AEROSOL DEPOSITION IN BENDS WITH TURBULENT FLOW[1]

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Abstract

The losses of aerosol particles in bends were determined numerically for a broad range of design and operational conditions. Experimental data were used to check the validity of the numerical model, where the latter employs a commercially available computational fluid dynamics code for characterizing the fluid flow field and Lagrangian particle tracking technique for characterizing aerosol losses. Physical experiments have been conducted to examine the effect of curvature ratio and distortion of the cross section of bends. If it curvature ratio ($\delta = R/a$) is greater than about 4, it has little effect on deposition, which is in contrast with the recommendation given in ANSI N13.1-1969 for a minimum curvature ratio of 10. Also, experimental results show that if the tube cross section is flattened by 25% or less, the flattening also has little effect on deposition. Results of numerical tests have been used to develop a correlation of aerosol penetration through a bend as a function of Stokes number (*Stk*), curvature ratio (δ) and the bend angle (θ).

I. Introduction

Aerosol losses in bends can be significant. For example, the wall loss of 10 μm aerodynamic diameter aerosol particles in a 25.4 mm (1-inch) diameter 90° bend at a flow rate of 57 L/min (2-cfm) is calculated to be 9.5% by the DEPOSITION code (Anand et al., 1993). The code predicts the same losses would occur in 95 m of vertical tubing of the same size at the same flow rate. A typical system that continuously extracts a sample from a stack or duct will have at least one bend, which is generally needed to change the flow direction of the sampled stream from parallel to the duct axis to perpendicular to the axis. For batch sampling applications, such as US Environmental Protection Agency (EPA) Methods 5 and 17 (US EPA, 1995a and 1995b), the losses of aerosol particles in a transport system are of little consequence because the inside walls are washed at the completion of a

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batch test to recover inadvertently deposited aerosol sample. In contrast, for continuous emission sampling (CES), the system must operate for extended time periods and may be required to provide samples for near-real time data on aerosol concentration in the stack or duct (continuous emission monitoring, CEM). Any losses on the internal walls of a sampling system degrade the quality of emission or concentration data. For sampling potentially significant nuclear sources, EPA requires that methodology for CES must follow the protocol of the American National Standards Institute N13.1-1969 (ANSI, 1969), which stipulates that an evaluation shall be made of aerosol losses in a sampling system. However, EPA also permits US Department of Energy facilities (DOE) to use Alternate Reference Methodologies (EPA, 1994). The Alternate Reference Methodologies require that at least 50% of 10 μm aerodynamic diameter (AD) aerosol particles must penetrate through a transport system from the free stream in a stack or duct to the collector or analyzer. Use of the DEPOSITION software for determining compliance with this requirement is part of the Alternate Reference Methodologies.

The DEPOSITION software includes submodels for predicting losses in probes, straight transport lines, bends, and expansion and contraction fittings. For the bends, the software currently uses the model of Cheng and Wang (1981) for laminar flow and the model of Pui et al. (1987) for turbulent flow. Because most flows in sample transport systems are turbulent, the model of Cheng and Wang is not generally applicable. The model of Pui et al. only takes into account the effect of the Stokes number, and as it shall be shown herein, the curvature ratio and bend angle also affect deposition in turbulent flow. In this study, we established a numerical base for penetration of elbows and used that data base to develop a correlation model to predict particle penetration. Such a model could be used in the DEPOSITION software.

In the numerical modeling effort, we have assumed that geometrical extent of the a bend encompasses only the region where the centerline of the bend is curved, Figure 1a. On the other hand, tests with physical models involved geometries where the extent of the bends reached the same two points in space, Figure 1b. The reason for using different geometries is that the purpose of the numerical work is to establish a data base for the correlation model. When a user employs the correlation model, deposition in any straight tubing attached to the bend will be analyzed separately from the bend itself. But, when we seek to compare the effects of curvature ratio on deposition, it is necessary to add straight tubing onto bends with small values of δ to provide a common basis of comparison, so that a bend with a short curvature ratio will not have an apparent advantage over a curve with a large curvature ratio as a result of the smaller distance that the flow travels in the bend.

Flow Considerations.

Flow through straight tubes is generally characterized by the Reynolds number, with the flow being considered laminar when the Reynolds number, $Re = \rho U d_t / \mu$, is less than about 2300, turbulent when the flow is greater than about 3000 and transitional between those values. Here: ρ = fluid density; U = average (spatial) fluid velocity; d_t = tube diameter; and, μ = fluid viscosity. On the other hand, flow through bends of circular tubing depends upon both the Reynolds number and the curvature of the bend and can be characterized the Dean number, De, which is:

$$De = \frac{Re}{\delta^{1/2}} \tag{1}$$

where: $\delta = R/a$; R = radius of curvature of the bend; and $a = d_t/2$ = tube internal radius. The parameter δ is the curvature ratio of the bend. Flow is considered laminar for $De \leq 370$, which corresponds to a Reynolds number of 1170 for a curvature ratio of 10; however, the secondary flow in a bend causes the overall flow to be more stable. The critical Reynolds number can be as large as 7800 for a curvature ratio of 7 (Soh and Berger, 1984).

In general, flow through a bend is developing, so aerosol particle deposition should vary with length along the bend. For this reason, angle of the bend was treated as a variable in this investigation.

Particle deposition.

Landahl and Herrmann (1949) proposed a model for deposition of aerosol particles in a bend, where the deposition depended only on Stokes number (*Stk*). The Stokes number is defined as:

$$Stk = \frac{C \rho_p D_p^2 U}{9 \mu d_t} \tag{2}$$

where: C = Cunningham's slip correction (Fuchs, 1964); ρ_p = particle density; D_p = particle diameter; and, μ = dynamic viscosity of air. Davis (1964) used aerosol particles to visualize the secondary flow patterns due to laminar flow in pipes with a bend angles ranging from 30° to 180°; however, no data on the particle loss in the pipe were gathered. Cheng and Wang (1975) developed a model for the impaction efficiency of aerosol particles in 90° bends. Their model was based on an analytical laminar flow solution and the correlation they developed gave penetration as a function of the Stokes number, curvature ratio, and bend angle. Crane and Evans (1977) performed numerical calculations to predict the behavior of aerosol particles in laminar flow in 90° bends. They examined curvature ratios ranging from 4 to 20 and their results showed reasonable agreement with those of Cheng and Wang (1975). Chen and Wang (1981) re-examined the deposition of particles in pipe bends. They concluded that in the laminar flow regime, the aerosol particle deposition was mainly a function of Stokes number and flow Reynolds number for curvature ratios between 4 and 20. Pui et al. (1987) experimentally evaluated the deposition of aerosol particles in a 90° bends for Reynolds numbers of 100, 1000, 6000, and 10,000; and curvature ratios of 5.7 and 7. They suggested the penetration does not depend on either curvature ratio or Reynolds number and offered the following correlation for predicting the aerosol particle penetration in 90° elbows:

$$P = 10^{-0.963\,Stk} \tag{3}$$

where: P is the aerosol particle penetration. Tsai and Pui (1990) used a three-dimensional numerical procedure to examine the aerosol particle deposition for laminar flow in a pipe with a 90° bend. They found significant variation in the deposition efficiency as a function of curvature ratio. They also noticed an influence of the inflow velocity profile on the deposition efficiency. Their results using a parabolic inlet velocity profile agree well with the results of Cheng and Wang (1981).

Goals of the Present Study

There have been significant recent developments in numerical predictions of three dimensional flow fields and in particle tracking. For example, FLUENT, which is a commercially-available finite volume code (Fluent, Inc., Lebanon, NH) accommodates prediction of three dimensional turbulent flow fields using advanced turbulence models. Abuzeid et al. (1991) developed a numerical scheme for particle tracking in turbulent flows. Gong et al. (1993) used the Abuzeid approach to model aerosol sampling by a shrouded probe in an axi-symmetric (two-dimensional) turbulent flow field. Good agreement was obtained with experimental data. In the present study, that model was extended to particle tracking in three-dimensional flows, and it was used in combination with a three-dimensional flow field to predict particle losses in bends. At the present time, the only model for predicting aerosol particle penetration in turbulent flow through bends is the empirical correlation of Pui et al. (1987). A goal of this study was to evaluate the effects of bend angle, curvature ratio, Reynolds number and Stokes number, and to develop a correlation that would taken into account the necessary parameters. Also, we sought to determine experimentally the effects of curvature ratio and flattening of the cross section of a bend, and to generalize those results as design criteria.

II. Methodology

Physical experiments.

The bends were fabricated by milling the correct curvature ratio into a split block of wax, then adding tube stubs to either end of the bend. Care was taken that the transitions between the bends and the tube stubs were smooth. For all bends, tube diameter was 16 mm and the distance from the entrance plane of the bend to the centerline of the exit tube was 151 mm. The layout was setup so a bend with a value of $\delta = 20$ would require no additional straight sections; whereas, for all other bends, with smaller values of δ, straight tube stubs were added. To investigate the effect of flattening of the bend cross section, we fabricated six identical 90° bends from 16 mm diameter tubing that had curvature ratios of 10. At the 45° location, the bends were pinched to reduce the diameter in the radial direction.

The apparatus used in testing bends is shown in Figure 2. Monodisperse aerosols were generated with a vibrating orifice aerosol generator (Berglund and Liu, 1973) from a solution of a non-volatile oil (oleic acid) and an analytical tracer (sodium fluorescein) dissolved in a volatile solvent (isopropyl alcohol). A particle size of 10 μm aerodynamic diameter (AD) was used for all tests. The monodisperse aerosol was drawn into a mixing chamber plenum with a blower. A clean-up filter, which was placed in front of the blower, collected the excess aerosol.

An upstream aerosol sample was collected by replacing the bend with a sampling filter. The bend was then inserted into the flow system and an aerosol sampling filter was used to collect a downstream sample. Analytical tracer was eluted from the filters and quantified. The penetration, P, was determined from:

$$P = \frac{c_e}{c_i} \tag{4}$$

where: c_e = aerosol concentration at the exit section of the elbow; and, c_i = aerosol concentration at the inlet section. The flow rate through the system was measured with a calibrated rotameter and corrected for the actual pressure level in the system. Four replicate experiments were conducted for each set of experimental conditions.

Numerical Calculations.

Flow fields were setup through use of FLUENT. Because the flow in bends can be turbulent, with swirl, the traditional engineering κ-ϵ turbulent closure model is not adequate. Instead, a more accurate model, the Reynolds stress model (RSM), was used to describe the turbulent behavior of the flow. In the RSM, each Reynolds stress component, the turbulence dissipation rate and the velocity components are calculated. An example of the flow field in a bend is shown in Figure 3, where the velocity vectors are illustrated for a location that is two tube diameters downstream of the bend exit plane.

Particle trajectories in bends were calculated by solving the particle equations of motion as affected by the gravitational force, particle inertial force and fluid drag. In the equation for particle motion, the instantaneous fluid velocity is needed, which consists of mean and turbulent components. The mean velocity is available from the flow field computation, and the fluctuating component is generated from Gaussian random sampling of Reynolds stresses. The duration of interaction between particle and turbulence eddy is determined by the eddy lifetime, which, in turn is determined by the turbulent kinetic energy and the dissipation rate. The penetration of aerosol through a bend is calculated by tracking a large number of simultaneously released particles and determining which are deposited on the walls and which penetrate the bend.

A series of numerical experiments were conducted to establish a grid independent solution. Based on these studies, a grid size of $103\times21\times25$ was used. A similar set of numerical experiments was use to establish the time steps for particle tracking. A time step of 10^{-5} s was selected, which ensures at a particle travels at least 5 steps within a turbulence eddy.

Computations were carried out for bends with curvature ratios of 2, 4, and 10; and for bend angles of 45°, 90° and 180° at a Reynolds number of 8210. The effect of varying the Reynolds number was investigated by maintaining the Stokes number constant and varying the Reynolds number over the range of 3200 to 19,800.

III. Results

Validation of the Numerical Model. Initially, we attempted to use a particle tracking model that is imbedded in the FLUENT software; however, the agreement with experiment was not satisfactory. As a consequence we developed the three dimensional extension to the model of Gong et al. (1993). A comparison of the numerical predictions with experimental results is given in Table 1. Results are shown for different bend angles, curvature ratios and mean flow velocities. For a given set of conditions, the relative difference between the experimental value and th numerical predicition is 5%. The numerical value is higher, and the standard error of the estimate is 4%. for example, if the numerically predicted penetration is 50%, the experimental value will be about 52.5%, with an error of ±2%.

Effect of Turbulence on Particle Deposition

A flow field was setup for a 45° bend with a curvature ratio of 10, and for a Reynolds number of 8210. The penetration of particles of 5, 10 and 15 μm AD was then determined with and without the turbulence model for particle tracking. The results, which are shown in Table 2, illustrate the need for including the effects of turbulence on particle motion. For example, at a particle size of 10 μm AD, the predicted penetration is 80% without including turbulence and 62% with turbulence. Neglecting the efect of turbulence on particle motion would cause unacceptable errors in the analyses.

Effect of Reynolds Number on Aerosol Penetration

Numerical predictions were made of the effect of flow Reynolds number on aerosol penetration through a 90° bend that has a curvature ratio of 10. In the calculational procedure, the Stokes number was held constant and the Reynolds number varied from 3200 to 19,800. The results, which are shown in Figure 4, suggest that the effect of Reynolds number is sufficiently small such that it can be neglected. Over the range of Reynolds numbers tested, at a Stokes number of 0.67, the penetration ranges from 22% to 27%; and, at a Stokes number of 0.074, the penetration varies from 87.5 to 89.5%.

Experimental Results Showing the Effect of Curvature Ratio on Penetration

With reference to Figure 5, results are shown on the effect of curvature ratio on penetration for a range of Stokes numbers. The Stokes number was varied by changing the flow rate through a bend. Bends were designed as illustrated in Figure 1b to allow direct comparisons on the effect of curvature ratio, i.e., tube stubs were added to bends with short radii of curvature. The results show that increasing the curvature ratio improves the aerosol penetration. For example, at a Stokes number of 0.3, a bend with a curvature ratio of unity has a penetration of 32%, a bend with $\delta = 2$ has $P = 42\%$, and if $\delta = 4$, $P = 50\%$. However as δ is increased from 4 to 20, the penetration only changes from 50% to 58%. Also, there is very little difference in penetration between bends with curvature ratios of 4 and 10. These results suggest that a bend with a curvature ratio of 4 should be satisfactory for aerosol transport. The curvature ratio of 10 recommended in ANSI N13.1-1969 is probably too conservative.

Experimental Study of the Effect of Flattening of the Bend Cross Section

Test conducted on pinched bends provided the results shown in Figure 6 . The degree of flattening is the amount by which a diameter was reduced, divided by the original tube diameter. The bends used in these tests had initial diameters of 16 mm with curvature ratios of 10. The data show that the penetration decreases with flattening; however, if the flattening is less than about 25%, the effect is quite small. For example, at a Stokes number of 0.3, the penetration decreases from 52% to 45% as the degree of flattening is increased from 0% to 25%. On the other hand, as the flattening is increased from 25% to 50%, the penetration decreases from 45% to 16%. These data suggest that if a bend is somewhat flattened (less than 25%) during the fabrication process, the aerosol penetration characteristics would not be significantly impacted.

Numerical Modeling of Aerosol Penetration

Computational results were generated for a range of Stokes numbers ($0.07 \leq Stk \leq 1.2$); for bend angles of 45°, 90° and 180°; and for curvature ratios of 2, 4 and 10. The results are presented in Figures 7a, 7b, and 7c in the form of penetration as a function of Stokes number for constant values of the curvature ratio. With reference to Figure 7a, which is for a bend angle of 45°, it appears that curvature ratio has a pronounced effect on penetration; however, that is illusionary because of the smaller path length through which the aerosol must flow in the smaller curvature ratio bends. The experimental data shown in Figure 5 present a more appropriate view of the effect of curvature ratio, where those data are based on all bends starting and ending at the same points in space.

The data shown in Figures 7a, 7b and 7c have been used to generate a correlation of aerosol penetration as a function of Stokes number, curvature ratio and bend angle. We chose a functional form for the correlation that would have the appropriate limiting conditions over the range of the correlation of $P \to 0$ for large Stokes number, and $P \to 1$ for small Stokes number. The functional form that we selected is:

$$\ln P = \frac{c_1 + c_2 \ln Stk + c_3 \ln^2 Stk + c_4 \theta}{1 + c_5 \ln Stk + c_6 \ln^2 Stk + c_7 \theta} \tag{5}$$

where each c_i is a function of the curvature ratio, δ. A three-dimensional surface fitting program (TableCurve 3D, Jandel Scientific, San Rafael, CA) was used to generate least squares fits of the data for each curvature ratio. The results are shown in Figures 8a, 8b and 8c for curvature ratios of 2, 4 and 10, respectively. Values of the coefficients as functions of the curvature ratio were then obtained by using a two dimensional curve fitting program that was based on use of least squares (TableCurve 2D, Jandel Scientific). The results are:

$$
\begin{aligned}
c_1 &= 6.77 - 12.8\exp(-\delta)\\
c_2 &= -9.18 + 62.4\exp(-\delta)\\
c_3 &= 11.3 - 66.3\exp(-\delta)\\
c_4 &= -0.00393 + \frac{0.0277}{\delta}\\
c_5 &= -2.23 + \frac{8.49}{\delta^2}\\
c_6 &= 2.39 - 13.94\exp(-\delta)\\
c_7 &= 0.0055 - 0.0609\exp(-\delta)
\end{aligned}
$$

A comparison of predictions from the correlation model (Equation 5) with those from Pui et al. model (Equation 3) is shown in Figure 9. Good agreement is obtained between the two models for the case of $\delta = 10$; however, the model of Pui et al. under predicts the correlation model for the case of $\delta = 2$.

The need for inclusion of bend angle into the correlation model can be demonstrated by reference to Figure 10, where computational results are shown for the average deposition of aerosol per radian of bend angle, as a function of Stokes number. The developing nature of the flow causes the aerosol loss/radian to be less in a 45° bend than in a 90° bend for most Stokes numbers, although at a Stokes number of 1.2, the deposition/radian for a 45° bend is somewhat larger than in a 90° bend. For Stokes numbers less than 0.3, the aerosol particle loss/radian is about the same in either a 90° bend or a 180° bend; however, for larger Stokes numbers, the aerosol losses/radian can be considerably less in a 180° bend than in a 90° bend. This suggests that in most cases, the penetration of aerosol through a 180° bend cannot be treated as the product of the penetration of two 90° bends in series, nor can the penetration through a 45° bend be treated as the square root of the penetration through a 90° bend. Rather, the bend angle needs to be considered as a variable.

IV. Summary and Conclusions

This study employed a combination of numerical and experimental techniques to characterize aerosol penetration through bends. Agreement was achieved between numerical and physical experiments when the numerical approach was based on use of a specially developed three dimensional particle tracking technique. It was also demonstrated that turbulence needs to be included in a particle tracking model.

The effect of Reynolds number upon particle deposition was examined numerically through calculations made with the Stokes number and curvature ratio held constant. Based on experimental evidence, Pui et al. (1987) stated that there is no Reynolds number effect. Although the numerical results show some dependency of penetration upon flow Reynolds number, the effect does not seem to be sufficiently significant to warrant its inclusion in any correlation model. For Stokes numbers of 0.07 to 0.7 and a curvature ratio of 10, the aerosol penetration does not change by more than 5% when the Reynolds number is varied from 3200 to 19,800.

Physical experiments were conducted to investigate the effect of curvature ratio on aerosol penetration. The bends were constructed such that each bend had the same initial and final spatial co-ordinates, regardless of the curvature ratio. There is a continuum of change of penetration with bend angle, where the aerosol penetration increases with the curvature ratio. However, the change is much greater for curvature ratios less than 4 than it is for the larger curvature ratios. ANSI N13.1-1969 recommends that the curvature ratio should be at least 10, but the results of this study suggest that the value could be four.

When bends are fabricated from straight tubing, there is a tendency for the tubing to flatten. The flattening can be minimized by filling a tube with oil prior to bendin it, and maintaining the oil at a high pressure during the bending operation. Because that approach is expensive as compared with simpler techniques (that can cause flattening) we experimentally evaluated the effect of flattening upon aerosol penetration. Ninety degree bends were pinched at the 45° location and tested for aerosol penetration. The degree of flattening of the bends was from 0% to 50%, where the degree of flattening is the ratio of the change in diameter (caused by the pinching) divided by the initial diameter. If the degree of flattening is less than about 25%, it does not have a substantial impact on aerosol penetration.

Numerical experiments were carried out to characterize the penetration of aerosols through bends. The geometrical extent of the bends covered only the region of tubing where the radius of curvature is non-zero. Calculations were conducted for a range of Stokes numbers, curvature ratios and bend angles. Results were used to generate a correlation model that designers and users of aerosol transport systems can employ to predict aerosol penetration. The correlation is valid for $0.07 \leq Stk \leq 1.2$; $45° \leq \theta \leq 180°$; and $2 \leq \delta \leq 10$. Of immediate interest to us is the use of such a model in DEPOSITION software. A comparison of the correlation model with the empirical model of Pui et al. shows good agreement for $\delta = 10$; however, the model of Pui et al. under predicts the present correlation for $\delta = 2$. Also, the model of Pui et al. is limited to 90° bends..

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Table 1. A comparison of experimental data and numerical predictions of aerosol penetration through bends. Additional length was added to the inlet and outlet sections of the numerical configurations so the geometries would be similar for both numerical and experimental testing.

Elbow Angle	Curvature Ratio, $\delta = R_t/a$	Velocity, m/s	Numerically Predicted Penetration	Experimentally Observed Penetration[1]
45°	10	7.7	62.7%	61.8±2.1%%
90°	10	7.7	51.0%	58.3±1.7%
180°	10	7.7	27.7%	28.5±0.9%
90°	2	7.7	42.9%	39.8±1.1%
90°	4	7.7	47.2%	54.1±0.6%
90°	10	18.6	12.2%	12.1±0.3%

[1]The value following the ± sign is one standard deviation.

Table 2. A comparison of numerically predicted aerosol penetration through a 45° bend with and without the turbulence in the particle tracking model. The curvature ratio is 10 and the flow Reynolds number is 8210. Inlet and outlet tube sections were added to the geometrical configuration to make it similar to that shown in Figure 1b rather than Figure 1a.

Particle Diameter, µm AD	Penetration without Turbulence in the Particle Tracker	Penetration with Turbulence in the Particle Tracker
5	97%	82%
10	80%	62%
15	46%	35%

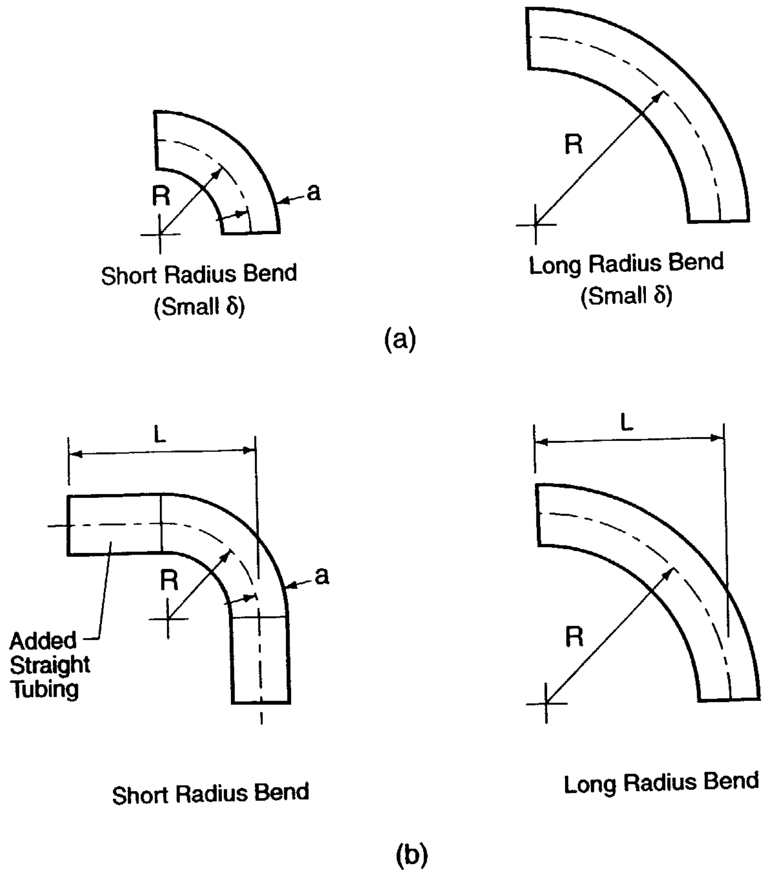


Figure 1. Geometries of bends used in a) numerical modeling, and b) physical testing.

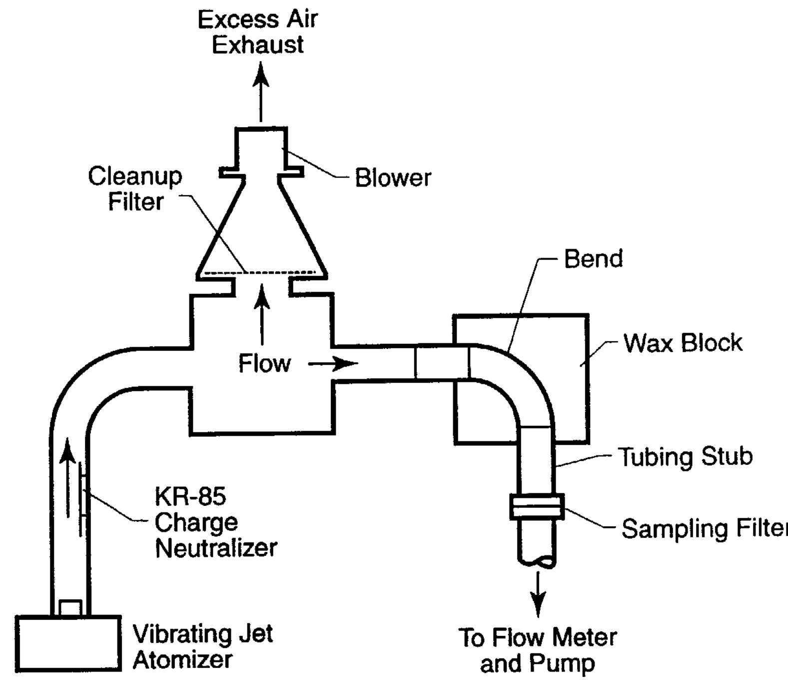


Figure 2. Experimental apparatus used in testing aerosol losses in bends.

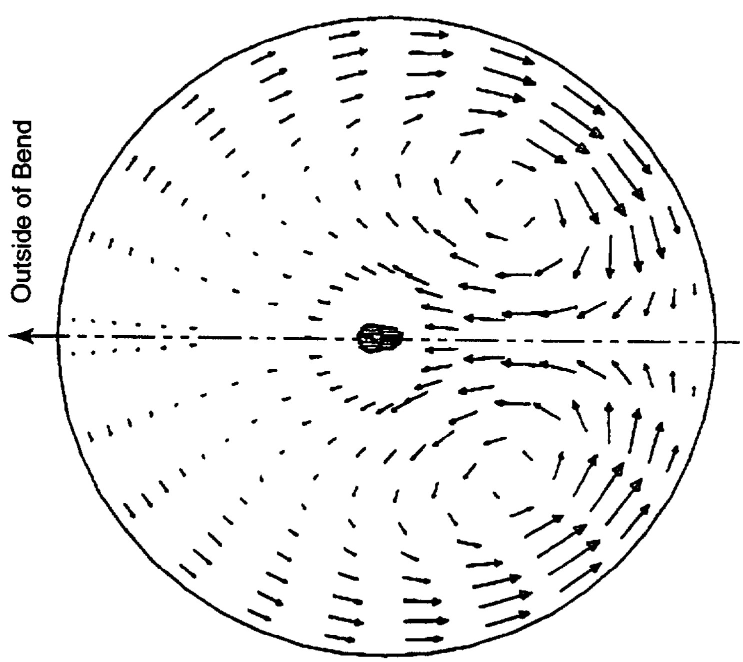


Figure 3. Secondary flow field at a distance of two diameters downstream from the exit plane of a 90° bend. The tube size is 16 mm, the Reynolds number is 8210, and the curvature ratio is 10.

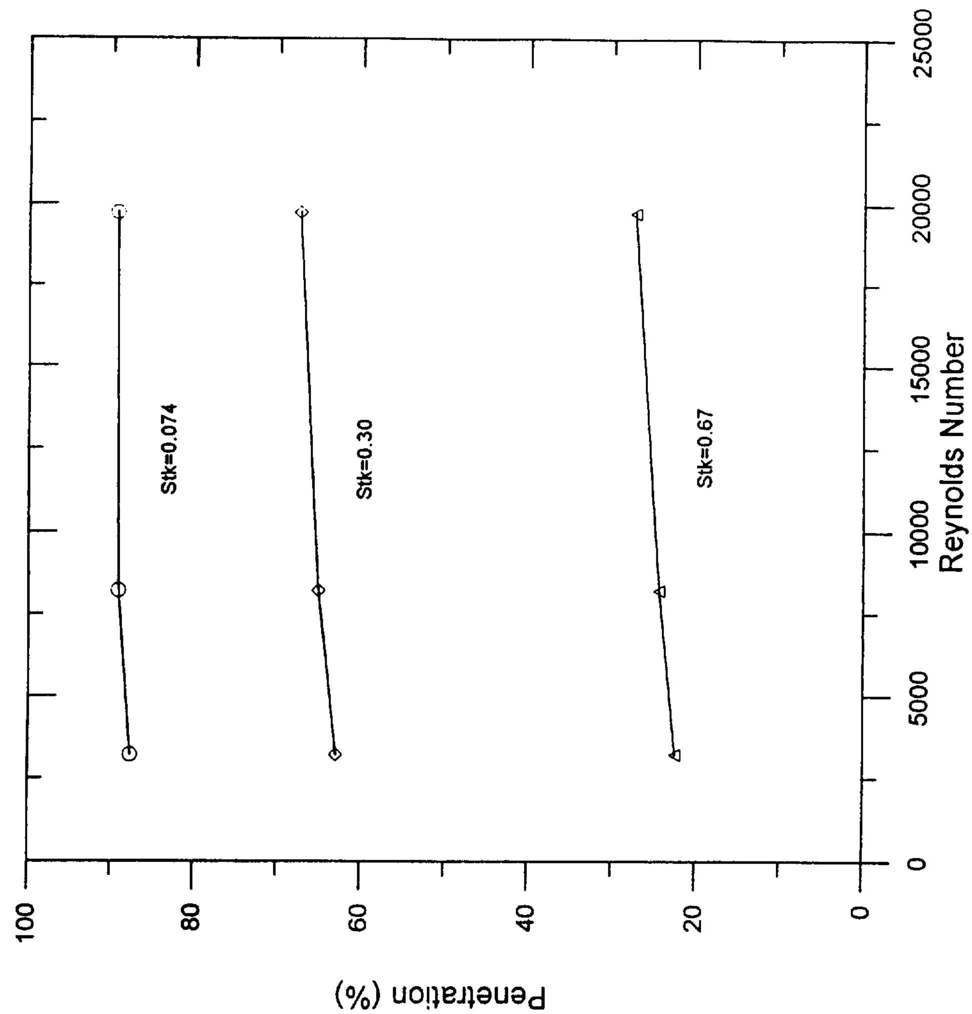


Figure 4. Numerical prediction of the effect of flow Reynolds number on aerosol penetration through a 90° bend with a curvature ratio of 10.

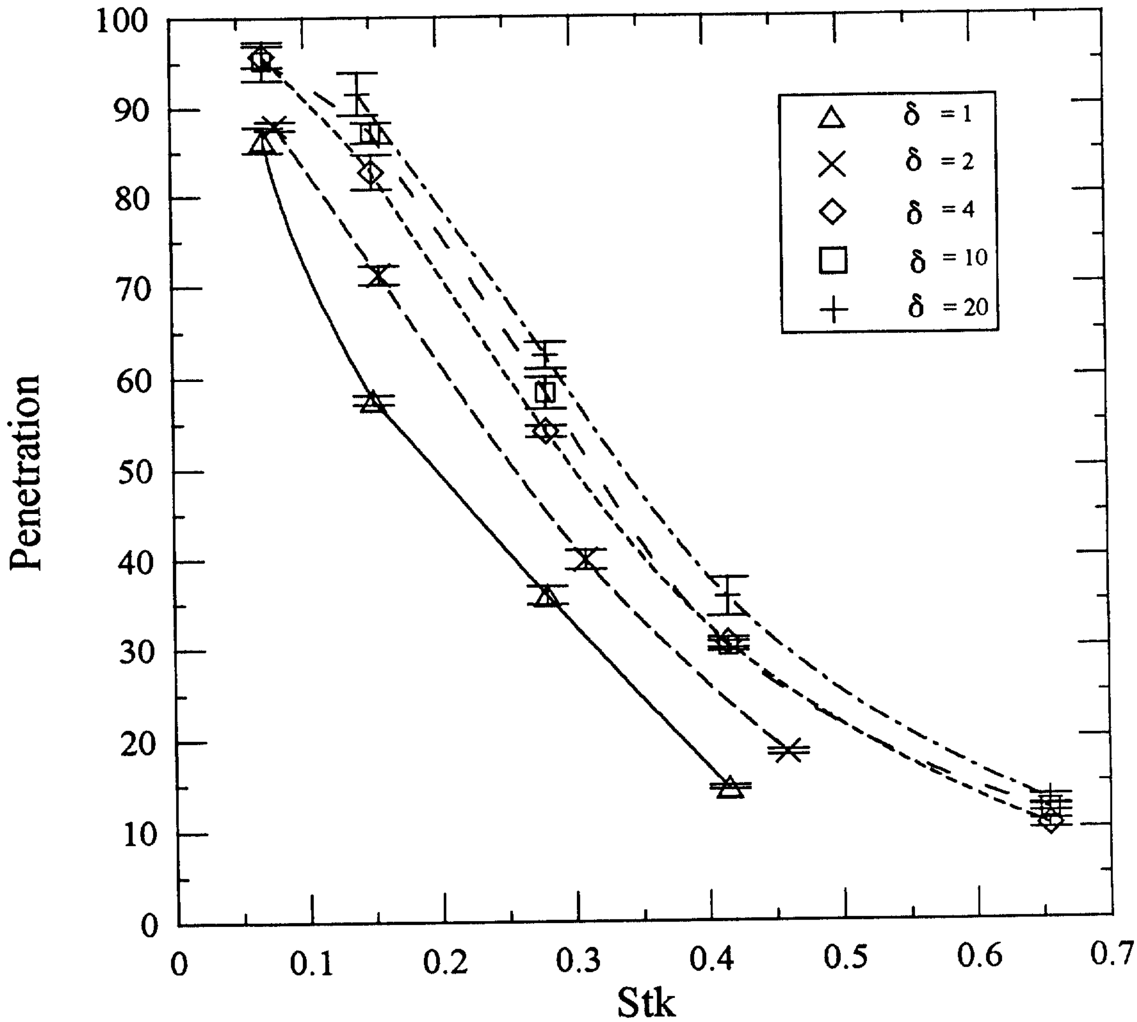


Figure 5. Experimental results showing the effect of curvature ratio on aerosol penetration through bends. The bends were designed as illustrated in Figure 1b, i.e., tube stubs were added to the bends with short radii of curvature.

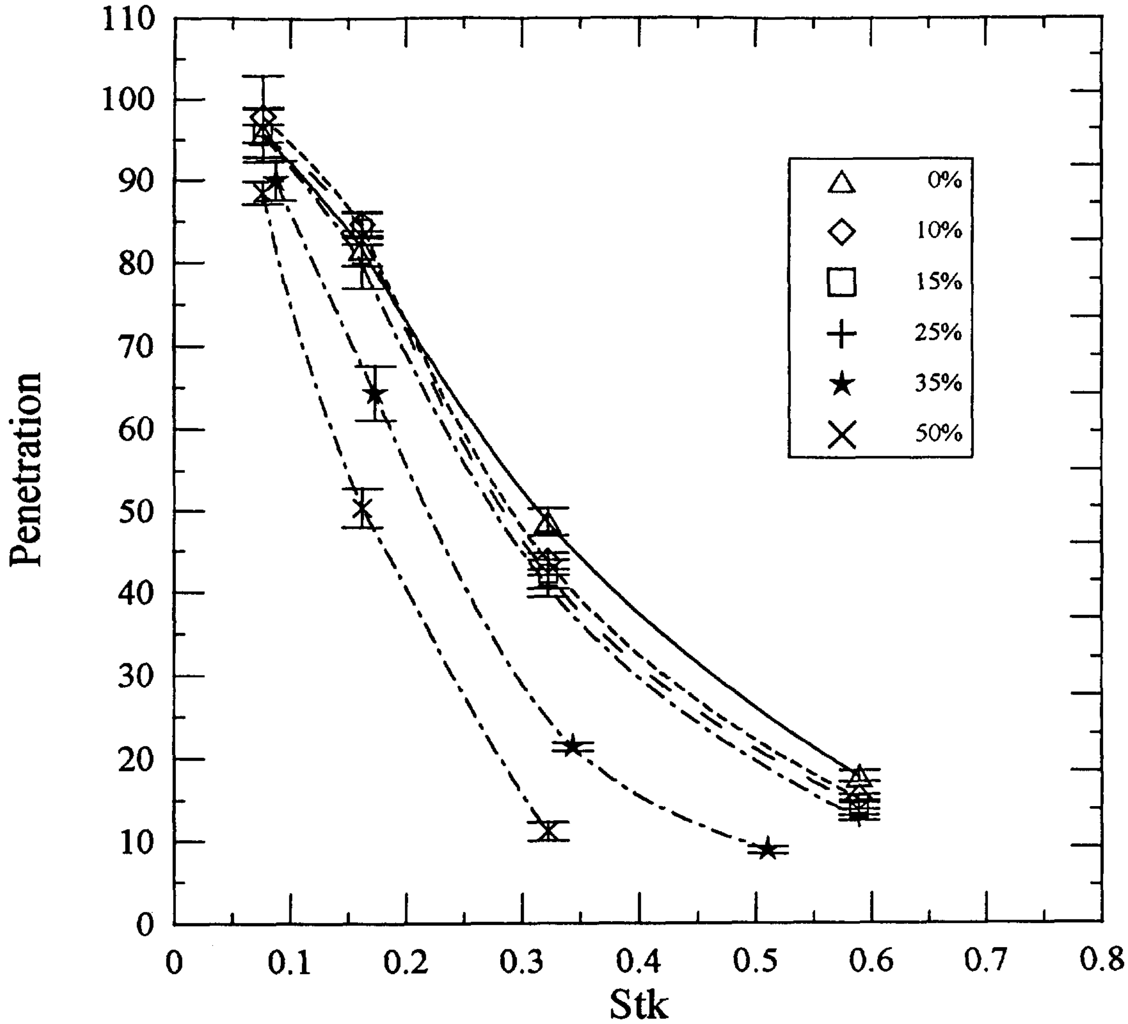
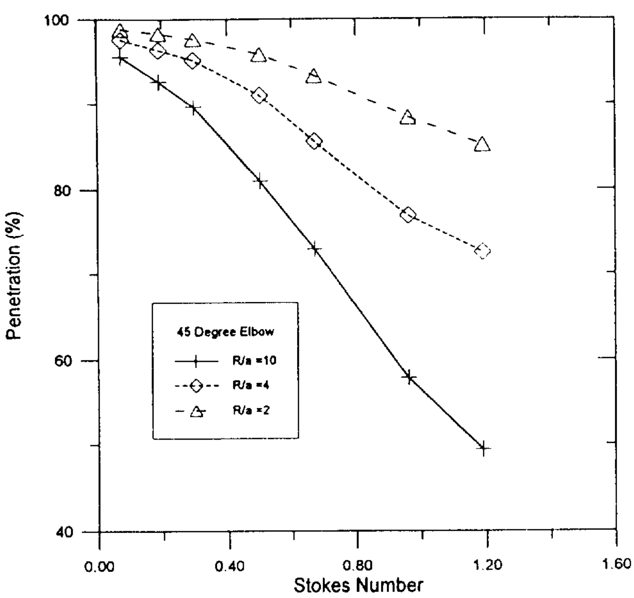
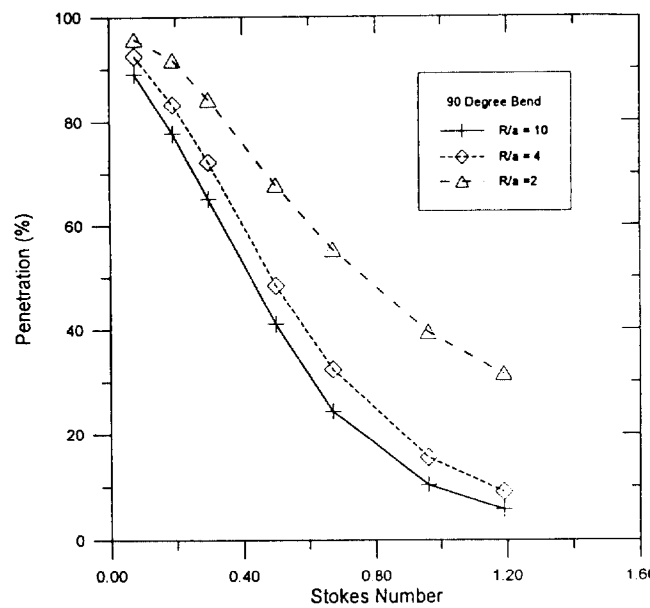


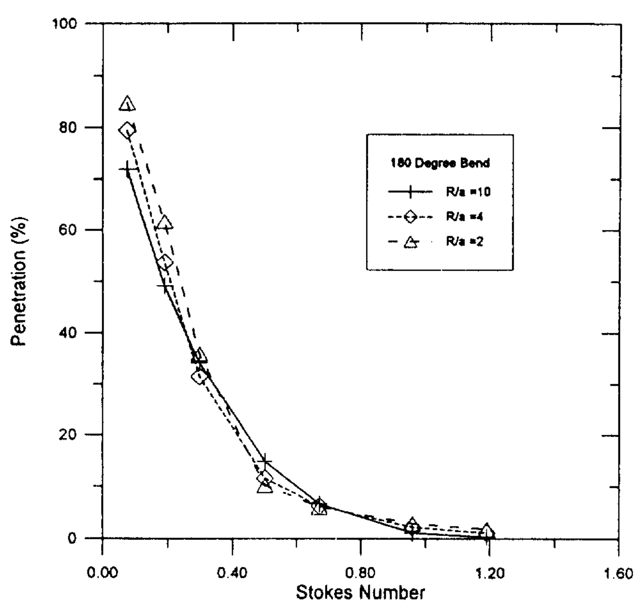
Figure 6. The effect of flattening the cross section of a bend. A 90° bend was pinched at the 45° location. The degree of flattening is the amount by which the tube diameter was reduced divided by the initial diameter. Data are for a tube that was initially 16 mm diameter with a curvature ratio of 10. Particle size used in the testing was 10 μm AD.



a)



b)



c)

Figure 7. Numerical results that show penetration as a function of Stokes number for constant values of curvature ratio and Re = 8210. a) Bend angle of 45° b) Bend angle of 90°. c) Bend angle of 180°.

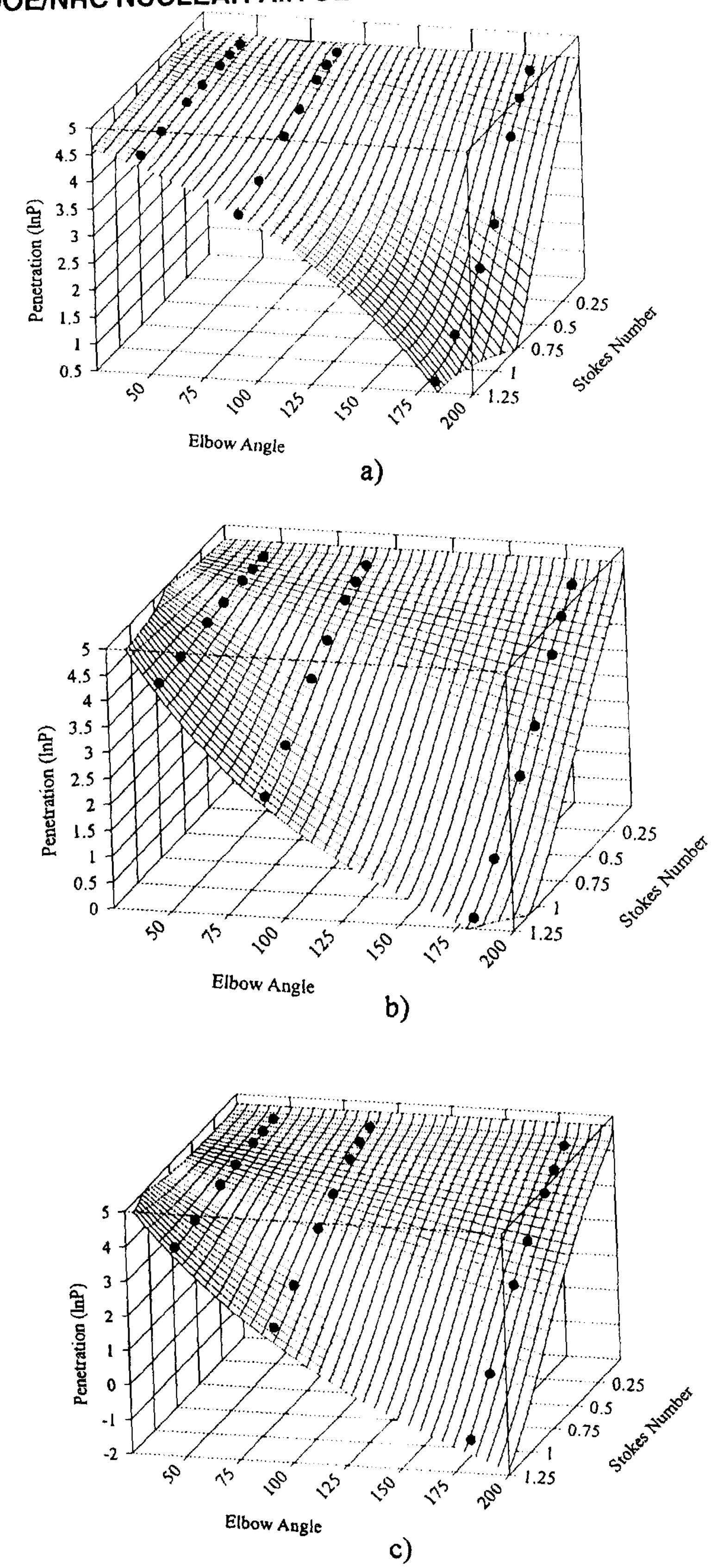


Figure 8. Surface fitting of penetration as a function of Stokes number and bend angle, for constant values of curvature ratio. a) $\delta = 2$, b) $\delta = 4$, and c) $\delta = 10$.

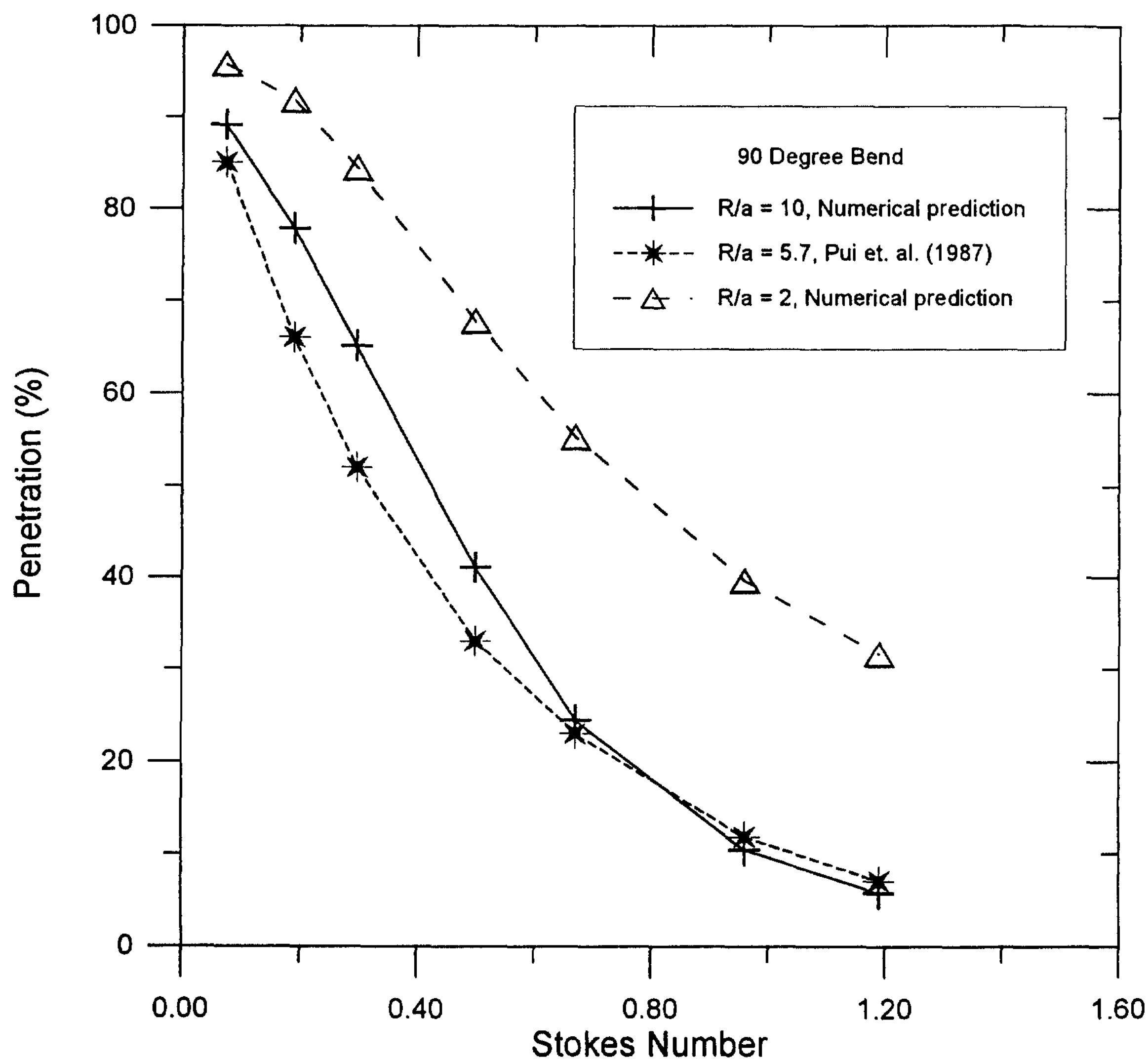


Figure 9. A comparison of the predictions of the correlation model (Equation 5) and the model of Pui et al. (1987).

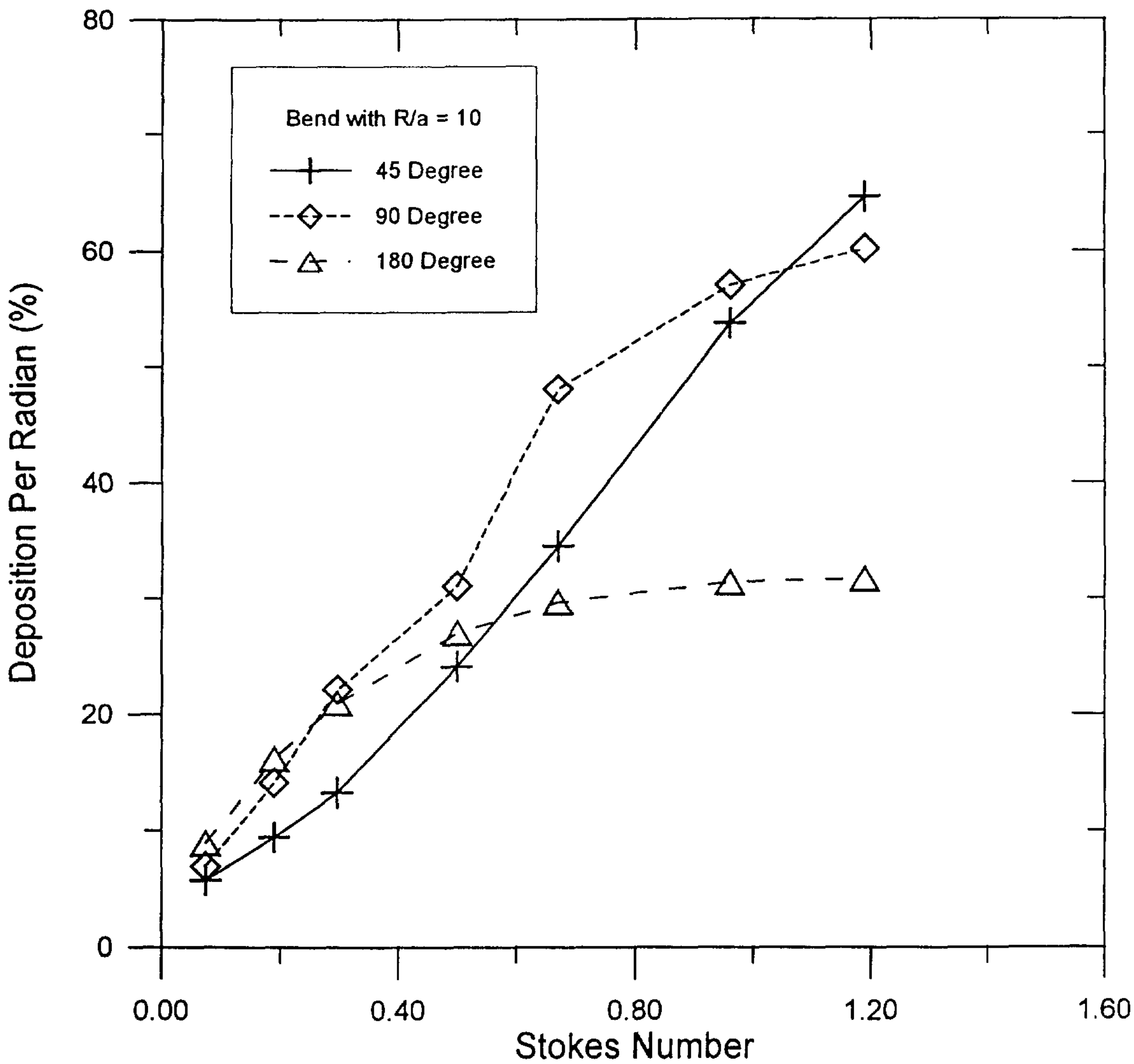


Figure 10. Effect of bend angle on deposition rate. The deposition per radian is the total aerosol lost to the internal wall of a bend divided by the bend angle.

DISCUSSION

FLEMING: How do you account for the effects of your filter sampling on your flow patterns in the downstream portion of the tube? How does that affect your flow patterns through the tube, and how do you sort that out?

MCFARLAND: What we do is assume that the sample transport line ends where the filter starts. Therefore, we make our predictions up to and including any sort of a transition, for example, an expansion or a contraction right ahead of the filter. However, the transport of aerosol from the free stream excludes the filter itself.

ADAMS: As most filter lines are lined and heated, would that have an effect on any of the data collection?

MCFARLAND: If a sample transport line was heated, I assume it is to prevent condensation of reactive gases or of water. In the code that we developed, the DEPOSITION code, we have built into it a sampling temperature and sample line pressure. The sample line pressure does not have a great impact on particle sampling transmission through a line. On the other hand, the temperature can have an effect. The temperature will influence the viscosity, which in turn will influence the particle DEPOSITION. But that is built into the deposition code, or at least into codes numbered 3.1 or higher. I am going to add that we have developed a Windows version of the DEPOSITION code. Those of you who have used the DEPOSITION code have a version which is DOS-only. The code in Windows-form is currently being reviewed by the sponsors of the work. I assume that we should be ready to release it within a couple months. If there is anyone that is interested in a copy, at no charge, leave a card with me and I will send you a free copy at the time that we do the release.

ENGELMANN: If you used the Reynolds number at the pinched bend, would you then find the deposition to be dependent upon Reynolds number? Have you any data on deposition downstream of the pinched bend? One might think it to be greater than deposition in straight tubes without bends.

MCFARLAND: In answer to the first question, we have not examined the effect of Reynolds number on a pinched bend. The data that we have on pinched bends is experimental, whereas our data on the effect of Reynolds numbers on un-pinched bends is numerical. With respect to the second question, the losses in a pinched bend are the sum of those in the pinched region and the regions of circular cross section in the bend. No experiments were conducted to directly compare losses downstream of pinched bends with the losses downstream of un-pinched bends; however, the data in Figure 4 show there are similar overall losses in bends that are pinched $\leq 25\%$, which suggests there may not be much difference between the losses downstream of pinched and un-pinched bends. Your comment on the losses in bends being greater than losses in straight tubes is well taken. Often the losses in bends are a couple of orders of magnitude greater than the losses in an equal length of straight vertical tubing.