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Scope
This Technical Reference covers the use, design and specifications of the Averaging Velocity Probes used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL
Calculations related to large scale Fire Product Collectors (FPC) rely on knowledge of the flow rate of air and products of combustion through the exhaust duct. Because velocity profiles in the ducts are generally non-uniform, there are two approaches to measuring the flow rate. The first is to rely on point velocity measurements and the application of a flow shape factor. The second approach is to measure the average velocity directly. Instrumentation used for point velocity measurements are covered in a separate document [1]. Averaging velocity probes are used to measure the average dynamic pressure across a section of pipe or duct, from which the velocity is calculated without requiring a flow shape factor. Components consist of the probe itself, plus a mounting bracket to attach the probe to the duct. A typical configuration consists of two or more probes mounted inside a section of FPC duct with tubing connecting the probes to a differential pressure transducer. A thermocouple is placed near the probe location to monitor the local temperature. The thermocouple and pressure transducer are connected to the data acquisition system. All instrumentation must be calibrated according to the manufacturer and ATF specifications.
**Velocity Profiles**

Flow in the FRL FPC exhaust ducts is turbulent, which generally causes velocity profiles to be flatter and more uniform. Additionally, each duct contains an orifice that is designed to enhance mixing. Despite this, velocity profiles in the FPC exhaust ducts are not uniform [2]. Figure 1 shows a chart of the velocity profile measured in the 14 MW FPC duct [2].

![Figure 1: Velocity profile measured in the 14 MW FPC duct.](image)

**PROBE DESCRIPTION**

**Volu-Probe**

The FRL uses externally mounted Volu-Probe Airflow Traverse Probes in the FPC exhaust ducts [3]. Figure 2 shows a schematic of the probe. The probe consists of two manifolds; one each for static and total pressure measurement. Each manifold has pressure ports spaced at equal area intervals as shown in Figure 3, producing a pressure representing the instantaneous average across the duct. Each manifold feeds to a 1.3 cm (0.5 inch) female NPT connection that is connected to a differential pressure transducer. The probes are mounted on one end with a 15.2 cm x 15.2 cm (6 inch x 6 inch) mounting plate, with the opposite end secured by a pin support. All components are constructed of stainless steel.
Figure 2: Schematic of the velocity traverse probes [2].
Figure 3: The surface area of the duct divided into sections of equal area.

**Mounting Bracket**
The probes are externally mounted to the duct using a 15.2 cm x 15.2 cm (6 inch x 6 inch) mounting bracket that is customized to fit the curvature of the exhaust duct (Figure 4). The mounting bracket is welded around a 10 cm (4 inch) hole in the exhaust duct. The probes are then inserted into the hole and the mounting plate is secured to the mounting bracket. High temperature fiber gasket is used to seal the space between the mounting plate and the mounting bracket as well as the duct wall at the end support.
Figure 4: The mounting bracket used to mount the probes to the exhaust duct.

**Probe Installation**
The probes are installed in the exhaust duct based on manufacturer’s specifications [3]. Specifications require that multiple probes are used to achieve the stated accuracy of $\pm 2 - 3 \%$, with the number of probes depending on duct diameter. The probes are installed at an angle from each other with an axial spacing of 3.8 cm (1.5 inch) between the centers of the manifolds on each probe (Figure 5). The static and total pressure manifolds from each probe are combined into a single static pressure line and a single total pressure line via 1.3 cm (0.5 inch) tubing and Swagelok tee unions. The tubing is connected to a single differential pressure transducer.

Figure 5: The layout of the velocity traverse probes in the exhaust hoods for two probes [3].
**TEMPERATURE MEASUREMENT**

In order to calculate velocity, temperature must be measured in addition to differential pressure. Typically this is accomplished by placing a thermocouple in the flow field, near the location of the probe. Further discussion on the use of thermocouples in the FRL can be found elsewhere [4].

**PRESSURE TRANSUCER**

**Setra**

The FRL uses Setra model 267 pressure transducers for FPC measurements [5]. These instruments are available with a wide range of input and output settings. Generally, a transducer with a range of 0 – 622.7 Pa (0 – 2.5 inches of water) and an output of 4 – 20 mA works well in FPC applications. Figure 6 shows a photograph of this instrument.

![Figure 6: Setra Model 267 Differential Pressure Transducer](image)

**Calculations**

**VELOCITY CALCULATION**

The velocity is calculated according to the relation:

\[ V = C \sqrt{\Delta P T} \]  \hspace{1cm} (1.0)

where \( \Delta P \) is the measured differential pressure, \( T \) is the measured temperature at the velocity probe, and the flow factor \( C \) is calculated from \( \sqrt{2/\rho_0 T_0} \) where \( T_0 \) is the reference temperature and \( \rho_0 \) is the fluid density at the reference temperature [6].

**UNCERTAINTY CALCULATION**

The uncertainty of the FPC exhaust duct velocity measurements was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Special Publication 1007 [7], Technical Note 1297 [8], and the NIST Uncertainty Workshop [9]. The combined
standard uncertainty of the velocity is a combination of the uncertainty of its components given by the following equation:

$$u_c(V) = \sqrt{\sum s_i^2 u(x_i)^2}$$ (1.1)

where:

- $u_c(V)$ = Combined standard uncertainty of the velocity
- $u(x_i)$ = Standard uncertainty of each component
- $s_i$ = Sensitivity coefficient ($\partial V/\partial x_i$)

Using Eq. (1.0), the main sources of uncertainty in the velocity are the differential pressure and temperature measurements. Based on this, Eq. 1.1 can be applied to Eq. 1.0 to yield:

$$u_c(V) = \left[ (\sqrt{\Delta PT})^2 (u(C))^2 + \left( \frac{C}{2} \sqrt{\frac{T}{\Delta P}} \right)^2 (u(\Delta P))^2 + \left( \frac{C}{2} \sqrt{\frac{\Delta P}{T}} \right)^2 (u(T))^2 \right]^{1/2}$$ (1.2)

where:

- $u(C)$ = Standard uncertainty of the flow factor C
- $u(\Delta P)$ = Standard uncertainty of differential pressure measurement
- $u(T)$ = Standard uncertainty of the temperature measurement

**Flow Factor**

The flow factor is a constant, based on the properties of air at the reference condition $T = 300$ K and $P = 1$ atm. The uncertainty of this value ($u(C)$) is taken as zero.

**Differential Pressure**

The uncertainty of the differential pressure measurement is comprised of two components. The first component is associated with the probe, and the second is associated with the pressure transducer. Errors associated with the data acquisition system are negligible.

**Probe Uncertainty**

Volu-probe specifications indicate an accuracy of $2 – 3 \%$. For typical cold flow conditions in the 1 MW FPC ($T = 300$ K, $V = 17.3$ m/s, $\dot{m} = 6.8$ kg/s), the average differential pressure is $\Delta P = 175.3$ Pa. The corresponding error in the pressure measurement, assuming $3\%$ accuracy, is 10.52 Pa. Assuming a square distribution, the standard uncertainty is $u(\Delta P)_{\text{probe}} = 6.07$ Pa [8].

**Pressure Transducer**

The Setra 267 pressure transducer has a range of 0 to 622.8 Pa (0 to 2.5 inches of water). Setra lists the accuracy as $\pm 0.4\%$ F.S., the linearity as $\pm 0.38\%$ F.S., the hysteresis as $0.1\%$ F.S., and the repeatability as $0.05\%$ F.S [4]. It can be assumed that the errors from the pressure transducer
each have a rectangular probability distribution, in which case the standard uncertainty is calculated by dividing each component by $\sqrt{3}$ [8]. Since these are all based on the full scale range of the transducer, they are independent of the measured value.

The uncertainty of the differential pressure measurement also includes variations arising from random fluctuations that occur naturally in the measurements. The standard uncertainty of the random fluctuations is calculated using equation 1.3,

$$u = \frac{S}{\sqrt{n}}$$  \hspace{1cm} (1.3)

where:

$S =$ Standard deviation of the measurements in a sample

$n =$ Number of measurements in the sample

The standard uncertainty for the pressure readings, based on a sample containing 600 measurements, is $\pm 0.453$ Pa.

The standard uncertainties are combined in quadrature to calculate the combined standard uncertainty of the differential pressure readings. The result is $u(\Delta P)_{\text{transducer}} = 2.07$ Pa.

The uncertainty associated with the probe and the pressure transducer are combined in quadrature to yield a combined standard uncertainty in the pressure measurement of $u(\Delta P) = 6.42$ Pa.

**Temperature**

The temperature in the exhaust duct, $T$, is measured by a Type K thermocouple positioned at the center of the duct. The ATF FRL only purchases Type K thermocouples with a minimum accuracy of the greater of 1.1°C or 0.4% of the reading above 0°C. Assuming a reference temperature of 25°C, the error is $\pm 1.1$°C. It is assumed that the error from the thermocouple has a rectangular probability distribution, in which case the standard uncertainty is calculated by dividing each component by $\sqrt{3}$ [8]. The standard uncertainty for a temperature measurement at 25°C is therefore $\pm 0.635$°C.

The standard uncertainty for the random fluctuations, based on a sample containing 600 measurements, is $\pm 0.0021$ °C.

The standard uncertainties are combined in quadrature to calculate the combined standard uncertainty of the temperature readings. The result is $u(T) = 0.635$ °C. This translates to a relative combined standard uncertainty of 2.54 %.

**Summary**

Equation 1.2 is used to calculate the combined standard uncertainty in the velocity for the conditions $\Delta P = 175.3$ Pa, $T = 300$ K and $V = 17.3$ m/s. The resulting uncertainty is $u_c(V) = \pm 0.31$ m/s.
References

4. ATF FRL Instruction, “Laboratory Instruction LI001 – Thermocouple.”