Experiments on Collection Efficiency. I. The Collection of a Vented Aerodynamic Probe

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ABSTRACT

This paper shows the necessity of determining experimentally the collection efficiency of an aerodynamic probe, before using it to collect an aerosol. The experimental techniques described herein, although applied to a particular probe, are general.

The collection efficiency of a vented probe is shown to be in excess of 1 at certain speeds and particle sizes while the experimental collection efficiency for a cylinder is close to theoretical predictions.

1. Introduction

During the summer of 1966, the Desert Research Institute conducted flights using a salt particle sampler (illustrated in Fig. 1). Behind the slit was a gelatin impaction medium. These flights were made in conjunction with project Hailswath and were intended to provide areal and vertical distributions of sodium chloride particles. The gelatin medium was impregnated with AgNO_3 , the reagent specified by Vittori (1956). Microscopic examination of the gelatin revealed that the apparent concentration of salt particles was not only higher than previously observed (Byers *et al.*, 1957), but also that many of the salt particles were smaller than the smallest size collectable using the Langmuir and Blodgett (1946) or Ranz and Wong (1952) collection efficiencies for simple shapes. The possibility that the spurious result was due to contamination of the sample while being analyzed in the laboratory while present in the first samples, was eliminated subsequently using the technique developed by Hoffer and Vittori (1966).

It was apparent that an experimental determination of the collection efficiency of odd shapes with slits would have to be made, if valid data were to be taken. One consideration in designing such an experiment is whether the aerosol or the sampling probe should be stationary. It is logical that better measurements of the aerosol can be made if it is stationary and in a confined space. The space, however, must be large enough so that the walls do not influence the result. In general, the number and size of the particles comprising the aerosol which is to be sampled by a moving probe can be determined accurately. If the aerosol moves, the determination of its properties is more difficult.

The confinement of the aerosol, its generation, and the method of propelling the probe through the aerosol require careful consideration to insure that a repeatable measurement can be made.

2. Experimental arrangements

The first experiments were conducted using an automobile to propel the probe or probes through a box containing an aerosol. These experiments showed a distinct difference between the collection by the sampler and the collection on spheres and cylinders. Fig. 1 shows the configuration of probes on the sampling arm as well as the shape of the salt sampler with its entrance slit.

Although the variation from sample to sample was large in these initial experiments, the cylinders and spheres had an average collection efficiency close to that predicted by Langmuir and Blodgett (1946). The observed collection efficiency is radically different from that which would be predicted if one made the usual assumption that a sampler of this shape could be treated as a cylinder or sphere. The use of an automobile on a drag strip for more than a crude experiment is unrealistic; the speed is limited; temperature contrasts between the ambient air and the air inside the confining box are impossible to avoid; and the car introduces turbulence around the box.

An alternate technique was developed as illustrated schematically in Fig. 2. The sampling probe, also illustrated in Fig. 1, was suspended from the 150 m long wire by a simple hanger onto the cylindrical body. The wire was stretched to a tension of 8620 bars. At this tension the sag in the wire over the 150 m length was minimal as was the lateral movement of the probe as it moved down the wire.

FIG. 1. The salt sampler and other probes as mounted in the initial experiments. Also shown is the scaled salt sampler probe used in the final experiments.

The probe (which models the salt sampler), hanger and body were propelled along the wire with solid-type toy rocket motors. The average weight of the probe, hanger and body was less than 70 gm. By using rocket motors with different amounts of thrust, a wide speed range (from less than 20 to over 130 m sec⁻¹) was attainable.

The speed of the probe was measured by interrupting light beams with the hanger. Two speed measurements were made on each experiment: one just prior to the probe entering the box, the other just after the probe left the box. The wooden tunnels on each end of the shed housing the box were used for this purpose. In the initial phases of data collection

FIG. 2. A schematic view of the experimental complex.

three speed determinations were made to test whether or not the probe was decelerating as it went through the tunnels and box. A negligible speed change (less than 5%) was noted.

3. The sampling chamber and aerosol

The sampling chamber has internal dimensions of 183 cm by 91 cm by 91 cm, a volume of $1.5 \times 10^6 \text{ cm}^3$. There are doors in both ends and a sliding panel in the front for easy access. It is thermally insulated, well sealed, and large enough so that the walls do not influence the probe. The aerosol is thoroughly mixed by an internally mounted fan.

The aerosol itself was generated from salt solutions. The liquid was atomized with an ultrasonic generator operating at a frequency of 100 kHz. The droplet distribution generated is stable if the liquid is delivered to the generator at a constant rate. Delivery of the liquid at a constant flow is easily attainable with a constant speed pump. The drop distribution was determined to be log normal. This permits the use of the normal statistics after a logarithmic transformation.

The stability of the drop distribution was shown by collecting droplets in silicone oil, photographing under the microscope, counting, and then comparing the distributions obtained at different times statistically. No statistically significant differences were noted.

Assuming that droplet coalescence can be neglected and that the concentration of the solute within the droplets is uniform, the number and size of the residual salt particles remaining after the droplets evaporate can be calculated. Experiments were conducted when the relative humidity was less than 30%; this ensured that the droplets had evaporated completely.¹ In addition, when the particles were collected on the bottom of the sampling chamber on hard gelatin they did not appear to have splashed (no satellite particles were observed) and the particles were cubic.

The salt particles were assumed to be uniformly distributed throughout the sampling chamber. This assumption was verified by the following procedure: An aerosol was generated with the fan stirring the air in the closed sampling chamber for the usual aerosol generation time of 5 min. At the end of that period the fan was shut off and the aerosol permitted to fall onto prepositioned gelatin-coated slides on the bottom of the sampling chamber. Twelve slides were distributed with random spacing for each experiment conducted. The slides were removed after 2 hr and the average number of particles per field of view determined for the various sampling positions. A two-

way analysis of variance showed that the assumption that the aerosol was uniformly distributed should not be rejected at the 95% confidence level.

The total number of particles in the box was calculated from the average number per field of view on the floor gelatin samples. The number obtained agreed within a factor of 1.6 with the calculation of the number of particles generated. (The smaller particles were not as frequently observed as would be calculated from the droplet distribution). For the purposes of the experimentation on probes containing a slit, the checks on the aerosol were adequate since the initial experiments indicated gross differences between theory and observation.

4. Data acquisition and reduction

Data were collected only when the humidity was low, the temperature warm, and the wind less than 2 mph. These conditions were selected to ensure that the droplets would evaporate and so that the wind could not sway the rocket or influence the aerosol within the box.

The experiment was performed as follows:

Air within the box was replaced with outside air which had passed through a thermal precipitator which removed all salt particles. After the box was aired a fresh aerosol was generated. While the aerosol was being generated, a new gelatin-coated film was placed on the probe and the rocket made ready for firing.

At the end of the 5-min generation time, the end doors opened by falling. When these doors fell clear of the wire they activated a circuit which fired the rocket. The elapsed time from the opening of the doors until the rocket had passed through the box was timed to be a maximum of 20 sec.

After the rocket had passed through the sampling chamber and stopped, the coated mylar film was removed from the probe, its gelatin surface sprayed to prevent contamination, and mounted on a glass slide. Since the silver nitrate in the gel reacts with the salt particle more rapidly under ultraviolet light, the slides were exposed to high intensity light for 15 min. The area of the sample surrounding the stagnation streamline was then photographed under the microscope. Generally, 30 fields of view were photographed for each sample. A high contrast, high ASA film was used, and by adding appropriate filters a white-on-black negative was obtained. The reaction sites were then sized and counted with a semi-automatic system. Data were subsequently processed using a computer. The original particle size was computed using the calibration given by Hoffer and Presley (1971).

The ratio of the theoretical number of particles in the path to the number of particles collected (collection efficiency) was obtained by the following procedures:

¹ A calculation showed that the time required for the droplets to evaporate completely was less than 10 sec under these conditions. The total mass of water added was 0.5 gm to a box of almost 2 m³. (The saturation vapor pressure was around 30 gm m⁻³ with a maximum environmental mixing ratio of 9 gm m⁻³.)

FIG. 3. Experimental collection efficiency as a function of speed. Each graph shows the results for a different size range of particles. The dots indicate the experimental data, and the circles the mean values. Two theoretical lines are given for each particle size. These are calculated values of collection efficiency at the stagnation point (solid lines) and average collection efficiency (dashed lines) for a 1-cm diameter cylinder.

1) The log normal plot was divided into six class intervals each containing 15% of the drops. The lowest and highest 5% were discarded.

2) The particle sizes comprising each class interval were computed using the assumptions that the salt concentration was uniform, each drop evaporated, and each drop produced one particle.

3) The number of particles collected within each class interval was determined by counting the experimental data. The ratio of the observed number of particles to the theoretical number was computed.

5. Collection efficiency of the probe

Fig. 3 shows the collection efficiency as a function of particle size and speed of the probe for the vented probe with a slit entrance. The vented probe is identical to the salt sampler in front-end configuration, except that the former is shorter in height. The salt sampler itself and the probe used in the initial studies were both vented.

The apparent size of an error on a logarithmic scale is misleading since the length of an error bar is distorted when plotted on a nonlinear scale; therefore, the error bars for the collection efficiency are omitted. As can be seen from the data points there was a slight variation in speed for rocket engines with identical specifications.

The method of venting influences the collection efficiency. For our probe and sampler, the air entered through the front slit and left at the back. The sampler was vented by drilling holes on the back side of the metal shield. The salt sampler was vented by means of an air space between the body and the back of the shell. If a probe is vented or deviates from a simple shape, it must be calibrated. If calibration is impossible, then the probe must be made to collect as a simple shape.

The probe throughout the size range investigated and over the speed range studied collected more particles than anticipated from the theory (if an assumption concerning shape is made). The simultaneous experiment with the probe and simple shapes showed that the collection of spheres and cylinders satisfactorily agreed with Langmuir and Blodgett (1946). Experimental error does not account for the differ-

ences. This increased collection accounts for what was observed during the summer of 1966.

If the head of the probe is taken to be a 1 cm radius sphere, the Reynolds number at the slowest speed is close to 2×10^4 while at the highest speed it is around 8×10^4 . Obviously, the flow is turbulent with eddy shedding. This should cause a low pressure region to develop in the rear of the probe which in turn would cause a higher flow through the probe and hence a greater particle collection.

Regardless of the physical explanation, the vented probe does collect more particles than a simple shape. Therefore, any vented probe which has been calibrated will yield a statistically meaningful result for a smaller sampled volume than a simple shape. This permits a higher spatial resolution.

This study has not examined the effects of varying the flow through the probe by controlling the ventilation at the back of the probe. This will be dealt with in a subsequent paper. Thus, no definite comment can be made concerning the collection of Formvar samplers such as that described by McCready and Todd (1964). However, any ventilation should lead to increased collection.

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