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PRELIMINARY DESIGN OF A PROTOTYPE PARTICULATE STACK SAMPLER

by

J. C. Elder, L. G. Littlefield, M. I. Tillery, and H. J. Ettinger

ABSTRACT

A preliminary design of a prototype particulate stack sampler (PPSS) has been prepared, and development of several components is under way. The objective of this Environmental Protection Agency (EPA)-sponsored program is to develop and demonstrate a prototype sampler with capabilities similar to EPA Method 5 apparatus but without some of the more troublesome aspects. Features of the new design include higher sampling flow; display (on demand) of all variables and periodic calculation of per cent isokinetic, sample volume, and stack velocity; automatic control of probe and filter heaters; stainless steel surfaces in contact with the sample stream; single-point particle size separation in the probe nozzle; null-probe capability in the nozzle; and lower weight in the components of the sampling train. Design considerations will limit use of the PPSS to stack gas temperatures under approximately 300°C, which will exclude sampling some high-temperature stacks such as incinerators. Although need for filter weighing has not been eliminated in the new design, introduction of a variable-slit virtual impactor nozzle may eliminate the need for mass analysis of particles washed from the probe. Component development has shown some promise for continuous humidity measurement by an in-line wet-bulb, dry-bulb psychrometer.

I. INTRODUCTION

The Environmental Protection Agency (EPA)/Division of Biology and Environmental Research (DBER) pass-through funded program "Optimize Filters and Stack Probe for Aerosol Source Sampling," has been in progress since October 1975, passing through an evaluation stage in which the standard manual stack sampling method for particulates, EPA Method 5,[1] was examined for needed improvements.[2] Extensive evaluation of sampling filter efficiency showed very high efficiency of four types of glass fiber filters for solid particulate at the 120 ± 14°C, 28 ℓ/min conditions specified by the method. Problem areas in the standard Method 5 train appear to be deposition in the probe (particularly in the nozzle),[2] handling of awkward and heavy components, frequent breakage of glass components comprising most of the train, alteration of the aerosol within the train, and formation of pseudoaerosols by conversion of SO_2 or SO_3 to the sulfate. The method is not equipped for particle size determination and requires extensive probe washing and sample weighing, usually not providing results of the test until several days later. Isokinetic sampling during a typical one-hour period to accomplish a single traverse of the stack is difficult to maintain and not continuously monitored on an absolute basis; only after the test is complete and corrected sample volume (dry air basis) calculated can it be determined that the ±10% limits were observed and the test was valid. Lack of a continuous method of moisture measurement, combined with limited calculating capability, delays the test results. Further, the Method 5 test requires preliminary testing to determine velocity profile (Method 2) and gas composition (Method 3). The advantages of a sampler that requires only a single visit to the stack, minimal sample handling and weighing operations, no probe washing, and shorter sampling times would be welcome in the field of particulate stack sampling and would justify some additional cost on the original unit. Although price of a production unit is difficult to estimate without knowing when and how many units might be produced, we predict that $10-12k will be the approximate cost.

A preliminary design incorporating the more desirable of these features into a general purpose particulate stack sampler has been prepared. Increased flow rate (double the 28 ℓ/min of most Method 5 samplers commercially available) will permit either shorter sampling time or larger sample mass. The other features of primary interest are: electronic calculating/display of calculated variables such as stack velocity, sample volume, and per cent of isokinetic sampling conditions; electronic continuous readout instrumentation for temperature, pressure, flow, and humidity; reduced weight in individual packages; stainless steel surfaces contacting the gas stream; structural strength necessary to reduce breakage; single-point particle size classification in the nozzle; optional in-stack particulate filter to simplify sampling at low stack moisture conditions; and, if time and funding permit, a null-probe device that will greatly simplify stack sampling. Each of these features will be discussed in as much detail as possible at this stage of development.

It was not our intention to provide an all-purpose sampler capable of gas and particulate sampling of all stack types. Design specifications that the proposed design will meet are listed in Table I. Our experience in the early stages of the study and experience of others has shown that not all the conditions encountered in particulate stack sampling can be accommodated by a single sampler. It was our judgment that the design specifications should accommodate the most common ranges of stack temperature, pressure, and humidity. Beyond this, several options could be provided that allow sampling under special conditions outside these ranges. The prototype particulate stack sampler (PPSS) will not, for example, be applicable to high-temperature conditions in the typical incinerator stack. Nor under all conditions will it be applicable to the high-temperature, nearly saturated conditions of the power plant stack at the outlet of a scrubber.

The PPSS will also incorporate SI or metric units to replace the British system of engineering units commonly used in existing samplers. Conversion of units should not be difficult if consistency of units is observed within the PPSS, and external data, such as barometric pressure, are entered into the calculating/display system in the proper units.

II. PRELIMINARY SYSTEM DESIGN OF THE PPSS

The conceptual design of the PPSS is shown schematically in Fig. 1. The primary components are (1) an in-stack nozzle capable of inertially separating the particle size distribution into two fractions (single cut-point capability), (2) a straight, heated, stainless steel probe with smooth internal surfaces and an extension to provide up to 3-m inside-stack length, (3) a heated 200-mm-diam filter holder, (4) a wet-bulb, dry-bulb psychrometer, (5) air-cooled desiccant high-capacity dryer, (6) mass flow meter, (7) carbon vane rotary pump, (8) a calculating/display system, and (9) temperature and pressure instrumentation to allow continuous display of important variables and periodic calculation of corrected sample volume, stack flow rate and total volume, and per cent of isokinetic conditions. A device is being considered that will perform a null-probe function. As sample nozzle velocity deviates from stack velocity by an amount detectable by the device, a manual adjustment in the nozzle opening reduces the deviation to an acceptable level without changing size cutoff characteristics of the nozzle. This and other design features are described in greater detail below.

A. Variable-Slit Nozzle

The variable-slit nozzle, shown in Fig. 2, has been proposed as a versatile single cut-point size selective sampler by Forney.[3] Its principle of operation is based on virtual impaction, in which the larger particles in the gas stream intrude into a volume of relatively stagnant air and, being unable to negotiate a sharp turn at that point, proceed to a collection filter within the nozzle. A bleed flow of about 15% total flow is drawn through the collection filter. The smaller particles that successfully negotiate the turn proceed along the probe to the main sample filter. By selection of appropriate length of the slit L, width of the slit W, and separation between slit and virtual surface S, the device will provide separation of particles above and below a desired size with a characteristic efficiency similar to the standard impactor. Peak efficiency for collection of particles larger than the desired cutoff will not exceed about 93%, as noted by Talley[4] and Newton[5] in separate experiments using a round jet virtual impactor and a variable-slit virtual impactor, respectively.

The proposed variable-slit nozzle is small enough to pass through a 7.6-cm (3-in.) pipe coupling. The dimensions W, S, and L remain fixed during a stack sampling run to yield a relatively constant cutoff diameter. This also requires constant sample flow through the nozzle, which we have set at a nominal 56 ℓ/min. Isokinetic conditions can be maintained by adjusting the nozzle opening N by mechanical linkage during the run. Once the values of L, W, and S are determined experimentally for the desired cutoff (about 3-μm aerodynamic equivalent diam (D_{ae}) 56 ℓ/min total flow), any change in stack velocity within a range somewhat lower than nozzle throat velocity ($N > W$) is matched by opening or closing the hinged nozzle wall by rotation of a threaded rod from outside the stack. A null-probe device described later provides equal velocity information required in making this adjustment.

Virtual impaction offers the advantage of low particle rebound and minimal wall losses. Assuming the cutoff and wall loss characteristics of the sampler nozzle will be known, we can

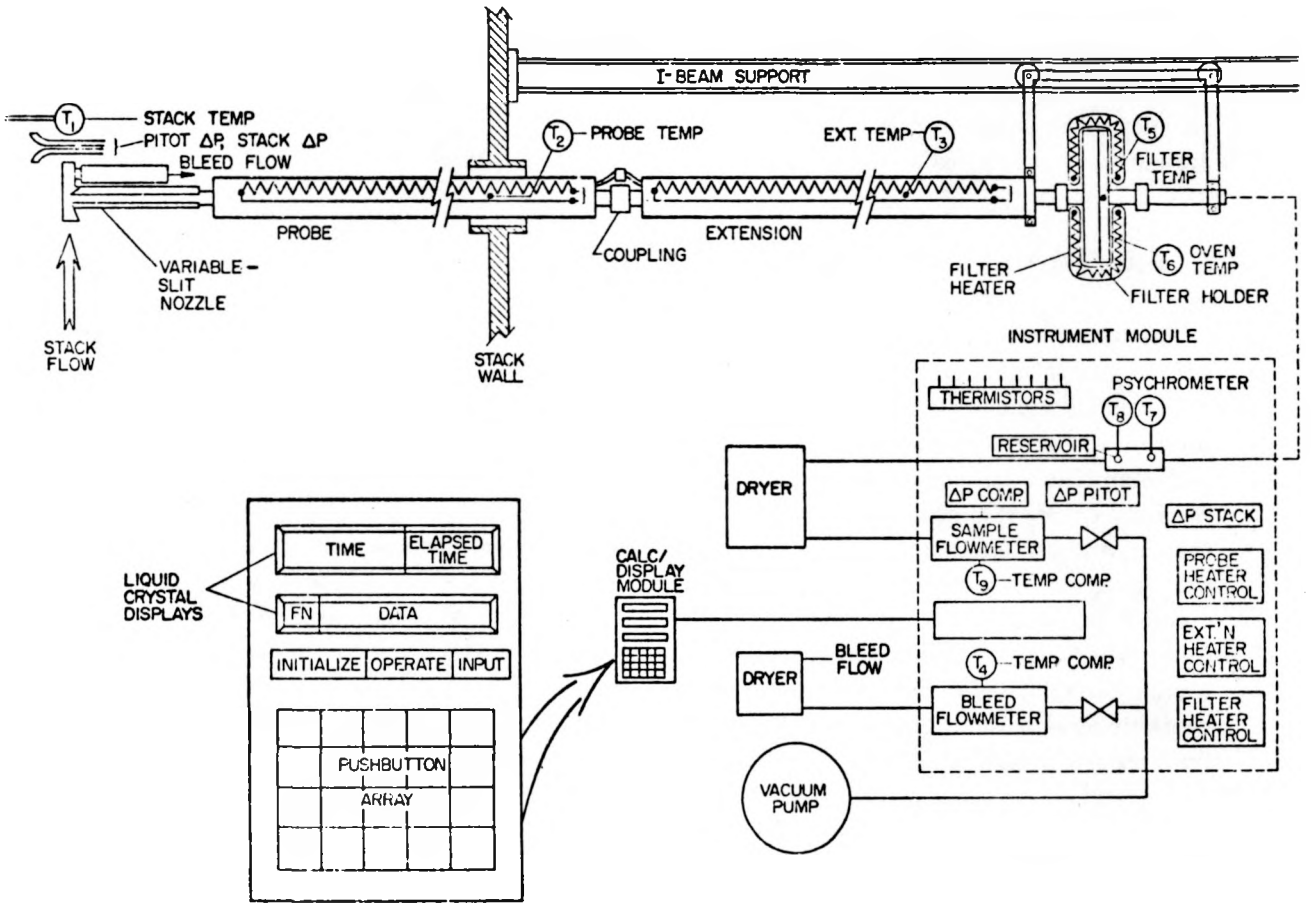

Fig. 1.

A schematic of the prototype particulate stack sampler.

TABLE I

DESIGN RANGES OF THE PPSS

Variable	Units	Range or Limit
Stack diam	m (feet)	<6.0 (20)
Stack gas temp	°C	20-320
Stack gas pressure	mmHg	<+2
Stack gas velocity	m/s	2-22[a]
		2-40[b]
Stack gas humidity	% RH	20-95
Stack SO_2 conc	ppm (mass)	5000
Stack CO_2 conc	ppm (mass)	10^5
Probe gas temp	°C	120-320
Probe gas flow	cm^3/min	42-70 x 10^3
Filter temp	°C	120 ± 14
Probe gas Reynolds number	---	1800-2800
Port diam	cm (inches)	>7.6 (3.0)

[a]Variable-slit nozzle.

[b]Gooseneck nozzle.

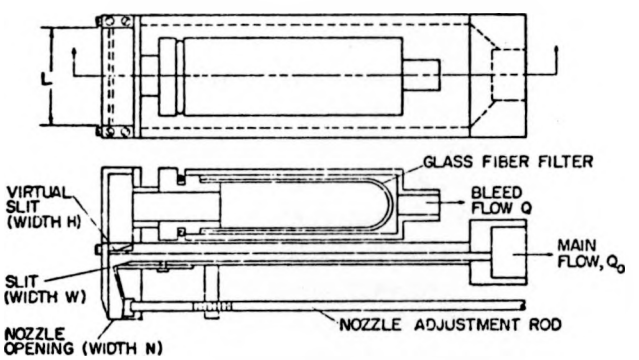

Fig. 2.

Diagram of variable-slit virtual impactor.

arrive at a correction factor for any wall losses in the nozzle and apply this to the mass collected on the bleed collection filter. If this can be done accurately and consistently, the need for probe washing and mass analysis of material collected in the probe will be eliminated.

Characteristics of a slit impactor of the configuration shown in Fig. 2 are difficult to describe and are not supported by extensive experimental data. However, the collection efficiency of particles by a rectangular jet can be described by its relation to the dimensionless Stokes number, STK, where

$$STK = \frac{\rho_p D_p^2 C Q}{9 \mu L W^2} \quad , \text{ and}$$

where

ρ_p is particle density, g/cm^3;
D_p is particle diameter (geometric), cm;
C is Cunningham slip correction, dimensionless;
Q is total flow through the jet, cm^3/s;
μ is gas viscosity, g/cm-s;
L is jet length, cm; and
W is jet width, cm.

For an assumed ratio of jet-to-impaction surface separation to jet width (S/W) of about 2, particles with $\sqrt{STK} = 0.68$ have been determined theoretically to be collected with 50% efficiency (Marple).[6] This particle size or D_{50} would be the customary "effective cutoff diameter" expressing the characteristic cutoff of an impactor stage. However, for our case of a single cut-point nozzle, we would prefer to calculate a cutoff size that yields over 90% efficiency for a specific particle size, 3-μm D_{ae}, a size roughly separating the fine and coarse fractions. Since an S/W = 2 is physically convenient within dimensional restraints of overall nozzle size and appears to yield reasonably sharp cutoff characteristics, it was selected for incorporation into the basic design of the nozzle. An S/W = 2 provides 90% efficiency at $\sqrt{STK} = 0.8$. In the absence of applicable experimental data, we have chosen to calculate dimensions of the nozzle based on Marple's suggestions for a standard rectangular impactor and experimentally determine the final dimensions of the variable-slit virtual impactor.

Slit lengths and widths required to collect 90% of particles of various sizes at a flow rate of 56 ℓ/min are shown in Table II. These values of D_{90} are based on $\sqrt{STK} = 0.8$. For example, D_{90} = 2.6-μm for S/W = 2, L = 4.0 cm, W = 0.10 cm, ρ = 1.0 g/cm^3, C = 1 (for $\approx$ 3-μm particles), μ = 240 x 10^{-6} g/cm-s at 120° C, and Q = 56 x 10^3 cm^3/min. Reynolds number under this condition is 1361, calculated by the expression

$$Re = \frac{2 \rho Q}{\mu L} \quad ,$$

where

ρ is gas density, g/cm^3;
Q is flow rate, cm^3/s;
μ is gas viscosity at 120°C, g/cm-s; and
L is slit length, cm.

This Re is within the 500-3000 range suggested as optimum by Marple. These dimensions, then, will provide a reasonable first approximation in an experimental program to finalize L, W, S, Q_{total}, and Q_{bleed}.

B. Null-Probe Device

At present, we plan to proceed with stack velocity measurement by S-type pitot differential pressure as measured by an electronic pressure transducer. Additionally, a null-probe device is being considered for maintaining isokinetic conditions. This device, described by F. H. Smith[7] and shown in Fig. 3, provided static pressure taps internal and external to the nozzle. The small differential pressure induced by velocity imbalance was sensed by a micromanometer and minimized to achieve isokinetic conditions. The difficulty with this device is sensing the low differential pressure required to achieve $0.9 < V_{nozzle}/V_{stack} < 1.1$. Smith reports this $\triangle P$ to be about 50 Pa (5 mm H_2O) at 9.1 m/s and detectable by a hand-operated micromanometer, but perhaps would not be acquired with acceptable sensitivity by a continuous reading differential pressure transducer. Typical full-scale ranges for ultra-sensitive differential pressure transducers are approximately ± 250 Pa. Although this may limit the usefulness of this null-probe sensor, its applicability may be demonstratable, especially if further searching locates a high-sensitivity, miniaturized differential pressure transducer, which could be mounted on the probe near the nozzle.

C. In-Stack Filter Holder

Placement of a filter holder in the stack gas stream is not novel and will soon become an EPA-approved procedure.[8] The advantages of an in-stack filter are (1) reduced deposition on extraneous surfaces and (2) no further need for probe and filter heating. A major disadvantage appears when entrained droplets in the stack gas stream blind the filter. The PPSS will provide the capability for sampling with an in-stack filter connected to the variable-slit nozzle or with the out-of-stack filter connected to a gooseneck nozzle.

TABLE II

SLIT VELOCITY AND REYNOLDS NUMBERS AT SEVERAL SLIT DIMENSIONS AND FLOW RATE = 56 ℓ/m

Length L	Width W	Velocity	Cutoff D_{90}	Reynolds No.
3.5 cm	0.10 cm	2667 cm/s	2.42×10^{-4} cm	1555
	0.15	1778	3.63	1555
	0.20	1333	4.84	1555
4.0	0.10	2333	2.59	1361
	0.15	1555	3.88	1361
	0.20	1167	5.17	1361
4.5	0.10	2074	2.74	1210
	0.15	1383	4.11	1210
	0.20	1037	5.49	1210

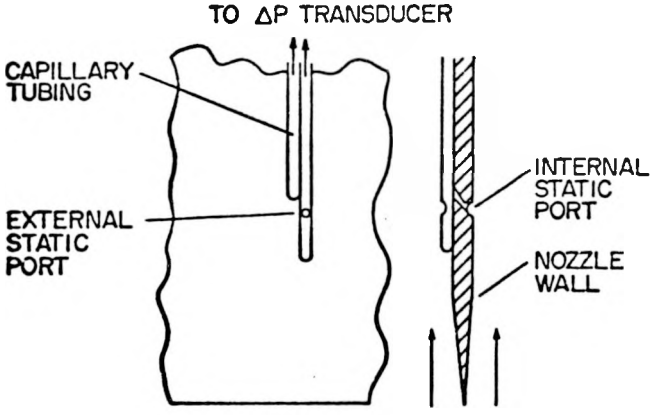

Fig. 3.
Static pressure null-probe device.

D. Instrumentation

Instrumentation in the PPSS capable of transmitting continuous voltage signals for calculating and display purposes will replace the mechanical and manual methods of flow, pressure, and moisture measurement now part of Method 5. These instruments must perform with accuracy and precision at least equivalent to the Method 5 instrumentation. Necessary channels of instrumentation are listed in Table III.

1. Mass Flow Meter. Since the particulate mass concentration is desired in terms of dry gas volume at standard temperature and pressure (or dry gas mass), it is necessary to determine total volume and moisture volume and subtract the two, or measure dry gas mass directly using a mass flow meter. The latter approach provides a simpler and more direct method, requiring no temperature or pressure compensation within specified ranges. The gas will be dried prior to entering the flow meter. Some error will be incurred if constituents of the gas change from the calibration gas. This could occur if the calibration gas is pure, dry air and the stack gas contains SO_2, CO_2, or some other combustion product gas. Gas analysis prior to each particulate sampling run would be required to provide correction factors.

TABLE III

LIST OF INSTRUMENTATION CHANNELS

	Sensors	Range or Max	Type	Signal	Overall Precision
T_1	Stack temp (T_s)	20-325°C	RTD	0-5Vdc	±2°C
T_2	Probe temp	20-325°C	RTD	0-5Vdc	±2°C
T_3	Extension temp	20-150°C	RTD	0-5Vdc	±2°C
T_4	Bleed flow temp compensation	20-150°C	Thermistor	0-5Vdc	±1°C
T_5	Holder temp	20-150°C	Thermistor	0-5Vdc	±1°C
T_6	Oven temp	20-150°C	Thermistor	0-5Vdc	±1°C
T_7	Dry-bulb temp	20-150°C	Thermistor	0-5Vdc	±0.5°C
T_8	Wet-bulb temp	20-150°C	Thermistor	0-5Vdc	±0.5°C
T_9	Sample flow temp compensation	20-150°C	Thermistor	0-5Vdc	±1°C
DP1	Stack velocity	±34 mb	Variable reluctance	±5Vdc	±0.05 mb
DP2	Flow compensation	±340 mb	Variable reluctance	±5Vdc	±5 mb
DP3	Moisture compensation	±340 mb	Variable reluctance	±5Vdc	±5 mb
DP4	Null-probe	±2.5 mb	Variable reluctance	±5Vdc	±0.02 mb
Q_1	Sample flow rate	0-0.0028-kg/s	Thermal	0-10Vdc	±0.00005 kg/s
Q_2	Bleed flow rate	0-0.0028-kg/s	Thermal	0-10Vdc	±0.00005 kg/s
C_1	Clock time	24 h: 60 s			
C_2	Elapsed time	0-3600 s			
C_3	Stop watch	0-3600 s			

The flow meters have been purchased for PPSS application. A Datametrics hot-wire mass flow meter Model 1000-.5B is considered the primary flow meter for both main and bleed flow streams. It is compact and lightweight and has been used successfully in other areas of our laboratory. Its output is nonlinear, but the instrument is supplied with linearizing signal conditioning. This dc voltage signal is integrated within the calculating/display system to provide total sample volume.

An alternate flow transducer, a turbine flowmeter (Flow Technology Model FTC-8), has been purchased for evaluation. Output of this instrument is produced as each rotor blade passes an external pickoff coil, thereby modulating an rf field generated in the pickoff by a range-extending amplifier. The pulse frequency from the amplifier is proportional to volumetric flow rate and is converted from digital to analog signal similar to the dc voltages of other instrumentation channels. The advantage of the turbine flowmeter over a thermal flow sensor is its direct indication of flow volume in the presence of gases other than the components of air. Its output will, however, require compensation for temperature and pressure changes. Again, the flowmeter will be exposed only to dry, particle-free gas.

Flow control is performed by manual adjustment of needle valves in the main flow stream and the bleed flow stream. This adjustment should be infrequent since normal operation with the variable-slit nozzle specifies constant flow at 56 ℓ/min. Variation in flow rate would be caused only by filter loading, which should be minimal.

2. Moisture Measurement. The PPSS will contain an instrument for measuring moisture content of the sample gas stream. A second source of total moisture will be available by total weight change in the dryers, which will be described later. The moisture content is required only under the condition where sampling flow must be adjusted to maintain isokinetic conditions, e.g., a gooseneck nozzle without null-probe capability is used as in Method 5. In the gooseneck case stack velocity is indicated by pressure differential from the S-type pitot and probe nozzle velocity is calculated using sample gas volume plus water vapor volume divided by nozzle cross-sectional area. The capability for moisture measurement will also be necessary in the PPSS for demonstrating the effectiveness and accuracy of the null-probe device.

The primary moisture measuring device is the wet-bulb, dry-bulb psychrometer. It is placed immediately behind the sample filter where temperature of the gas stream is maintained above dew point. This temperature is expected to be in the range 90-95°C. Cross-sectional area of the duct containing the psychrometer is selected to produce at least 3 m/s velocity past the wet-bulb wick at 56 ℓ/min, which is minimum recommended velocity for equilibrium cooling by evaporation. The psychrometer is arranged as shown in Fig. 4. The wick material is cotton (muslin) used in most psychrometers. Cotton does not provide resistance to the acids (primarily dilute H_2SO_4) encountered in some applications. However, the life of a wick is expected to be acceptably long in most atmospheres. The wick is fed from a water reservoir through a stainless steel tube approaching within 3 mm of the thermistor thermometer from the downstream side. Covering the feed tube with wick for the final 7.2 cm adjusts the temperature of the feedwater within the tube very near the wet bulb temperature. This feature prevents cooling or heating of the wet bulb by the feedwater. Assuring the wick stays wet is the only other difficult problem. This is accomplished by setting water level within a large area reservoir to the proper head above the wick, which is roughly horizontal. Pressure in the reservoir is equalized with line pressure to prevent suction of water by other than wicking action.

The wet-bulb, dry-bulb psychrometer was selected on the advice of Wiederhold[9] and Worrall,[10] who state that psychrometers may be used up to dew points of 100°C with reasonable accuracy (about 5% maximum error). Other methods of moisture measurement such as cooled-mirror

dew-point devices, hygroscopic salt devices, and semiconductor devices are severely limited by maximum ambient temperature, usually about 50°C.

The calculation of humidity ratio (mass water vapor/mass dry air) is presented in the Appendix. This calculation is very sensitive to changes in wet-bulb depression but relatively insensitive to changes in pressure. Thermistors and circuits with high accuracy and stability are required. Experimental results using this psychrometer at 90°C or greater are described later.

A hygrometer was tested as a direct-reading instrument (Thunder Scientific BR101 humidity sensing element). Its response in terms of per cent relative humidity indicated by a gravimetric humidity standard was not adequately stable. The manufacturer expected much greater stability, although he had not operated the sensor above 50°C and did not know what to expect at high temperatures (130°C maximum short-term exposure). Testing of the hygrometer under such severe conditions has been terminated.

3. Pressure Measurement. Four pressure channels are required in the PPSS: pitot differential pressure from which stack gas velocity is determined; pressure in the sample line at the psychrometer and at the flow measurement section to allow pressure compensation of these signals; and differential pressure at the null-probe device. Pressure within the stack to allow calculation of total stack volumetric or mass discharge is measured occasionally by connecting one leg of the pitot to one of the existing transducers. The operating ranges of these instruments are provided in Table III. The instruments purchased for these applications are Datametrics variable-reluctance, differential-pressure tranducers with miniaturized carrier demodulators which supply dc voltage to the calculating/display system. The output signal is linear over the range of interest (lower two-thirds of the operating scale) and is proportional to the difference between pressure in the duct and atmospheric pressure.

4. Temperature Measurement. All temperatures except stack temperature T_1, probe temperature T_2, and extension temperature T_3 are sensed by thermistor connected as shown in Fig. 5. This includes the wet-bulb, dry-bulb thermometers for the psychrometer described earlier.

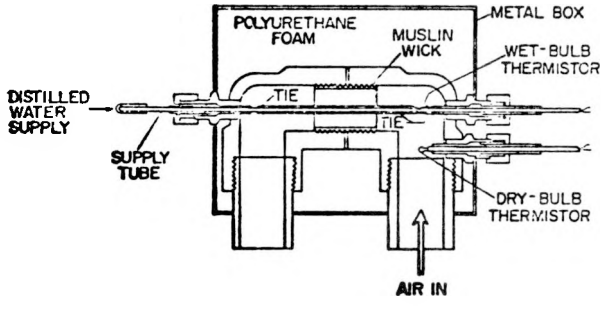

Fig. 4.
Arrangement of wet-bulb, dry-bulb psychrometer.

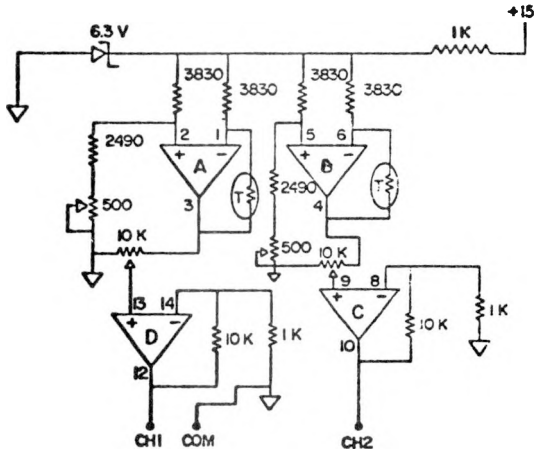

Fig. 5.
Schematic diagram of thermistor circuit, using RCA 4136 N quad operational amplifier.

The thermistors selected for this application are Yellow Springs Thermilinear 0-100°C devices which show good linearity and response. The accuracy of the measuring circuit is generally within ±0.2°C over the range 0-93°C; its stability appears good, showing a standard deviation on the difference between two thermistors in an oil bath to be 0.05°C. This order of stability is required by the psychrometric calculation which is based on wet-bulb, dry-bulb depression. Sensitivity of the thermistor circuit is set at 0.1 V/°C, far exceeding response of any thermocouple.

Stack temperature, probe temperature, and extension temperature sensors are presently Chromel-Alumel thermocouples in the probe, which is already fabricated. Conversion to resistance thermometers at these locations is in progress (Yellow Springs Platinum RTD 0-138 AX).

E. Calculating/Display System

Los Alamos Scientific Laboratory (LASL) Group E-5, Mini-Microcomputer System Group, was requested to submit a proposal to design, fabricate, and test a calculating/display system as an integral part of the PPSS. The system would incorporate a microcomputer and microprocessor needed to calculate stack volumetric flow rate, sample flow rate, isokinetic variation, and various temperature and pressure compensation factors. A block diagram of the system is shown in Fig. 6.

General features of the calculating/display system are as follows.

1. Operates on 115-Vac, 60-Hz line power.
2. Stores program memory in firmware (read-only memory, to be retained when power is removed).
3. Displays data in large (1.3-cm) liquid crystal displays (LCD) visible in strong sunlight.
4. Updates and displays calculated values every minute or on demand; displays all other inputs on demand.

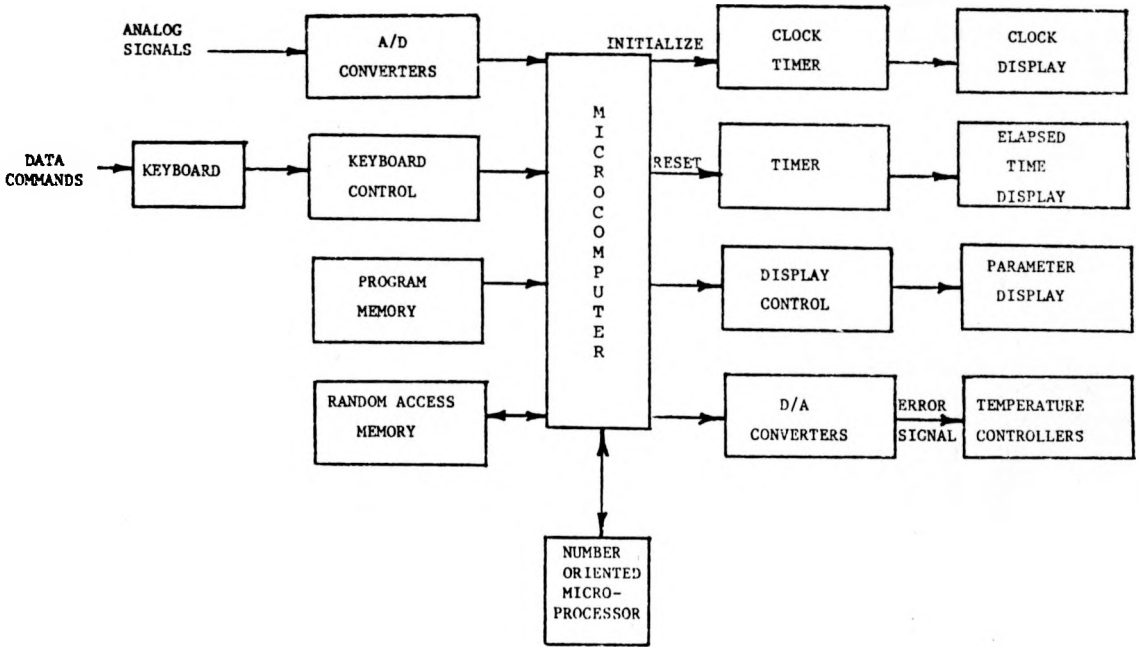

Fig. 6.
Block diagram of H-5 stack sampler calculating/display system.

5. Provides clock time, elapsed time, and stop watch capability.

6. Permits input of externally generated data needed in calculations, such as barometric pressure, nozzle diameter, pitot coefficient, molecular weight of stack gas, etc.

The National Semiconductor MM 57109 MOS/LSI number-oriented microprocessor is recommended for the number processing/calculation. This 28-pin dual in-line package provides scientific calculator instructions (key level language) with reverse polish notation entry. The capabilities of this device include all of the functions available on the HP-21 hand calculator. The Intel ASM 48 single-component microcomputer is recommended for data sequencing, computation processing and display updating. Such a combination is described in Ref. 11. This report summarizes a similar existing system developed for another LASL group.

The analog-to-digital processing of 15 analog input signals can be handled with a 16-channel 8-bit analog-to-digital converter, the National ADC 0816. The keyboard entry requirement can be satisfied with a Digitran (16-key) Minikey low-profile keyboard and an Intel programmable keyboard/display interface-integrated circuit 8279. The interface-integrated circuit can also provide data sequencing to the decoder/drivers of the liquid crystal displays.

In the similar, existing calculating system, each parameter was stored in BCD scientific notation with eight mantissa digits, two exponent digits, and sign information for the mantissa and exponent. This parameter storage required six 8-bit bytes of random access memory (RAM) in the microcomputer. The PPSS with 15 analog input parameters, 6 input constants prior to run, and approximately 10 additional calculation parameters to display on demand during the run would require 186 words of RAM memory. The Intel RAM 8111 provides 256 words of RAM. The program memory size can also be estimated,based on the similar existing calculating system that required 350 words for data sequencing and 250 words for data input and display (600 total). The increase in I/0 complexity of the PPSS is a factor of 2 or 3, which will require 500 to 750 words.

Group E-5 has the capability for developing the hardware, software, and firmware for the PPSS calculating/display system. Microcomputer software would be written in assembly language. No high-level language is available or planned for the ASM-48 family of microcomputers. An Intel ASM-48 assembler and microcomputer development system is available for creating software for the system. Testing of system hardware and software could be accomplished with the Intel In-Circuit Emulator. The final software will be located in PROM with the Prompt-48 programming tool. Complete ASM-48 microcomputer development and testing capability exists within Group E-5. Estimated unit price for the calculating/display system based on a quantity of 100 units is $3 100.

F. Equipment and Structural Arrangement

1. Pump. The vacuum pump selected for the PPSS is a Gast 1022 carbon vane rotary pump, which will provide 280 ℓ/min at 0 mmHg and 68 ℓ/min at −500 mmHg. Maximum pressure drop expected in the PPSS is 415 mmHg (100 mmHg occurring in the nozzle, 115 mmHg in the 200-mm filter holder, and 200 mmHg in the dryer). The Model 1022 pump weighs 21.5 kg and is the heaviest component in the PPSS. In general, weight of any other major component will be limited to about 15 kg.

2. Support Structure. The probe of the PPSS will be supported by an I-beam cantilevered outward from the stack. This arrangement, shown in its basic form in Fig. 1, is similar to Method 5 arrangement. The probe is clamped in two places by a trolley device which straddles the filter holder. Total weight of the probe and separation distance of the two clamping points have not been determined.

3. Probe and Heater. The probe is Type 304 stainless steel pipe. Its inside diameter is 2.32 cm and the wall thickness is 0.115 cm. Reynolds number inside the probe at 56 ℓ/min is 1920, within the transition region between laminar and turbulent flow. Particle transmission should be high. There are no bends or diameter changes in the probe. The present design calls for a sleeve 6.365 cm in diameter to protect the heater and temperature instrumentation leads. The sleeve is easily removable for replacement of the probe heater. Total weight of the probe (extension not included but weighing about the same as the probe) is 4 kg.

The probe heater consists of 884-cm chrome heater ribbon (0.014 Ω/cm) double-spiral wound over four layers of glass tape insulation. The tape is wound on 1.3-cm centers over the leading 52 cm of the probe and 1.9-cm centers for the remainder of the probe. The heater is covered by an additional four layers of glass tape insulation. Total heated length is 130 cm.

4. Dryers. Lightweight dryers containing silica gel desiccant are provided for both the main and bleed streams. The dryer is designed for either air or ice bath cooling. The design concept proposes silica gel crystals packed within stainless steel bellows tubing. The tubing is flexible and may be supported on a wire rack with handle. The whole assembly may be immersed in an ice bath if high-moisture, high-temperature conditions require this. A change in mass of the dryer can be used as a measure of total moisture in the sample gas stream. Recharging is accomplished by replacement of desiccant or drying by passing warm, dry air through the dryer.

III. RESULTS AND DISCUSSION

A. Virtual Nozzle Testing Results

Design of a nozzle to replace the gooseneck nozzle was based on the concept of placing an impactor of known characteristics at the point just inside the tip where unavoidable deposition was shown to occur in the evaluation program. Possible advantages were (1) fine-particle (3-μm and smaller) mass fraction could be separated from the coarse fraction, (2) minor deposition in the remainder of the train by particles <3 μm would make probe washing unnecessary, and (3) the two fractions would be located on two easily weighed samples, i.e., the impactor surface and the glass fiber collection filter. The concept appeared sound but testing of several impactor types that collect and hold high percentages of the >3-μm particles has not been successful thus far. An 0.8-cm round jet (as shown in Fig. 7a) was directed toward a flat, bare surface 0.8 cm away. At 113 ℓ/min, this nozzle was expected to provide a 95% collection efficiency for 3-μm D_p particles. Several test runs using 4-μm D_p Eosin Y aerosols showed negligible amounts collected on the impaction surface, 35% to 62% of total mass depositing inside the body. This deposition appeared in two rings as though one ring was composed of the particles making the turn but being projected radially outward with sufficient velocity to reach the wall, and the other ring composed of the particles that impacted on the impaction plate but rebounded and were carried radially outward to strike the wall at another location. A test run with a 2-μm D_p aerosol showed less than 0.25% on the impaction plate and about 20% on the body. These poor collection characteristics discouraged use of the normal impactor and prompted design of a virtual impactor as shown in Fig. 7b. Recommended bleed flow was 17%. Against the 4-μm D_p dye aerosol, the virtual collector collected 28.7% (0.69% on the collector face, 13.7% on the inside walls, 14.4% on the filter), 36% on the body, with the remainder (35.5%) going to the main filter. High flows are apparently beyond the capability of samplers of this physical size and the virtual collector has rather poor collection efficiency at these high Reynolds numbers (~15 000). This led to reduction of total flow to 56 ℓ/min and, coincidentally, to a change in nozzle configuration to the variable-slit nozzle described earlier.

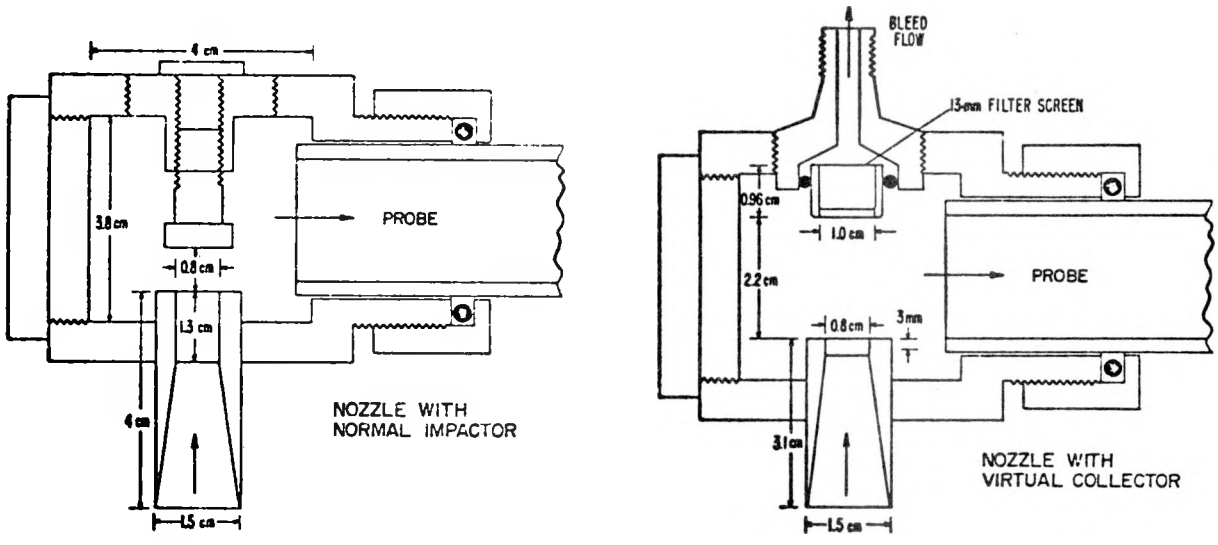

Fig. 7.

Experimental nozzle configurations.

B. Psychrometer and Hygrometer Testing Results

Accuracy and response characteristics of a wet-bulb, dry-bulb psychrometer and a solid state hygrometer have been studied in a test system as shown in Fig. 8. In the absence of a humidity standard, several calibrating techniques were attempted. The first entailed placement of a preweighed desiccator downstream of the test section. With this method it was difficult to obtain consistent results because at high humidities, a desiccator of reasonable size became saturated within a very short time. A more satisfactory method of determining amount of water put into the airstream was to determine the mass of water evaporated from the boilers. This was accomplished by measuring initial mass of hot water in the boiler, heating the water to boiling in a short time, operating the system for long periods during which humidity readings were recorded each minute, then measuring the remaining mass of hot water. With appropriate temperature corrections, the mass change is equivalent to mass of vapor in the mass of dry air passed through the system. In general, the amounts of water vaporized are large enough (1 to 2 kg) that the losses during heatup and cooldown are negligible.

Our experience with the psychrometer showed the instrument to be difficult to set up. It was susceptible to several problems: inconsistency of wicking material (evaporation rate not constant); inability to keep the wick wet and clean; cooling the wet-bulb thermometer with feed water beyond cooling by evaporation; feeding water at a nonuniform rate and temperature; drift of thermometer (thermistor) calibration; and possible deterioration of the wick due to formation of H_2SO_4 in the presence of SO_2 gas. The results with the latest version (cotton wick) show overestimationof the humidity compared with the "evaporated mass" method by about 6% if error is calculated on the basis of

$$\% \text{ Error} = \frac{(\text{expected} - \text{actual})\ 100}{\text{actual}}$$

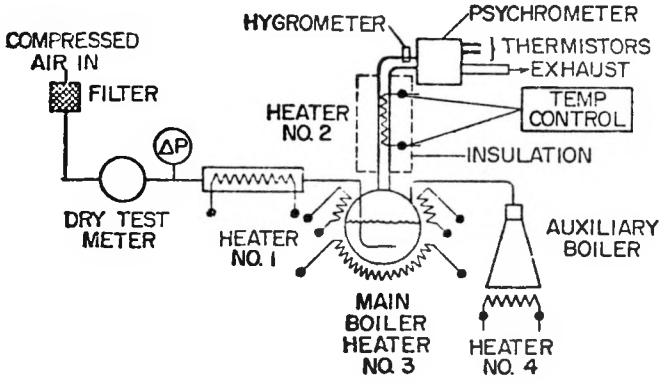

Fig. 8.
Humidity test system.

where actual moisture mass is the "evaporated mass" result. After a correction factor is applied, the variance is expected to be about ±4% (±1 std dev).

Humidity ratio intermediate weight was calculated by three methods, although the Berry psychrometric calculation shown in the Appendix is preferred.[12] The first of the alternate methods assumed adiabatic saturation near the wet bulb and allowed calculation of humidity ratio based on enthalpy values taken from steam tables.[13,14] Another method of calculating humidity ratio uses Carrier's equation, which makes several assumptions to simplify the adiabatic saturation relationship.[13] This equation requires only the wet-bulb and dry-bulb temperatures and saturation pressures to calculate partial pressure of vapor. The calculation is simple but requires moderate amounts of computer memory to provide table lookup. All three methods of calculating humidity ratio provide sufficient consistency to permit using any one of them in the temperature range 90 to 95°C. The Berry reference calculation has the advantage of requiring no table lookup and is the preferred method, despite a requirement for more extensive software.

The total mass of vapor was then the product of humidity ratio and total dry air mass. Volume flow rate of the air and vapor mixture required for calculation of a nozzle velocity for isokinetic conditions is obtained by the following relationships:

$$Q_m = \frac{M_a T_{st} R (1 + W_{vl})}{P_{st}}$$

and

$$I = \frac{V_n}{V_{st}} = \frac{M_a T_{st} R (1 + W_{vl})}{V_{st} A_n P_{st}} ,$$

where

I is the dimensionless ratio of probe nozzle velocity and stack velocity ($0.9 < I < 1.1$);
M_a is mass flow rate of dry air (mixture of diatomic gases), kg/s;
T_{st} is temperature of stack gas, K;

R is gas constant, 287 D_a m^3/kg K;
W_{v1} is humidity ratio in the sample stream, kg vapor/kg dry air;
V_{st} is stack velocity, m/s;
A_n is nozzle area, m^2; and
P_{st} is stack absolute pressure, Pa.

The success of this technique of determining frequently updated isokineticity depends on the validity of our assumptions of water entering the probe as vapor (not droplets) and the vapor adhering within reasonable limits to the perfect gas law. Our observations of the behavior of the psychrometer show it can perform within a predictable error and could, with correction by an average error, indicate the humidity ratio within ±4% at any point in the expected range of humidity. Checking that the wick is wet under all conditions would be an essential part of the operator's job but is a relatively minor task.

SUMMARY AND CONCLUSIONS

A preliminary design of a PPSS is in progress and has been described in this report. Some components of the design have been fabricated and are undergoing test. The primary features of the sampler are (1) nominal 56 ℓ/min sampling flow rate, (2) electronic transducers for pressure, temperature, flow, and humidity ratio, (3) stainless steel surfaces and components not subject to breakage, (4) electronic calculating/display system providing direct display of updated data such as stack velocity, sample volume, and per cent isokinetic, (5) automatic control of probe and filter heaters, (6) single-point particle size classification in the nozzle, (7) a null-probe device, and (8) manageable weight of individual components. A locally developed wet-bulb, dry-bulb psychrometer provides continuous indication of moisture content of the gas stream. The psychrometer is a particularly promising device in the severe conditions of high temperature (90 to 95°C) and high humidity in which the device must operate.

Several nozzle configurations (to replace the existing gooseneck nozzle of Method 5) have been tested with rather poor results. A single cut-point nozzle with normal impactor and another with circular jet virtual impactor displayed excessively heavy wall losses, mostly attributable to high flows and small air passages (high Re). The small sampling port size (7.6 cm) commonly found in stack sampling has restricted overall size of the nozzle and probe and has severely hampered the effort to provide a single cut-point nozzle. A variable-slit virtual impactor is being considered for the single cut-point device but has not been tested. This nozzle in combination with a null-probe device built into its wall would greatly simplify obtaining a particulate sample under isokinetic conditions; i.e., moisture measurements could be eliminated and, assuming wall loss characteristics are known, analyses of probe washing samples could be eliminated.

In general, the PPSS has the operating capability of the existing Method 5 sampling train and has eliminated the obvious problem areas. However, as demonstration of the prototype gets under way, other problems may arise in the novel areas of the PPSS design. The effect of particulate deposition on the null-probe device is not known; the effect of acid on the psychrometer wick and of presence of CO_2, SO_2, and other contaminants on behavior of the psychrometer are not known. Also, stainless steel surfaces in the PPSS provide greater probability for formation of sulfate aerosols than in the glass components of the Method 5 train. Neglecting wall losses and determining particulate mass only by weight change of glass fiber filters not as susceptible to sulfate aerosol formation will circumvent the pseudoaerosol problem. Experiments are being planned to study the other problems mentioned above.

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APPENDIX

PER CENT RELATIVE HUMIDITY AND HUMIDITY RATIO CALCULATION METHODS[12]

Equations:

$$w = \frac{w' L_w - (T_d - T_w) C_p}{(T_d - T_w) C_p' + L_w} ,$$

$$w' = \frac{0.622\ e_w}{P_m - e_w} ,$$

$$e_w = 6.11 \times 10^{\left[\frac{7.5\ T_w}{237.3 + T_w}\right]} ,$$

$$e_s = 6.11 \times 10^{\left[\frac{7.5\ T_d}{237.3 + T_d}\right]} , \text{ and}$$

$$\%RH = 100\ \frac{P_m\ w}{(0.622 + w)\ e_s} .$$

Nomenclature:

w = humidity ratio of air at stack conditions g (vapor)/g (dry air);
w' = humidity ratio of saturated air at T_w, the wet-bulb temperature, g/g;
T_d = dry-bulb temperature, °C;
T_w = wet-bulb temperature, °C;
L_w = latent heat of vaporization = 597.3 − 0.566 T_d, cal/g;
c_P' = specific heat of dry air, cal/g-K;
c_P = specific heat of saturated air, cal/g-K;
P_m = absolute pressure, mb;
e_w = saturation partial pressure of water vapor at T_w, mb;
e_s = saturation partial pressure of water vapor at T_d, mb; and
A = 0.622 = ratio of molecular weights of vapor to air.