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Constant Volume Sampler CVS-7000 Series

－Variable Flow CVS-7600 type based on Sub-Sonic Venturi Flowmeter－

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Constant Volume Sampler CVS-7000 Series
—Variable Flow CVS-7600 type based on Sub-Sonic Venturi Flowmeter—

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<Abstract>

The constant volume sampler has been used for more than 35 years to sample gasses from automobiles tested in emissions laboratories. More recently, the need to test vehicles operating on alternative fuels and LEVs (low emission vehicles) have made new demands on the performance of these samplers. Alternative fuels can produce much more water as a combustion product, increasing the flows needed for condensation free sampling, while the LEVs need lower flow rates since the concentrations that must be measured are already very low.

Since conventional CVSs are limited in the number of different flow rates they can offer, it has become necessary to improve the sampler in order to provide laboratories with a device that offers more flexibility to adapt to different fuels, driving cycles and ambient conditions. The CVS-7000 series includes a new type, the model 7600, that meets these requirements.

This paper describes how this is accomplished by combining sub-sonic flowmeters for flow measurement, heated components for preventing condensation, and mass flow controllers for maintaining a proportional sample. The package integrates seamlessly with the MEXA-7000 to offer a convenient system for flexible sampling and analysis of vehicle emissions.

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定容量試料採取装置　CVS-7000シリーズ
—サブソニック・ベンチュリ流量計を備えた可変流量型CVS-7600—

1. はじめに

定容量試料採取装置（CVS）が1970年代の初頭に実用化されていらい，自動車排ガスの質量測定が可能となった．排ガスの環境への影響は，単位走行距離（1マイル）当たりに排出される汚染物質の質量（g）で評価される．自動車をシャシダイナモに乗せて，路上での走行状態を再現し，排出される排ガスの質量を測定する．

CVSは次のような原理で働く．

(1) 自動車から排出されたガス（ダイレクトガス）に希釈用大気（希釈空気）を加えて混合する（混合ガス）．このとき，混合ガスの流量が一定になるように希釈量を調節する．

1. Introduction

The CVS, or constant volume sampler, was first applied in the late 1950's to make possible the measurement of the mass of exhaust emissions. Before that time, emissions tests had been based on concentration limits. Since the effect on the environment is assessed by the grams of pollutants emitted by vehicles per mile driven, a sampling system was needed that could measure the mass of these emissions while the vehicle was operated through a sequence of accelerations and decelerations that approximated normal driving.

These sampling devices operate by mixing the vehicle's exhaust and ambient air at a constant combined flow rate. As the vehicle produces more exhaust, less ambient air is mixed with it in order to keep the total flow constant. In this manner, the total volume of the mixture is easy to determine from the time of the sampling multiplied by the constant flow rate. A small sample of these gasses is collected during the same sampling period. This sample is analyzed later for the concentrations of the pollutants. Today, CVS units do not actually operate at a constant rate of flow, but the name CVS is still used.

The modern devices included in the CVS-7000 series have taken advantage of electronics and computer technology to lower the cost and improve the precision of the CVS. All these sampling systems must perform the following three functions:

—Prevent the condensation of water in the sample before it can be measured. The exhaust is diluted to the point where the water vapor in it will not condense when cools to room temperature.
—Measure the total diluted exhaust volume over a sampling interval, so the mass of emissions can be calculated.
—Collect a proportional sample of diluted exhaust in a sample bag for later analysis. At any time, the rate of flow of sampled gasses and the total rate of flow of diluted exhaust through the CVS must be in the same proportion.

2. New requirements

More recently, the requirements of testing modern vehicles make it necessary to have a more flexible and adaptable CVS. Vehicles today may use alternative fuels

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(2) 混合ガスを一定量抽出し（サンプルガス），各汚染成分の濃度を測定する．
(3) この濃度と混合ガスの体積とを演算処理して，ダイレクトガス中の各成分の質量を求める．

CVSには次のような機能が必要となる．

＊サンプリング中に，排ガス中の水分が冷えて凝縮しない程度に大気で希釈する．
＊サンプリング中の全時間にわたって混合ガスの体積を測定し，質量を算出する．
＊サンプルガスの流量と混合ガスの流量の比率は常に一定である．

2. 新たな要求事項

近年，CH_3OH, CNG, LPGなどの代替燃料車が開発されている．これらの排ガスは水分を多く含むため，希釈空気量を増やさなければならない．一方，排ガスの低濃度化（LEV）にともない，サンプルを希釈し過ぎないよう注意が必要である．このため，CVSは車種/燃料/環境に合わせた流量の最適化が必要となる．固定流

such as Methanol, CNG and LPG. Burning these fuels produces more water, requiring more dilution and higher CVS flow rates.

However, the same vehicles are likely to be LEVs, or low emission vehicles. The emissions from these vehicles are very low, and the concentrations produced have become more difficult to measure accurately. It is clearly important not to over-dilute these samples, making them even more difficult to measure. For this reason, the CVS flow rates need to be lower.

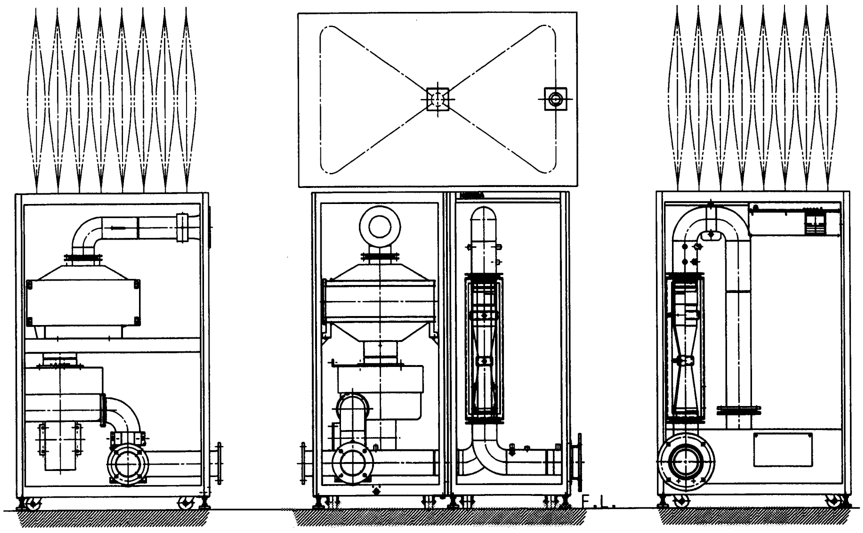

Fig.1 The CVS-7600

To meet these conflicting requirements, a CVS needs to operate at the correct flow rate for each vehicle, fuel and ambient condition. CVS units based on fixed flow metering orifices however, are only able to operate at a relatively small number of fixed flow rates. The CVS-7600 offers a flow rate that can be set for any value over the range of flows needed for vehicle emissions testing. The figure 1 shows the overveiw of the CVS-7600. Proper choice of this flow rate allows the CVS-7600 to operate at the theoretically minimum possible flow rate, making the maximum pollutant concentrations available for analysis.

The figure 2 shows a simplified diagram of the CVS-7600.

The key points are:

—A variable speed blower and motor controller. The speed of the blower deter

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量制御式オリフィスを使ったCVSの設定流量は限られているが，CVS-7600では理論的に最小の流量で作動でき，高い分析感度が得られる．

CVS-7600（図1）には次のような特長がある．

＊速度可変式ブロアにより，車種/燃料/環境に合わせて流量を最適化できる．

＊サブソニック・ベンチュリーにより，広い流量範囲を測定できる．

＊マス・フロー・コントローラによりバッグへの流量を最適化できる．

＊サンプルガスの流路の加熱により，水分の凝縮が防止できる．

＊スムース・アプローチ・オリフィス型流量計（SAO，オプション）により希釈空気の流量を測定できる．（生ガス流量＝混合ガス流量－希釈空気流量）この手法は，サンプルガスの応答遅れや減速走行時の燃料カットなどの影響を受け難く，CO_2トレーサ・ガス法より優れている．

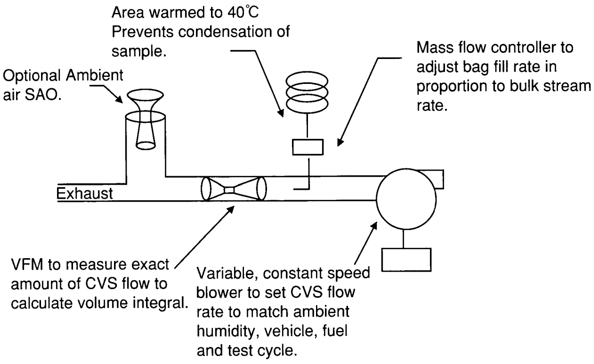

Fig.2 Simplified diagram of the CVS-7600

mines the bulk stream flow rate, providing the flexibility to set any desired speed, depending on the vehicle, the test cycle and the conditions of the ambient dilution air.

—A subsonic venturi for measuring the total bulk stream flow rate. Two pressure transducers are used in order to accurately measure flows over a wide dynamic range.

—Mass flow controllers are used to regulate flow to the sample bags. These controllers keep sample flow to the bags proportional to the main flow rate. They also can adjust the flow rate according to the length of the measuring period so a proper amount of sample is collected. In this way, there is always enough gas to analyze even for short test phases. It also avoids the risk of overfilling the bags with longer test phases.

—Sample lines carrying the diluted exhaust to the bags are heated to prevent any condensation from forming when the vehicle accelerates, causing the dewpoint of the diluted gasses to become temporarily high.

—As an option, a smooth approach orifice (SAO) can be installed in the ambient flow path of the mixing T in order to measure the ambient air flow. This offers a means to determine the vehicle exhaust flow by subtracting this from the main flowrate. This has advantages over the CO_2 tracer method for determining exhaust flow, since it is not affected by the inherent delays for the tracer gas to reach the analyzers or a lack of tracer gas when fuel is cut off on decelerations. This SAO can also be conveniently used as a built-in calibration device.

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3. 体積の測定

体積の算出が容易なため初期のCVSには定容積型ポンプ(PDP)が使われていた．その後，臨界流量ベンチュリー型(CFV)のCVSが開発された．CFV型オリフィスでは，両端の圧力降下が大きくなると，スロート部の流速は音速に到達する．この流速と測定時間の積がオリフィスを通るガスの体積に相当する．流速は温度の関数だが，MCUで補正する．CVS-7100とCVS-7300はこのタイプである．

一方，CVS-7600では，速度可変型ブロアで流量を設定し，サブソニック・ベンチュリー型流量計(subsonic-VFM)で測定する(図２)．

VFMのスロート部(図３)での流速は音速より遅く，ベルヌーイの原理に基づいて作動する．VFMの流量は(1)式で，CFVでは(2)式となる．CFVの臨界流量特性は，VFMのサブソニック流量が飽和した状態である(図４)．

CVS-7600では，入口圧力，スロート圧力，入口温度をVFMから高速に読取って

3. Measuring the volume

The first CVS's used a positive displacement pump running at a constant rpm and preceded by a heat exchanger. This simplifies the problem of measuring volume, since it is a simple matter to take the number of revolutions of the pump together with the pump calibration to calculate a volume.

Later, the critical flow venturi or CFV type CVS, represented in the CVS-7000 series by the 7100 and 7300 models, was developed. This type uses the CFV metering orifice to fix a given flow rate. It is a physical property of this kind of orifice that when the pressure drop across it is large enough, the gas velocity in the throat reaches the speed of sound and the flow rate through it becomes an easily determined, fixed value. The volume of gas through the orifice is the simple product of this flow rate and the time period of the test phase. The flow rate is actually dependent on the temperature, but the Main Control Unit integrates this and provides an accurately measured volume.

The CVS-7600 performs the same functions by using a variable speed blower to set the flow and a subsonic venturi flow meter (VFM) to measure it. The VFM (figure 3) is similar to the CFV, however the speed of the flow in its throat is less than the speed of sound, so it is called a sub-sonic venturi. It measures the flow but does not regulate it. As with any head type flowmeter, this device operates according to the Bernoulli principle. The pressure in the throat is proportional to the square of the flow rate. When the compressibility of the gas is taken into account, the flow is given by the following equation:

$$Q_{std} = K \cdot C_d \cdot Y \cdot \frac{\pi}{4} \cdot d^2 \cdot \sqrt{\frac{\Delta P}{P}} \cdot \frac{P}{\sqrt{T}} \quad \cdots\cdots (1)$$

The flow through the CFV type orifice is given by:

$$Q_{stD} = \frac{C_1 P}{\sqrt{T}} \quad \cdots\cdots (2)$$

The critical flow property used by the CFV is the limiting case of the sub-critical flow used by the VFM, as can be seen on the figure 4.

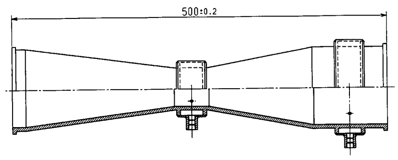


Fig.3 Subsonic venturi flow meter (VFM)

* equation 1
Q_{std} : standard flow rate
K : conversion constant
C_d : discharge co-efficient
Y : expansion factor
d : orifice throat diameter
ΔP : throat differential pressure
P : inlet pressure
T : inlet temperature

* equation 2
Q_{std} : standard flow rate
C_1 : orifice co-efficient
P : inlet pressure
T : inlet temperature

MCUで演算して正確な体積を求める．

4. 凝縮の防止

CVSは，多量の水分を含んだ排ガスを大気で希釈して，サンプルガスの露点を室温より下げる働きをする．希釈ガス流量は，希釈用大気の相対湿度，排ガスの水分濃度および排ガスの量によって決まるが，これらがいかに変動してもCVSは常に最適流量に設定できなければならない．

排ガス中の水分濃度は，燃料の種類，とくに水素の含有量に依存する．メタノール車はガソリン車比べ倍近い水分を含む（図５）．

排ガス量は車の燃費によって変わる．所定の排ガス試験モードでの走行距離と燃費から，燃料の消費量（CO_2の排出量に比例）が分かり，最終的に排ガスの総量を求めることができる．ガソリン車をEPA75 Phase Ⅰ（LA-4）で走行させたときの，燃費と排ガスの総量の関係を示す（図６）．このように，大気の湿度，燃費，燃料

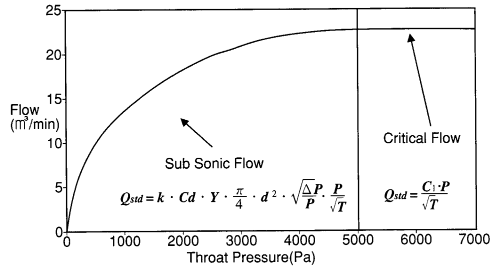


Fig.4 The flow property of the VFM & CFV

The CVS-7600 collects the inlet pressure, throat pressure and inlet temperature from the VFM at a high sample rate and calculates the instantaneous flow rate. Its Main Controller Unit integrates the volume from these instantaneous values. This insures an accurate volume measurement.

4. Preventing Condensation

An important function of the CVS is to manage the water in the exhaust gas. It does this by adding enough ambient air to the wet exhaust so that the dewpoint temperature of the resulting mixture is below the ambient temperature. This requirement is described by the following equation:

$$Q_{CVS} = \frac{\left[\frac{[H_2O]_{TP}}{[H_2O]_{sat}} - R\right] Q_{TP}}{1-R} \quad \cdots\cdots (3)$$

＊ equation 3
Q_{cvs} : flow rate through CVS
$[H_2O]_{TP}$: water concentraion in tailpipe exhaust gasses
$[H_2O]_{sat}$: saturated water concentraion at test temperature
R : relative humidity of dilution air
Q_{TP} : flow rate of exhaust gas

From this we see that the amount of flow needed depends on the relative humidity of the dilution air, on the concentration of water in the exhaust, and on the amount of exhaust. It becomes clear that a modern CVS needs to supply the appropriate flow rate for any combination of these conditions.

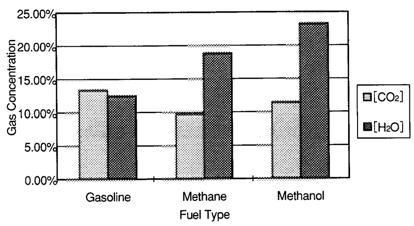


Fig.5 Exhausted gas compositions of various fuels

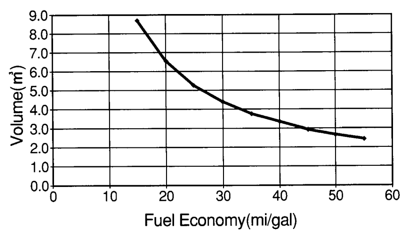


Fig.6 Total amount of exhaust gas vs fuel economy Gasoline fueled vehicle during EPA P1

の種類が分かれば，CVSで必要な流量が計算で求めることができる（図７）．

車が加速すると，排ガス総量（水分も）が平均値を上回り，混合ガスの露点が室温より高くなり，水分が凝縮する恐れがある．逆に，アイドリング時には露点より十分に低くなる．そこで，加速からアイドリングまでの排ガスをバッグに補集すると，露点のバラツキは小さくなる（図８）．

水分の凝縮を防止するため，ダイレクトガスの採取点からバッグ補集点までサンプリング系全体を40℃まで加熱する必要がある．一方，バッグに補集されたサンプルは，積分効果のために特別に加熱する必要はない．

5．比例サンプリング

CVS-7600では，MFCとPIDコントローラによって，サンプルガスと混合ガスの流量比が所定の値になるようにしている．このために，サンプルガス採取点と希釈サンプルバッグとの間，および，希釈空気採取点と希釈空気バッグの間にMFC

The concentration of water in the exhaust depends on the fuel type, especially on the amount of hydrogen in the fuel. The following figure 5 shows the water and CO_2 concentrations produced for some common fuels. Note that methanol produces almost twice the amount of water as gasoline.

The amount of exhaust gas containing this concentration of water that a vehicle emits depends on its fuel economy. Driving a car through a test cycle requires a certain amount of energy, which comes from burning the fuel. If we know the distance of the driving cycle and the fuel economy of the vehicle, we can determine how much fuel it will burn. From this the total amount of exhaust gas produced can be determined. Figure 6 displays this result for a gasoline fueled vehicle during the first phase of the EPA 75 test.

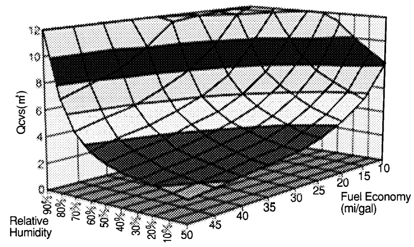


Fig.7 Required CVS flow vs humidity and fuel economy Gasoline (y=1.85) at 20℃

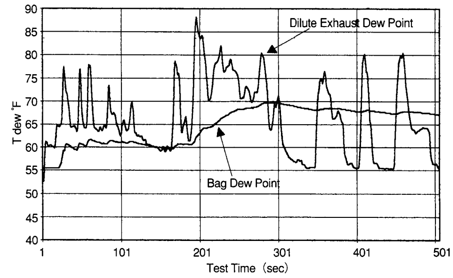


Fig.8 Dewpoint temperature in sample bag and in sample line during phase I of EPA 75 test (Minimum dilution at 50%RH and 68°F)

Thus the CVS flow rate required to hold the water from the vehicle's exhaust depends on an interesting combination of the ambient conditions, the fuel type and the fuel economy of the vehicle. With this information, the dilution equation given above can calculate the optimal flow rate. Figure 7 shows this graphically.

When a vehicle accelerates, the volume of exhaust (and water vapor) exceeds the average level and the resulting dewpoint temperature of the diluted exhaust will exceed ambient temperature, creating a possibility of condensation. Similarly, during idle periods, the dewpoint temperature will be below ambient temperature. As these gasses collect in the sample bags, these fluctuations in dewpoint temperature are integrated and the variations are not nearly so great. The figure 8 shows this situation for the first phase of the US EPA 75 test.

From this information we see that the lines carrying the diluted gas from the sampling point to the bags need to be heated to 40℃ to prevent condensation. Because of the integrating effect of collecting the sample gasses in the bags, the dewpoint in the bags themselves rises only slightly above ambient, so extra heating is not required.

5. Proportional sampling

The CVS-7600 maintains the proportionality of the sample flow to the main flow by means of mass flow controllers and PID controllers. In this way, sample flows and bulk-stream diluted exhaust flows are maintained at the desired ratio.

を設けて，サンプルガス流量を制御している．そして，MCUでバッグの容量と試験時間とから必要流量を計算し，MFCの設定値としている．

混合ガスの流量は，ブロアをフィードバック制御することによって一定に保たれる．MCUは，希釈空気，燃料，燃費などから所定の流速を求めてブロアに送信するとともに，実際の流量を毎秒10回算出してフィードバックする．

6. MEXA-7000シリーズとの統合

CVS-7000シリーズのオペレーティング·システム (OS) とウィンドウ·グラフィック・ユーザ・インターフェースはMEXA-7000シリーズと共通であり，CVS-7000用に別のコンピュータを用意する必要はない．また，コンピュータは，一つの高分解能タッチ・スクリーン方式 のCRTで操作できる．

To control sample flows, the mass flow controllers are installed between the dilute sample point and the dilute bags and between the background sample points and the background bags. The Main Control Unit calculates the desired flow from the size of the sample bag and the length of the testing phase. It provides this value as the setpoint for the mass flow controller.

The bulk stream flow of diluted exhaust is maintained by feedback adjustments to the speed of the blower. The Main Control Unit provides a setpoint signal for the desired standard flow rate as determined from the considerations outlined above. It also calculates the standard flow rate ten times a second. This signal is the process variable for the PID controller feedback loop.

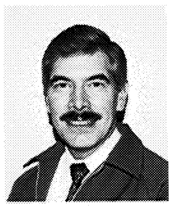
6. Integration with the MEXA-7000

The CVS-7000 series uses the same software operating system and windowed graphical user interface as the MEXA-7000. It runs on the same hardware platform, so an additional computer for the CVS-7000 is not needed. This user interface smoothly integrates with the MEXA-7000 user interface to provide uniform and consistent operation of both devices. Both the sampler and the bench are operated conveniently from the same large format, high resolution touch-screen operator's CRT monitor.

7. Summary

The application of the CVS-7000 series in the emissions laboratory offers users a new opportunity to enhance their ability to measure emissions. With the variable flow CVS-7600, one can adjust the sampling to the meet the specific requirements of a given vehicle on a given day for a given test cycle. It is no longer necessary to accept merely the best available flow setting and compromise the test result. Each test can be operated at the theoretically optimum point.

The smooth integration of the control computer and user interfaces with the MEXA-7000 offers both cost advantages and an ease of use. CVS-7000 Software uses the same operating system as the MEXA-7000 and can operate in the same computer, saving the costs of multiple controllers. The CVS-7000 user interface has the very same look and feel as the MEXA-7000 interface, making it both easy to learn and easy to operate.



William Silvis
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Technical Applications

7. まとめ

自動車排ガス試験室にCVS-7000シリーズを導入することにより，排ガス測定に新たに機能の拡大が期待できる．CVS-7600では，オペレータは，試験車の種類，大気の状態，試験サイクルなどの具体的な条件に合わせて最適の状態で試験ができる．

（抄訳　編集部）