USE OF HEATED CRITICAL FLOW VENTURI SAMPLE PROBES
TO MAINTAIN PROPORTIONAL FLOW

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Abstract

The Notice of Proposed Rule-Making (NPRM) for methanol-fueled vehicles proposes using sample probes heated to 235°F when sampling for methanol or formaldehyde. When using a critical flow venturi constant volume sampler (CFV-CVS) to measure exhaust flow, critical flow venturi (CFV) sample probes must be used to obtain a constantly proportional exhaust sample. The gas temperature at the sample CFV must be the same as that of the bulk stream for the sample flow to be constantly proportional (when a heat exchanger is not used to control dilute exhaust temperature). Tests conducted with a sample CFV heated to 235°F indicated that the gas temperature at the CFV was not the same as the bulk steam temperature. This caused a measurable (approx. 3%) change in flow through the CFV. The conclusion is that a heated CFV may not be able to maintain constantly proportional flow if the temperature of the dilute exhaust stream varies. There are viable alternatives to this approach, such as using a heat exchanger in the CVS or insulating the venturi from the heated sample line.

Foreword

The Notice of Proposed Rule-Making (NPRM) for methanol-fueled vehicles (ref. 1) requires:

1. Proportional sampling of dilute exhaust for methanol and formaldehyde, and

2. Using heated probes (235 ± 15 F) when sampling for these two pollutants. If a critical flow venturi constant volume sampler (CFV-CVS) is used, the NPRM suggests simply heating standard CFV sample probes.

In CFV-CVS units which do not use a heat exchanger to control dilute exhaust temperature (as is the case with most light-duty CVS units), critical flow venturi sample probes are used to obtain a constantly proportional exhaust sample. If applying heat to the venturi causes a change in the temperature of the gas flowing through it, the flow through the venturi will no longer be constantly proportional to that of the bulk stream, as is required by the NPRM. Testing was needed to determine if a CFV could be heated without affecting the temperature of the gas flowing through it. This report gives the results of the testing, documents the difference, and recommends ways to obtain a heated, constantly proportional exhaust sample.

Summary

The test results indicate that heating a critical flow venturi (CFV) does change the flow characteristics of the venturi (other than those due to thermal expansion). The data obtained indicate that a sample CFV cannot be used to maintain constantly proportional flow if it is heated (without temperature control of the bulk stream), and that other alternatives will have to be explored if we wish to heat the probes used for methanol and formaldehyde sampling.

The most viable alternatives are:

1. Using a heat exchanger in the CVS. This would eliminate the need for CFV's in the sample lines.

2. Not heating the critical flow venturi and insulating it from the heated sample line. Sample losses should not occur at the venturi due to the high gas velocity.

I.   Introduction and Theory

Exhaust from methanol-fueled vehicles contains significant amounts of methanol and formaldehyde. EPA wishes to regulate emissions of these two pollutants for vehicles running on blends of 50% or more methanol. Current exhaust gas sampling systems used for testing gasoline vehicles are not equipped to measure methanol or formaldehyde.

The NPRM published in August 1986 outlines equipment and procedures required for methanol and formaldehyde sampling. In each case, one of the requirements is that sample collection lines and probes (including venturies) be heated to 235°F in order to avoid losses in the collection equipment (reference 1).

The theory of operation of critical flow venturi constant volume samplers (CFV-CVS) requires that the gas temperature at the inlet to all venturies be the same unless the temperature of the dilute exhaust stream is controlled (see Appendix C for theory of operation of constant volume samplers). The question this report addresses is: "Will the gas temperature at the orifice of the sample venturi be the same as at the bulk stream venturi if the sample venturi is heated?" If it is not, the sample obtained will no longer be a constantly proportional sample, which the NPRM requires.

II.   Apparatus and Procedure

It is very difficult to accurately measure the gas temperature at a critical flow orifice without altering the flow conditions. It is much easier to simply measure the flow through the orifice when heated and unheated. A change in gas temperature through the orifice can be seen as a change in flow.

The apparatus used for testing the probe in an unheated condition is shown in Figure 1. A 20 CFH smooth approach CFV was attached to the inlet of a Metal Bellows Pump Model MB-158 (standard equipment used for drawing bag samples at MVEL). The pump outlet was connected to a laboratory wet test meter. Instrument connections were made using 1/4" 316 stainless steel tubing and Swagelok fittings.

The apparatus used for testing the heated probe was identical except for the addition of a 95VAC heat tape and an Athena temperature controller set at 235°F. A type "J" thermocouple was attached to the outside surface of the probe, with the heat tape wrapped over it, to supply the feedback signal to the controller. Other temperature measurements were made using a fine tip "J" thermocouple and digital readout.
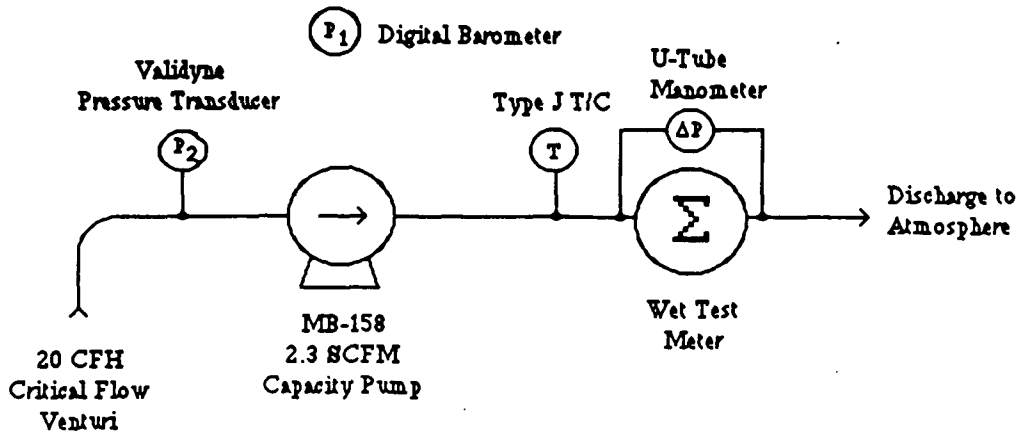
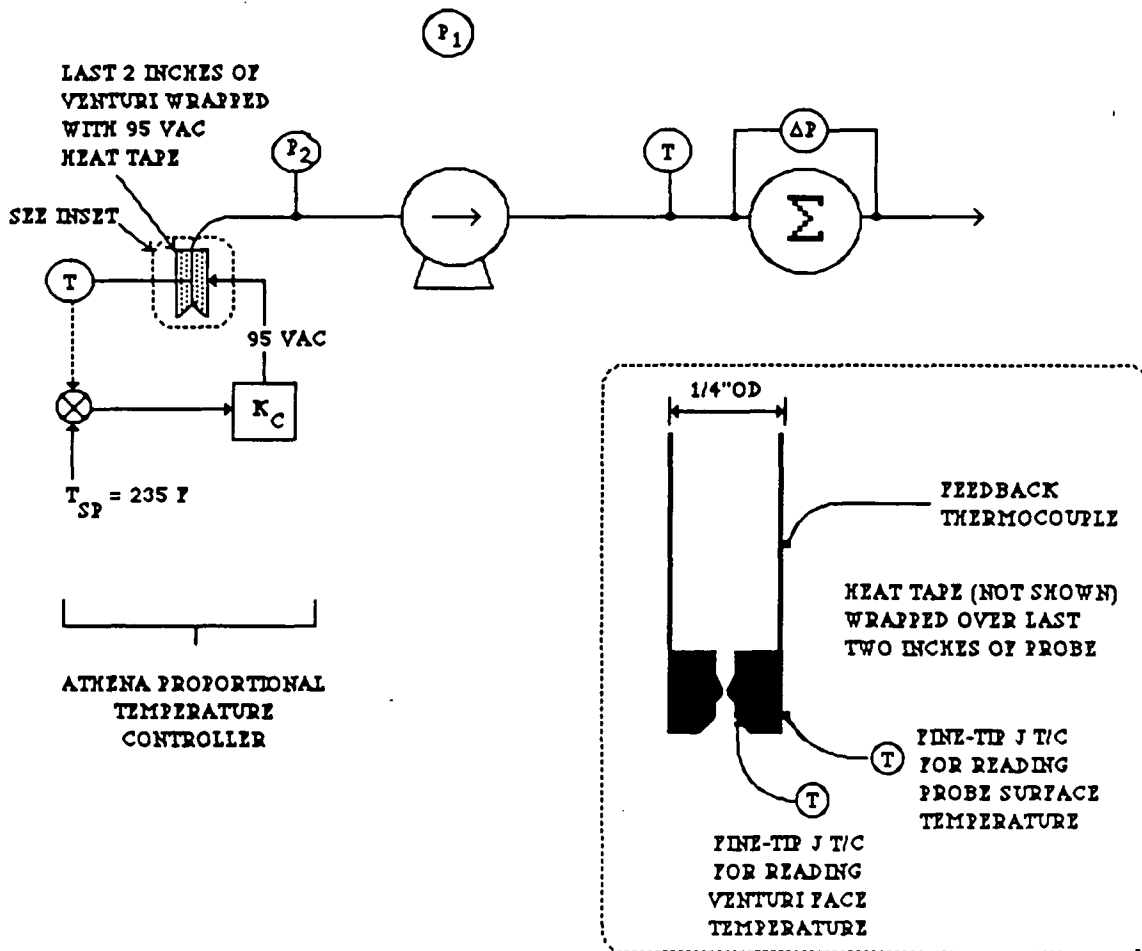FIGURE 1. Unheated Test Configuration

FIGURE 2. Heated Test Configuration

The sample pump was started approximately 20 minutes before any data was collected and allowed to run for the duration of the experiment (approximately 75 minutes). Experimental runs were performed by simultaneously taking an initial wet test meter reading and starting the stop watch, followed by stopping the watch and taking a final reading.

There are three main differences between the test set-up and the way a sample would really be collected in a CVS:

1. The temperature of the bulk steam would be 20-30°F higher than ambient temperature and would fluctuate (in this experiment the ambient air from which the sample is drawn is analogous to the bulk stream),

2. The bulk steam would be moving very fast, rather than not at all as in the test set-up,

3. The sampling systems to be heated will have flow rates on the order of 2 to 10 CFH, not 20 CFH as in the test set-up.

These differences are unimportant for the purpose of this test, which was to determine if heating the probe changed the gas temperature at the probe inlet. The apparatus used was sufficient for this purpose.

III.   Presentation and Discussion of Results

A sequence of nine tests were run as follows: tests 1, 2, and 3 were conducted with an unheated probe; tests 4, 5 and 6 followed immediately using a heated probe; finally, runs 7, 8 and 9 were made with an unheated probe as a check for any unforeseen changes in the equipment or surroundings.

The results for all runs are contained in Table 1. There appears to be a significant difference in flow for unheated and heated configurations. The results from Table 2 confirm this; there is a difference in flow of about 3 percent between heated and unheated runs, while the coefficient of variance is on the order of 0.1 percent.

Could the difference in flow be due to anything other than a change in gas temperature? The only other effect that could cause a change in flow is thermal expansion of the probe during heating. Calculations contained in Appendix B show that the inside radius of a cylinder increases as the temperature increases for materials with positive coefficients of thermal

expansion. This would cause the area available for flow to increase and, therefore, the flow would tend to increase as well. Since the flow decreased when the orifice was heated, it must be concluded that the change in flow was not the result of thermal expansion of the probe.

A further check on the consistency of the data is to calculate the temperature of the gas flowing through the venturi during heated runs. This calculation is shown in appendix B; the gas temperature was about 103°F for runs 4-6. This correlates very well with the observed face temperature of the probe which was about 105°F (data in App. A).

Table 1. Flow through CFV in Heated and Unheated Configurations

RUN	PROBE HEATED?	FLOW (SCFH)
1	NO	18.255
2	NO	18.188
3	NO	18.215
4	YES	17.625
5	YES	17.664
6	YES	17.629
7	NO	18.124
8	NO	18.130
9	NO	18.145

Table 2. Statistical Analysis of CFV Flow Data

RUNS	HEATED?	MEAN FLOW (SCFH)	SDEV	C.O.V. %	% CHANGE FROM RUNS 1-3	% CHANGE FROM RUNS 6-9
1-3	NO	18.219	0.027	0.150		
4-6	YES	17.639	0.017	0.099	-3.18	-2.72
7-9	NO	18.133	0.009	0.048		

In concluding this discussion, I feel I should address a question posed by several engineers when told of this problem, which is: "How can a gas moving at sonic velocity (1000 ft/s) have time to heat up as it moves through the venturi?"

It did not seem to make intuitive sense at the time, although it does if we think of this as a classical heat transfer problem. The pertinent heat transfer equation here is:

$$q/A = h(t_{wall} - t_{gas})$$

where q is the rate of heat transfer (BTU/hr), A is the heat transfer area (ft^2), and h is the local heat transfer coefficient (BTU/hr-ft^2-F). h is a function of fluid properties only; a typical correlation for predicting h is Dittus-Boelter (see reference 4), which is:

$$Nu = .023 \, Re^{.8} Pr^{.4}$$

$$Nu = \frac{hd}{k}, \quad Re = \frac{\rho vd}{\mu}, \quad Pr = \frac{\mu C_p}{k}$$

then
$$h = .023 \left(\frac{\rho vd}{\mu}\right)^{.8} \left(\frac{\mu C_p}{k}\right)^{.4} \frac{k}{d}$$

$$h = .023 (\rho v)^{.8} \left(\frac{C_p}{\mu}\right)^{.4} k^{.6} d^{-.2}$$

where

    Re = Reynolds number, dimensionless
    Nu = Nusselt number, dimensionless
    Pr = Prandtl number, dimensionless
    h = heat transfer coefficient, $\dfrac{BTU}{hr-ft^2-°F}$
    d = diameter, ft
    k = thermal conductivity, $\dfrac{BTU}{ft-hr-°F}$
    ρ = density, $\dfrac{lb}{ft^3}$
    v = velocity, $\dfrac{ft}{hr}$
    μ = viscosity, $\dfrac{lb}{ft-hr}$
    C_p = heat capacity, $\dfrac{BTU}{lb-°F}$

This correlation says that the heat transfer coefficient is proportional to velocity to the 0.8 power. In other words, h is almost directly proportional to the gas velocity, which reaches a maximum at the venturi. It is not surprising at all that the gas temperature changes significantly before it can move through the venturi because of this effect.

Recommendations

There appear to be three ways to circumvent the problem of sampling proportionally without using a heated CFV.

1. <u>Use a Heat Exchanger in the CVS</u> - Using a heat exchanger to hold the temperature of the dilute exhaust stream constant eliminates the need for CFV sample probes, so sampling can be done at a constant flow rate using a heated static probe. Appendix C gives the physical relationships that prove the validity of this method.

2. <u>Do not heat the CFV</u> - Heat the sample line up to the dilution tunnel, but don't heat the CFV sample probe. Sampling losses should not occur within the probe because of the high gas velocity, and also because the temperature within the dilution tunnel is high enough to ensure that water condensation will not occur within the probe. (Absorbtion by condensed water is thought to be the main source of methanol sampling losses. Formaldehyde losses are thought to occur due to both absorption by condensed water as well as polymerization in the presence of liquid water.)

3. <u>Use feedback control</u> - By putting a flow controller in the sample line which gets its set point from the CVS flow computer, proportional flow can be maintained as long as the response time of the controller is very fast. This method requires some modification of existing equipment, as well as a mass flow controller or equivalent flow control device for the sampling system. It is also not a true proportional method in the strictest sense, since there will always be some lag time between a change of flow through the bulk stream venturi and the controller's response to that change. However, for a controller with relatively fast response (95% of full scale in one second or less is typical for a good quality mass flow controller), the lag time should be negligible.

Of the three alternatives listed above, the first one is the most technically sound; it would also meet all requirements in the NPRM as it is now written. The only unresolved technical question is whether or not a heat exchanger affects methanol and formaldehyde emissions. It is unlikely that a heat exchanger would have an effect unless there were condensation occurring within the heat exchanger due to inadequate dilution of the raw exhaust.

References

1. NPRM-Methanol Fueled Vehicles, ECTD, OMS, Summer 1986, Sec. 86.109-88. Published in <u>Federal Register</u>, August 29, 1986, Vol. 51, No. 168.

2. Paulina, Carl. "Non-Proportional Sample Rates in a Critical Flow Venturi Constant Volume Sampler." EPA, OMS, EOD, TPB, January, 1982.

3. Perry, Robert H. <u>Perry's Chemical Engineers' Handbook</u>. New York: McGraw-Hill, 1984, p.5-14

4. Bennett, Carroll O., and Myers, John E., <u>Momentum, Heat, and Mass Transfer</u>. New York: McGraw-Hill, 1982, p.384.

Appendix A.   Raw Data Inputs and Calculated Outputs

RUN	PROBE HEATED?	V1 (CU FT)	V2 (CU FT)	t (SEC)	WET TEST METER TEMP (DEG F)	VENTURI FACE TEMP (DEG F)
1	NO	16.500	17.500	189.86	73	73
2	NO	18.000	19.300	247.72	73	73
3	NO	19.400	20.900	285.42	73	73
4	YES	32.300	33.600	255.64	73	105
5	YES	33.800	35.400	313.94	73	105
6	YES	35.500	39.200	216.26	73	105
7	NO	38.100	39.200	210.35	73	73
8	NO	39.300	40.700	267.64	73	73
9	NO	40.800	41.800	191.01	73	73

PROBE SURFACE (DEG F)	DELTA P (IN H2O)	P1 (IN HG) ABSOLUTE	P2 (IN HG) GAUGE	P2/P1* ABS PRESS RATIO	FLOW (SCFH)
73	0.1	29.078	-13.0	0.553	18.255
73	0.1	29.078	-13.0	0.553	18.188
73	0.1	29.078	-13.0	0.553	18.215
182	0.1	29.078	-13.0	0.553	17.625
182	0.1	29.078	-13.0	0.553	17.664
182	0.1	29.078	-13.0	0.553	17.629
73	0.1	29.078	-13.0	0.553	18.124
73	0.1	29.078	-13.0	0.553	18.130
73	0.1	29.078	-13.0	0.553	18.145

*According to fluid mechanics textbooks, the critical pressure ratio, Pc, required for sonic flow of air is 0.528 or less (ref. 3). However, this is really the ratio required for an orifice; the ratio can be much higher for a venturi, depending on the venturi design. For the sample venturies used at MVEL, Pc is about 0.6 , a number arrived at by experimentation with a margin of safety included (see reference 2). A Pc of 0.553 is well below the ratio required to maintain sonic flow for this type of venturi.

Appendix B. Calculations

1. Thermal Expansion of Heated Probe

Calculation of the change in size of the sampling probe orifice due to thermal expansion would require a detailed equation based on probe geometry, material, and temperature change. Unfortunately, equations available for calculating thermal expansion of solids are limited to the linear case. In order to more accurately predict the effect of heating under the conditions of the test, a simplified model was developed which attempted to take into account the cylindrical geometry of the orifice. The derivation is long and arduous, and it goes beyond the scope of this report to present it here. There were two important results that pertain to the problem at hand:

a. The formula for calculating the change in radius of a cylinder is:

$$r_2 = r_1(\beta \Delta t + 1)$$

where
r_1 = old radius
r_2 = new radius after heating
β = thermal expansion coefficient
Δt = temperature change

This is the same equation one would arrive at by assuming that the radius expands linearly with temperature.

b. If Δt and β are both positive, r_2 will always be greater than r_1. The orifice size will always increase as temperature increases. This means that the decrease in flow seen when the probe was heated could not have been due to thermal effects, since the orifice had to increase in size upon heating.

What was the maximum change in orifice size for this experiment? Since

Δt_{max} = 235 - 73 = 162 deg F
β = 9.6E-6 deg F^{-1}
r_1 = .016 inches

r_2 = .016((9.6E-6)(162) + 1)
r_2 = .0160248 inches

The maximum % change in area available for flow would be

$\%\Delta A_F = (\pi r_2^2 - \pi r_1^2)/(\pi r_1^2)$
$\%\Delta A_F = (.0160248^2 - .016^2)/.016^2$

$\%\Delta A_F = .3113\%$

2. Calculation of Gas Temperature at Venturi for Heated Runs

For a CFV at a given upstream pressure and gas composition, the mass flow rate through the venturi will be

$$\dot{m} = \frac{K}{\sqrt{T}}$$

Where $\dot{m}$ = mass flow rate, lb/hr

K = proportionality constant based on gas temperature and venturi design,

T = absolute gas temperature

Subscripts: 1 = unheated
2 = heated

$$(1)\ \dot{m}_1 = \frac{K}{\sqrt{T_1}} \qquad\qquad (2)\ \dot{m}_2 = \frac{K}{\sqrt{T_2}}$$

Dividing eqn. (1) by eqn. (2),

$$\frac{\dot{m}_1}{\dot{m}_2} = \frac{K}{\sqrt{T_1}} * \frac{1}{\frac{K}{\sqrt{T_2}}} = \sqrt{\frac{T_2}{T_1}}$$

Since

$$\dot{m} = Q\rho$$

where Q = volumetric flow rate, SCFH
ρ = density of air at standard conditions

substituting for $\dot{m}$ in the previous equation yields

$$\frac{Q_1 \rho}{Q_2 \rho} = \sqrt{\frac{T_2}{T_1}}$$

$$\frac{Q_1}{Q_2} = \sqrt{\frac{T_2}{T_1}}$$

Q_1 = 18.133 SCFH (runs 7-9)
Q_2 = 17.639 SCFH (runs 4-6)
T_1 = 73°F = 533°R
T_2 =?

$$\frac{18.133}{17.639} = \sqrt{\frac{T_2}{533}}$$

T_2 = 563.3°R

T_2 = 103.3°F

Appendix C. Theory of Operation
of Constant Volume Samplers

Constant volume samplers (CVS) use one of two methods to measure dilute exhaust flow and obtain sample at a rate proportional to the dilute exhaust flow. These two methods are described below:

1. <u>Critical Flow Venturi</u>. A sketch of a CFV-CVS is shown in Figure 3. As the raw exhaust flow rate varies, the temperature and pressure of the dilute exhaust stream changes.
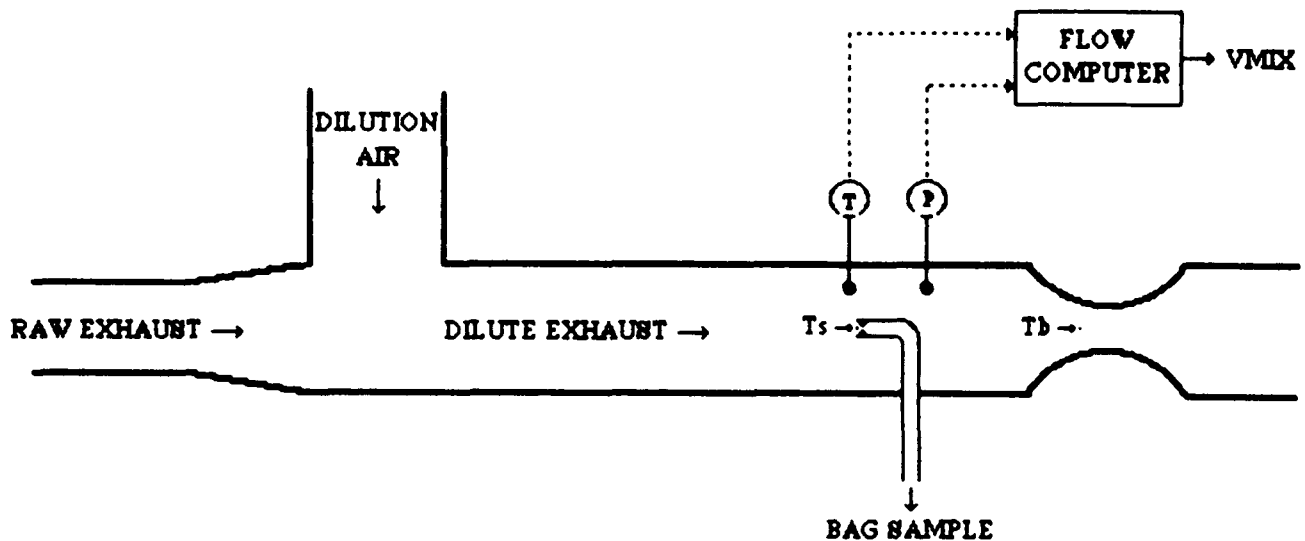
Figure 3. Critical Flow Venturi Constant Volume Sampler

The equation for flow of an ideal gas at a critical flow orifice is (see references 2 and 3):

$$Q = CA \sqrt{g_c k \frac{RT}{M} \left(\frac{2}{k+1}\right)^{\left(\frac{k+1}{k-1}\right)} \left[1 + \left(\frac{k-1}{2}\right)B^2\right]^{\left(\frac{1}{k-1}\right)}}$$

where
- Q = Volumetric flow rate (ft^3/sec)
- C = Coefficient of discharge (dimensionless)
- A = Cross-sectional area of orifice (ft^2)
- g_c = gravitational constant (32.2 ft/S^2)
- k = ratio of specific heats (dimensionless)
- R = ideal gas constant (1545 $ft-lb_f/°R-mol$)
- M = Molecular weight of gas ($lb/lb-mol$)
- T = Absolute gas temperature ($°R$)
- B = ratio of orifice diameter to pipe diameter (dimensionless)

For values of B less than 0.2 (the usual case), the bracketed term on the right is approximately equal to unity. For a given orifice and pipe size, A, B, and C are constants. For a given gas, k and M are constants.

The only variable left in the equation is T; therefore, for a given gas and orifice (or venturi), this equation takes the form

$$Q = K \sqrt{T}$$

where K is a dimensional constant that incorporates gas and venturi properties.

For the venturies in the CFV-CVS, the flows through each would be

$$Q_b = K_b \sqrt{T_b}$$

$$\text{and } Q_s = K_s \sqrt{T_s}$$

where the subscripts (b and s) refer to the bulk and sample streams, respectively.

Dividing, we get

$$\frac{Q_b}{Q_s} = \frac{K_b}{K_s} \sqrt{\frac{T_b}{T_s}}$$

If the ventures are located near each other, $T_b = T_s$; then

$$\frac{T_b}{T_s} = 1$$

and $\dfrac{Q_b}{Q_s} = \dfrac{K_b}{K_s}$ = a constant

Since the ratio Q_b/Q_s is a constant, the flows through the sample and bulk stream venturies will be constantly proportional to one another as long as the gas temperatures at each venturi are equal.

Notice that if the temperatures of the bulk and sample streams remain constant, it is no longer necessary that the temperatures of the two streams be equal. The flow will remain constantly proportional because all terms on the right hand side of the equation will be constant.

2. Positive Displacement Pump. A sketch of a PDP-CVS is shown in Figure 4. Dilute exhaust passes through a heat exchanger and reaches a constant temperature before entering the PDP. The unit is designed to maintain a relatively constant pressure at the pump inlet. Since T and P are constant, sampling of the dilute exhaust can be done with a static probe at a constant flow rate.
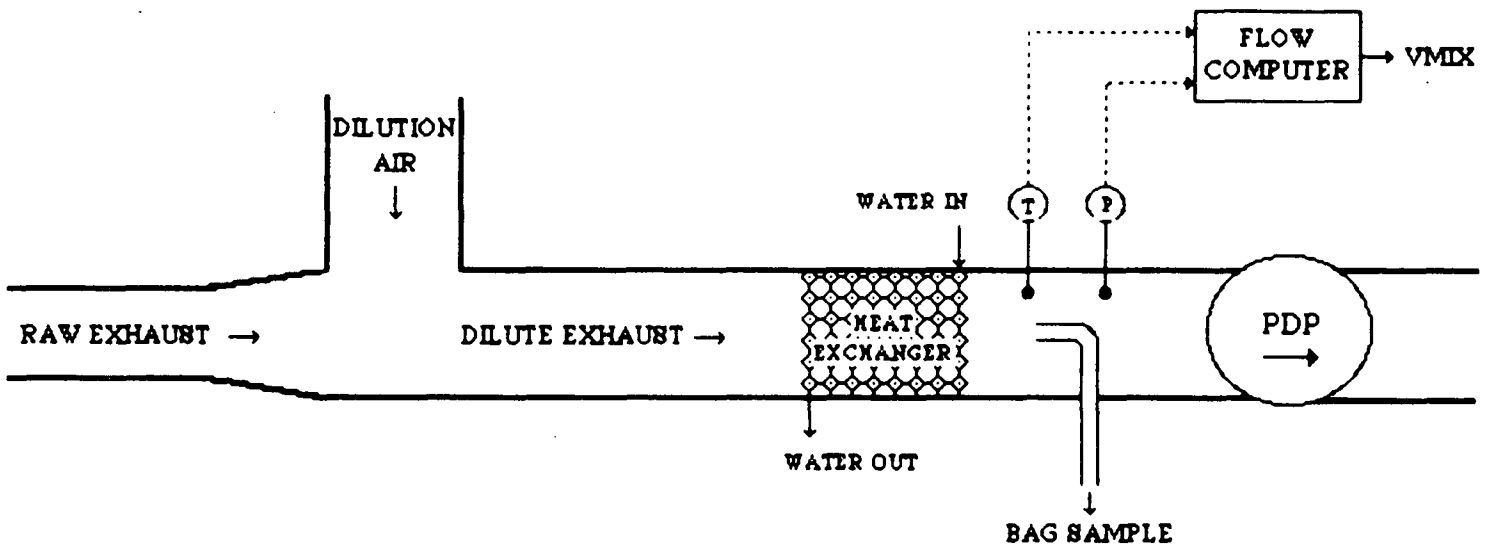
Figure 4. Positive Displacement Pump Constant Volume Sampler