that the use of micrometer-sized wires as the collectors of solid micrometer-sized particles over a wide range of incident flow velocities can be complicated by the absence of particle collision with the wire's surface at low velocities and by particle rebound from the surface at high velocities. For the present case of fire wires subjected to a laminar jet stream containing uniformly dispersed solid microspheres, distinct regions of particle collection were observed. Those regions were bounded by regions devoid of particles. The boundaries of those regions correlated with a critical velocity, below which particles do not reach the

FIGURE 5. Comparison of experimental adhesion probability versus particle kinetic energy with the data of Ellenbecker et al. (1980), Esmen et al. (1978), and Löffler (1974).



wire's surface, and another critical velocity, above which all incident particles rebound from the surface. For the regions of particle collection, agreement between measured and theoretical collection efficiencies can be obtained by postulating a particle adhesion probability. This probability is related directly to and decreases with increasing particle incident kinetic energy.

The experiments reported in this paper were part of the M. S. thesis work of K. Renken and were conducted in the Engineering Division Aerosol Laboratory at Argonne National Laboratory (Argonne, IL 60439). His partial financial support from the University of Chicago/Board of Governors Funds for Interactions with Universities under Work Project No. 04217 and the assistance of D. M. France, his M.S. thesis advisor, are gratefully acknowledged. Partial financial support of P. F. Dunn by the Electric Power Research Institute through Contract No. RP2351 with Argonne National Laboratory and through Contract No. R962939 between Argonne and the University of Notre Dame is also acknowledged.

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Received 30 June 1985; accepted 7 October 1986