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Journal

Journal of Aerosol Science, 25(4)

ISSN

0021-8502

Authors

Phalen, Robert F
Mannix, Richard C
Oldham, Michael J

Publication Date

1994-06-01

DOI

10.1016/0021-8502(94)90013-2

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Peer reviewed



0021-8502(94)E0037-X

SIDESTREAM CIGARETTE SMOKE DEPOSITION IN SURROGATE NASAL MODELS

ROBERT F. PHALEN, RICHARD C. MANNIX and MICHAEL J. OLDHAM

Air Pollution Health Effects Laboratory, Community and Environmental Medicine, University of California, Irvine, CA 92717-1825, U.S.A.

(First received 18 December 1992, and in final form 7 February 1994)

Abstract—It has been suggested that highly concentrated aerosols exhibit colligative behavior due to hydrodynamic interactions among particles. Such behavior includes enhanced settling rates (cloud settling) and possibly increased deposition efficiency upon inhalation. The purpose of our study was to determine whether or not concentrated sidestream cigarette smoke would deposit in an enhanced manner in hollow models that represented human nasal airways. Sidestream smoke wisps were generated by smoldering 1R3 University of Kentucky research cigarettes and were drawn horizontally through the models. The smoke aerosol had a mass median aerodynamic diameter of about $0.45 \mu\text{m}$ and a geometric standard deviation of about 1.3. Photographs indicated that the smoke consisted primarily of wisps that had characteristic diameters of about 0.3 mm and lengths that were typically greater than 1 cm. These wisps, which were surrounded by relatively particle-free air, were the entities that might exhibit cloud-like behavior. The average measured percentage deposition efficiency of cigarette smoke in the nasal casts was 4.5 ± 0.2 (SE). This value is close to what one would expect for particles of $0.45 \mu\text{m}$ aerodynamic diameter. Colligative behavior did not appear to produce measurably enhanced deposition in the surrogate nasal models.

1. INTRODUCTION

Smoke emanating from a lit cigarette (sidestream smoke) can be observed to form small ribbon-like wisps that persist in still air for seconds to several minutes. These wisps resemble small clouds surrounded by regions of relatively particle-free air. The purpose of our study was to examine the deposition efficiencies of such wisps in two life-sized hollow models that had dimensions based on the human nasal cavity. Prior to performing the study it was not clear whether the smoke would deposit in accordance with the macroscopic behavior of the cloud-like wisps, or in a manner expected for the submicrometer-size individual smoke particles.

Cloud behavior, also known as colligative behavior, arises due to hydrodynamic interactions among particles in highly concentrated aerosols. Furthermore, when particle clouds are surrounded by relatively particle-free air they are known to exhibit characteristic and rather unique behavior. The conditions under which cloud behavior occurs are relatively well understood for some cases. A cluster of particles will move as an ensemble rather than as individual particles in a wind if the net force on the ensemble (when treated as a single object) is much smaller than the sum of the forces on all of the individual particles in the cluster (Hinds, 1982; Reist, 1984). In this case, air flows around the cluster, rather than through it, and the cluster is said to behave as a cloud. Fuchs (1964) was able to simplify and quantify the conditions for cloud behavior in the case where wall effects are negligible with a "character of motion" parameter. As re-stated by Hesketh (1979), this theoretically derived parameter (M) depends on the number of particles (N) per cm^3 of gas, the effective cloud diameter (D_c) in cm, and the individual particle diameter (d) in cm. If M (which is defined in equation 1) greatly exceeds unity, then the ensemble moves as an entity.

$$M = 0.27\pi ND_c^2 d. \quad (1)$$

For the case of highly concentrated particles that are distributed in a confined volume where wall effects are significant, hydrodynamic interactions also alter their motion, but mathematical treatments are elusive (Fuchs, 1964).

An enhanced settling rate over that expected for the individual particles is one manifestation of cloud behavior. The enhanced settling rates of spherical clouds were treated by Hinds (1982) by considering the cloud as a single particle with a characteristic macroscopic diameter and a bulk density greater than that of air. The expression for the cloud settling velocity V_c is:

$$V_c = (4\rho_c D_c g / 3C_d \rho_g)^{1/2}, \quad (2)$$

where ρ_c is the net cloud density (density minus buoyancy), g is the acceleration due to gravity, C_d the drag coefficient of the spherical cloud, and ρ_g the density of the surrounding gas. The equation does not take into account the small effect of non-rigidity of the cloud, which produces internal circulation (Hinds, 1982).

Both mainstream and sidestream cigarette smoke have properties that imply the existence of significant cloud effects. The particle size distributions of mainstream and sidestream cigarette smoke generated under controlled conditions are well known (Landahl and Tracewell, 1957; Keith and Derrick, 1960; Phalen *et al.*, 1976; Hiller *et al.*, 1982, 1987; Davies, 1988). In brief, mainstream smoke aerosols have typical mass median aerodynamic diameters (MMADs) of 0.3–0.7 μm , and sidestream smoke aerosols typically have an MMAD of about 0.4 μm . Undiluted mainstream cigarette smoke typically has an initial concentration of about 3×10^9 particles cm^{-3} , which drops to about 8×10^8 particles cm^{-3} after 2 s. The number concentration in fresh sidestream smoke wisps is not known, but it may initially be similar to that of mainstream smoke. Given the measured sizes of individual smoke particles, one expects a total deposition in humans of about 10–20% for inhaled mainstream and sidestream smoke aerosols (Yeh *et al.*, 1991). Many investigators have measured the deposition of inhaled concentrated mainstream cigarette smoke, and the values reported range from 47 to 96% (Mitchell, 1962; Hinds *et al.*, 1983)—many times greater than that expected. The increase in particle size upon contact with humid air in the respiratory tract does not seem to fully resolve this paradox because the expected increase in size in the range of cigarette smoke particle diameters is likely to produce only a small change—perhaps even a lowering—in deposition efficiency (Hiller *et al.*, 1987). Martonen (1992) pointed out that hygroscopic growth of smoke particles is likely to increase their diameters only by a factor of 1.7. Also, coagulation, which increases the particle size, does not seem to be rapid enough during smoke inhalation to produce an exceptionally high deposition efficiency (Davies, 1988). In fact, exhaled cigarette smoke particles can be nearly identical in size to the inhaled smoke particles (Hiller *et al.*, 1987). Therefore, the cloud effect is a possible mechanism for producing the enhanced deposition of inhaled cigarette smoke. This effect was modeled by Martonen (1992) by postulating that air flow instabilities in the larynx and at bifurcations serve to create smoke clouds with maximum dimensions of about 0.3 cm—an upper size limit selected by considering the width of the glottic aperture. Also, Ingebrethsen (1989) presented a theoretical treatment of cloud behavior of the inhaled cigarette smoke front as it meets relatively clean residual air, concluding that “cloud movement may be an important mechanism of mainstream smoke deposition.” One notes that dilute cigarette smoke would not be expected to exhibit cloud behavior.

As part of continuing studies on the deposition of inhaled cigarette smoke, our study was designed to evaluate the hypothesis that concentrated sidestream cigarette smoke would deposit in surrogate nasal models in an enhanced manner (i.e. above the value predicted for individual smoke particles). Freshly generated sidestream smoke was chosen because it exhibits a cloud-like macroscopic structure and it has high particle concentrations. It is understood that our smoke was not typical of environmental tobacco smoke, except as it exists very near a smoldering cigarette.

2 METHODS

Our protocol involved (a) generating sidestream cigarette smoke wisps, (b) sizing the smoke aerosol and photographing the smoke so that cloud (wisp) dimensions could be measured, (c) drawing the wisps through hollow models, (d) measuring the smoke deposited

in the models and on back-up filters, (e) calculating the deposition efficiency in the models, and (f) comparing this measured efficiency with that expected for the constituent smoke particles. The experimental apparatus is shown in Fig. 1.

The hollow nasal models were designed using the dimensions of the human nasal cavity published by Scott *et al.* (1978). These dimensions not only were realistic with respect to the anatomy of the human nose, but they also yielded realistic pressure-drop vs airflow rate data and realistic deposition efficiencies for monodisperse particles (Scott *et al.*, 1978; Phalen *et al.*, 1989). Our adult-sized nasal models (Fig. 2), consisting of hollow cavities in silicone rubber cylinders, were used at steady airflow rates of 7.5 L min^{-1} in order to represent the average inspiratory flow through one side of the human nose during near-resting ventilation.

Smoke was supplied by a smoldering 1R3 University of Kentucky (Tobacco and Health Research Institute, Lexington, KY) unfiltered research cigarette. The cigarettes were stored in a sealed, humidity-regulated container at $23 \pm 2^\circ\text{C}$ and $60 \pm 2\% \text{ RH}$ for at least 24 h prior to their use. The smoke passively rose 55 cm in a vertical copper pipe 5.1 cm in diameter before being drawn through the model, sampled, or photographed. This distance was selected because it was greater than the distance required for the smoke stream to lose its rapid thermally driven vertical velocity. After about 45 cm of rise the smoke was seen to breakup into apparently randomly oriented ribbon-like wisps. For photographing the wisps, slit illumination (from a 300 watt carousel slide projector, Kodak, Rochester, NY) was provided and a 35 mm camera (Spotmatic F, Pentax, Honeywell, Denver, CO) fitted with a

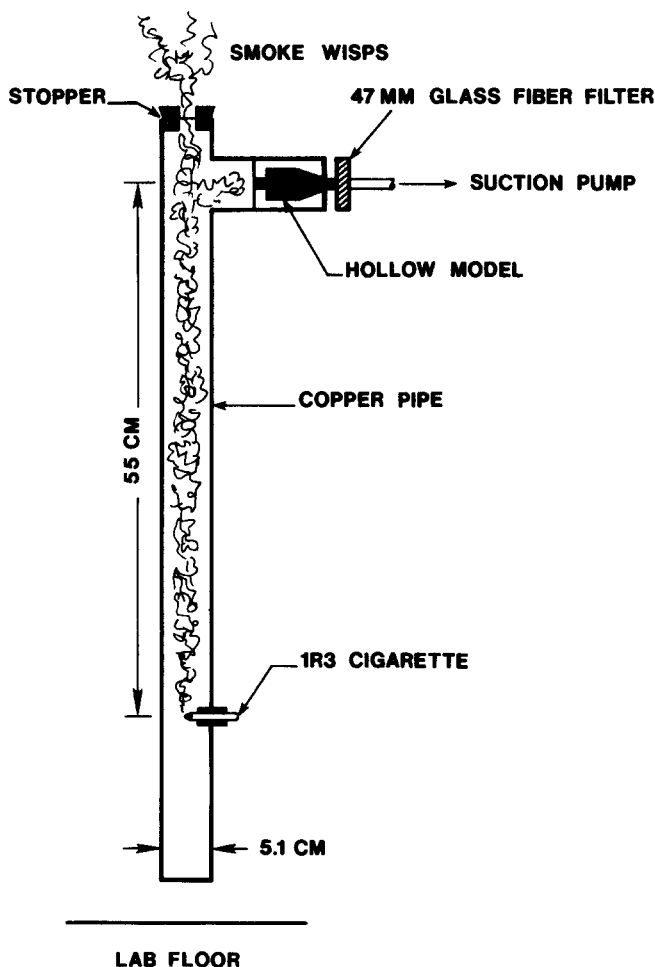


Fig. 1. Experimental apparatus for examining the deposition efficiency of sidestream cigarette smoke in hollow surrogate nasal models. For smoke photography and aerodynamic sizing, the model was replaced by a 35 mm camera and a 7-stage cascade impactor, respectively.

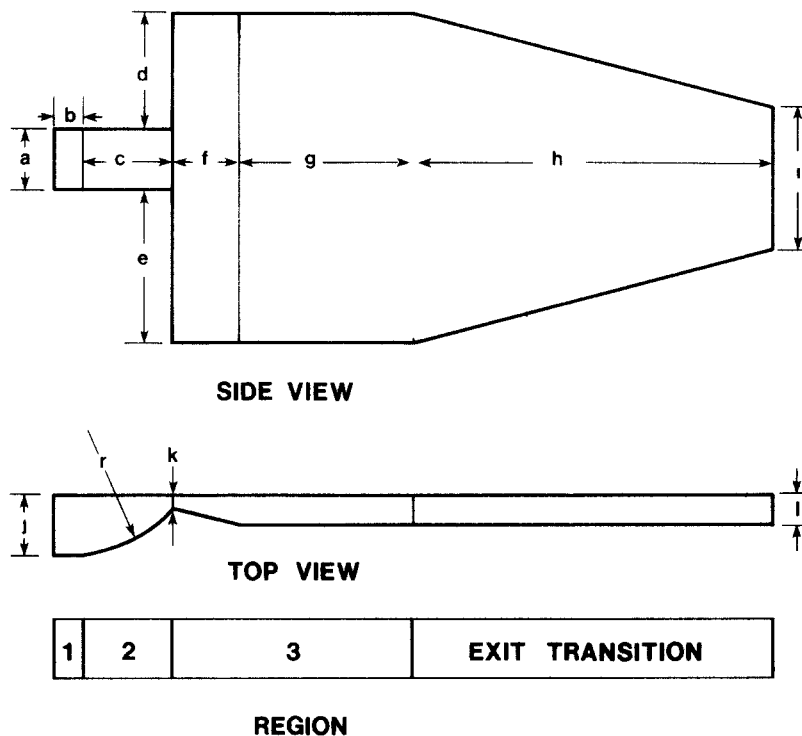


Fig. 2 Internal shape of the hollow surrogate nasal models used. The model represents the first three regions of the nasal cavity, which are anterior to the turbinates (4th region). The drawing is to scale, dimension $a = 1$ cm

50 mm close-up lens (Macro-Takmar, Honeywell, Denver, CO) and loaded with ASA 400 film (Tri-X pan, Kodak, Rochester, NY) was used. Exposure times of 0.25 s provided photographs with good resolution of the wisp detail. Wisp dimensions were measured by projecting the photographs on a screen and measuring the widths of 33 wisps with a 0.01 mm scale constructed from a grid photographed using the same slit illumination setup as was used to photograph the smoke.

In order to obtain estimates of the mass median aerodynamic diameter and geometric standard deviation (GSD) of the smoke aerosol, two calibrated Mercer-type seven-stage cascade impactors with back-up filters (Model MCR 02-140, In-Tox Products, Albuquerque, NM) were used. When sampling, an impactor was placed in the apparatus at the position previously occupied by the nasal model. A flow rate of 2 L min^{-1} was used. At this flow rate these impactors have stage effective cutoff diameters of 0.25, 0.42, 0.68, 1.15, 1.9, 3.1 and $5.1 \mu\text{m}$. The stainless steel impactor stages (uncoated) and the exit filters were sonicated for 15 min in isopropyl alcohol to extract the smoke deposits. The extracts—filtered using $0.2 \mu\text{m}$ pore size fluorocarbon syringe filters—were quantified using an absorption spectrophotometer (Spectronic 301, Milton Roy, Rochester, NY) operated at a wavelength of 350 nm. Two impactor samples were taken using each of the two identical impactors. The cascade impactor data were fit to a log-probability function (Fig. 3) and the MMADs and GSDs determined using a weighted, least-squares fitting program.

Each smoke deposition experiment with a hollow model was performed twice, and the smoke deposits were extracted by thoroughly rinsing the cast cavity with isopropyl alcohol until the rinse was free of smoke deposit. The deposit on the filter behind the cast was extracted in isopropyl alcohol and the cast and filter deposits measured with the spectrophotometer as previously described for the impactor samples.

Deposition efficiency in the hollow surrogate nasal models was compared to published values of measured and calculated monodisperse particle deposition for the human nose (Yu *et al.*, 1981; Yeh *et al.*, 1991; Heyder and Rudolf, 1977; Morrow *et al.*, 1966). If our measured deposition efficiency was not significantly higher than these accepted values for the human

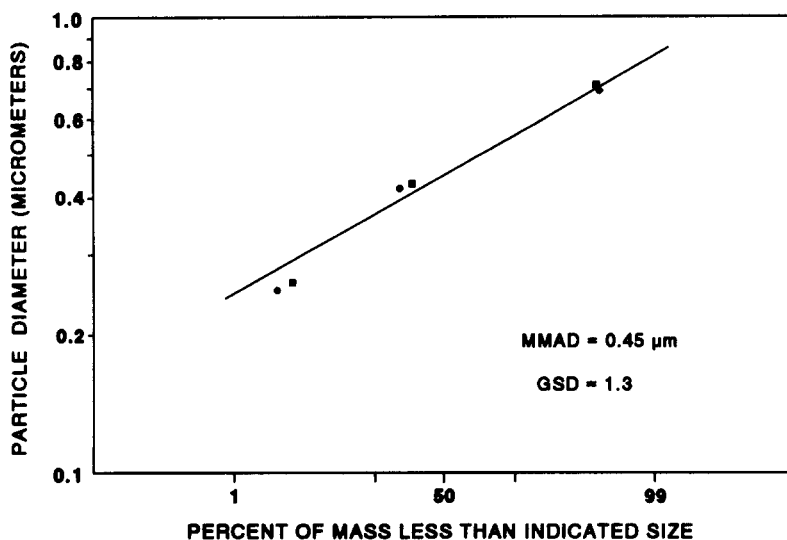


Fig. 3. Results of two size-distribution determinations on sidestream cigarette smoke. Two different 7-stage impactors of the same type were used.

nose, then we would consider the result as refuting our hypothesis that cloud behavior significantly enhances the deposition of sidestream cigarette smoke in the nose-like casts.

3. RESULTS AND DISCUSSION

The average MMAD of the cigarette smoke was $0.45 \mu\text{m}$ and the estimated GSD was 1.3, which are consistent with previously reported particle size distributions for cigarette smoke (Davies, 1988). Measurement of smoke wisps gave a mean diameter of $0.32 \mu\text{m}$, with a standard deviation of $0.26 \mu\text{m}$ (standard error = $0.04 \mu\text{m}$). The wisps were ribbon-like and had lengths of several centimeters. Because they were frequently longer than the photographic field of view, their lengths were not quantifiable. Two measurements of smoke deposition were made in each of two hollow models giving deposition efficiencies of 4.8, 4.5, 4.0 and 4.6%. The mean efficiency was thus estimated to be $4.5 \pm 0.2\%$ (SE).

The published values of the deposition efficiency of monodisperse particles in the diameter range of $0.3\text{--}0.5 \mu\text{m}$ in the human nose are similar to what we observed using our hollow models (Fig. 4). Yu *et al.* (1981) reviewed the literature and analyzed the results of particle deposition measurements in the human nose made by seven investigators. The mean nasal deposition efficiency for $0.45 \mu\text{m}$ particles predicted from this meta-analysis was 5.1% for humans at resting ventilation. Measurements of the deposition efficiencies of monodisperse $0.5 \mu\text{m}$ particles in four human subjects were made by Heyder and Rudolf (1977); their observed nasal deposition values were 4, 4, 4 and 3%. A recently developed computational model, taking into account both impaction and diffusion mechanisms in the human nose, was published by Yeh *et al.* (1991). Linear interpolation between their published values for 0.3 and $0.6 \mu\text{m}$ diameter particles yields a predicted nasal deposition efficiency of 4.1% in the human nose. These values for nasal deposition are all remarkably similar to that measured in our casts. On the other hand, the 1966 ICRP (International Commission on Radiological Protection) Task Group on lung dynamics (Morrow *et al.*, 1966) semi-empirical model for particle deposition in the human nose at resting ventilation predicts an efficiency of 0% for $0.45 \mu\text{m}$ diameter particles. At the time of this earlier model, impaction was the only deposition mechanism considered for the nose.

As noted above, observed deposition efficiency in the hollow nasal models was not significantly higher than the values found in actual human studies or predicted using a modern mathematical model that took particle diffusion into account. Therefore, the measured smoke deposition efficiency (4.5%) causes us to reject the hypothesis that cloud

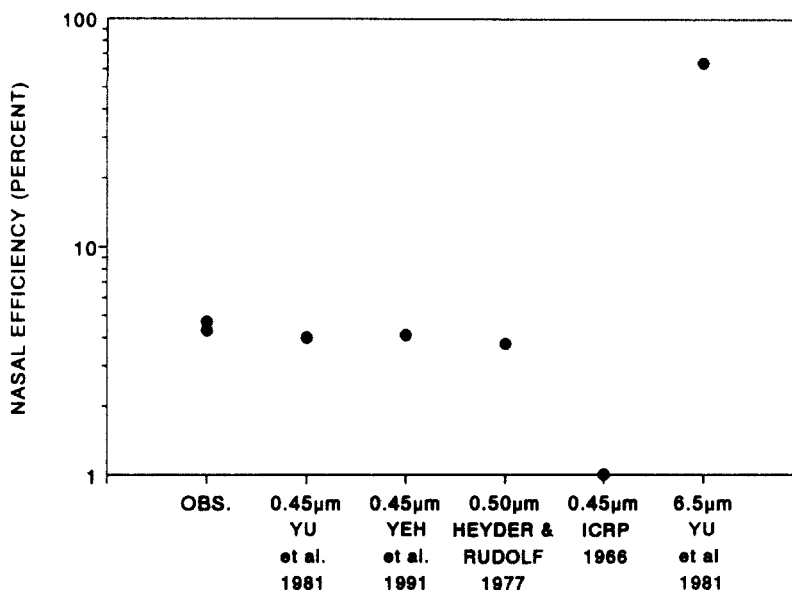


Fig. 4. Comparison of the observed deposition efficiency of sidestream cigarette smoke in our hollow models with published nasal deposition efficiencies for 0.45 and 6.5 μm diameter particles.

behavior produced enhanced smoke deposition in the hollow surrogate nasal models. Previous studies of particle deposition using our hollow models over a wide range of airflows with 0.8 and 2.02 μm diameter monodisperse polystyrene latex particles (Duke Scientific, Palo Alto, CA) indicated that our models gave deposition efficiencies that were very similar to those measured using human subjects (Phalen *et al.*, 1989).

Black and Pritchard (1984) estimated the total respiratory tract deposition efficiency of inhaled radiolabeled cigarette smoke in active cigarette smokers by studying clearance curves for the radiolabel. These investigators concluded that the cigarette smoke behaved as if it was equivalent to an aerosol with a MMAD of 6.5 μm . Our result does not refute the hypothesis that cloud behavior produces enhanced smoke deposition in areas beyond the nose such as the tracheobronchial or alveolar airways. Based on our observed wisp dimensions, however, smoke wisps might be expected to behave in free air as if they had aerodynamic diameters even larger than 6.5 μm . One presumes that forces produced by air turbulence, and other shear forces such as those on wisps that touched airway walls, were capable of disrupting wisps in our nose models. If we use an equivalent cloud MMAD of 6.5 μm (from the Black and Pritchard study) to provide a predicted value of nasal deposition efficiency, the analysis of Yu *et al.* (1981) provides a value of over 60% (also shown on Fig. 4). Clearly, the smoke in our study did not deposit as if it were composed of 6.5 μm particles. Thus, we conclude that cloud behavior probably did not significantly influence the nasal deposition of sidestream cigarette smoke; however, it may influence the deposition elsewhere in the respiratory tract, where shear forces are much smaller. Finally, our study does not rule out the possibility that factors other than cloud behavior are responsible, in part or even fully, for producing the enhanced deposition observed by others in human studies.

Acknowledgements—The research was supported primarily by the University of California Tobacco-Related Disease Research Program (Grant # 1RT-324), and in part by the National Heart, Lung and Blood Institute (Grant # RO1-HL39682). Dr Phalen is a member of the U.C. Irvine Occupational Health Center. The authors thank Dr Derek Dunn-Rankin of the School of Engineering, University of California, Irvine, for helpful advice, and Marie Tonini for word processing.

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