

Using Ejector Diluters to Sample Vehicle Exhaust at Elevated Pressures and Temperatures

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ABSTRACT

This paper presents an alternative and relatively simple method which allows the use of ordinary ejector-type diluters over a wide range of sample inlet conditions including elevated pressures and temperatures. After calibration of the ejector diluter, the dilution can be accurately characterized using only the pressures at the inlet and the outlet of the diluter and the sample temperature. The method is based on a semi-empirical, stationary model taking into account the critical parameters needed to predict the dilution factor. Under steady state operation it achieves accuracies estimated to be below $\pm 8\%$ (95% confidence interval) for diluter inlet pressures in the range of 1000 – 4000 mbar absolute and temperatures between 20 – 200°C. Performance under actual vehicle testing conditions is evaluated upstream of the DPF for a diesel vehicle run on a chassis dynamometer. Model predicted time resolved dilution factors were compared against oxygen tracer gas measurements for both steady state and transient operation, and confirmed the $\pm 8\%$ accuracy estimate.

1. INTRODUCTION

Driven by the ongoing debate over potential health effects [1, 2] and the environmental impact of vehicular exhaust emissions [3, 4], the legal emissions limits continue to be tightened (e.g. Euro 5 [5]). Specifically NO_x and particulate matter (PM) are expected to require considerably greater emission controls in the near future. At the same time the introduction of modern diesel engines as well as gasoline direct injection engines is being done as a means both to improve fuel economy and minimize the CO_2 emissions of transportation sources. However, the nature of these combustion processes, for example the known NO_x - PM trade-off, presents a challenge to developing these engines and

the associated aftertreatment systems and strategies to meet the future emission limit values. To succeed, reliable methods for quantifying the PM content in the vehicle exhaust are needed.

When studying the exhaust aerosol of combustion engines, dilution of the raw exhaust is necessary for various reasons. First, the concentration of the particulates to be measured needs to be reduced to a level which falls within the operating range of the measurement instruments. Second, the exhaust gas needs to be cooled down to an acceptable temperature without allowing condensation of the water vapor or other gaseous components. Processes like coagulation and chemical reactions, which may cause an unwanted modification of the aerosol to be measured, can be suppressed by an appropriate dilution of the sample. Furthermore, it is desirable that dilution should be similar to the process of exhaust entering the atmosphere to achieve realistic measurement results [6, 7].

Due to their simple design, ejector diluters are widely used in exhaust measurements. There are no moving parts, which assures a robust and uncomplicated operation and, thus, provides good stability and reliability over an extended time. A further convenience is that an additional pump is not necessary to draw the sample from the exhaust. Ejector diluters are usually calibrated for conditions where the inlet and the outlet of the diluter are at ambient pressure and temperature. However, the operating principle of these devices shows that the dilution ratio is considerably influenced by sampling conditions. At the elevated pressures and temperatures typically found in vehicle exhaust manifolds, use of the standard calibration factor can result in large deviations between the expected and the actual dilution factors. In some applications, especially when diluting hot exhaust, the diluter needs to be heated to prevent unwanted condensation. This will also change the behavior of the ejector diluter and lead to a shift in the dilution factor.

Modern automotive exhaust measurements have seen a growing need to sample under non-atmospheric conditions. For instance, measurements upstream of a diesel particulate filter (DPF) have become necessary in order to quantify the loading and the efficiency of these devices [8, 9]. Due to rapid changes in pressure and temperature of the exhaust, which occur during transient engine operation, the dilution ratio will undergo transient changes and measurement of the time resolved dilution is a challenging task. The critical value when calculating the true dilution ratio is determination of the varying sample flow. Because of its properties, especially the water and soot content, a precise direct measurement of the sample flow that goes into the diluter is very difficult when diluting raw exhaust. Therefore nearly all methods rely in practice on estimating the actual sample flow.

Beyond use of the manufacturer's nominal dilution factor [9, 10], other methods have been described for determining the actual dilution factors of ejector diluters, used in practical applications. Koch et al. [11] show an approach for calculating the volumetric dilution ratio of an ejector-type diluter using a differential pressure measurement. However, in emissions measurements a dilution factor which is based on concentration instead of the volumetric dilution ratio needs to be used. Giechaskiel et al. [12] also criticizes this issue and presents a more complex fluid dynamic-based model which can be used to iteratively calculate the actual value of the dilution ratio as a function of the ejector operating parameters. This model assumes stationary flows and was not checked for transient operating conditions. In some studies NO_x [6, 13] was used as tracer gas. Therefore, the concentration of the tracer gas needs to be measured in the raw sample as well as in the diluted sample downstream of the diluter. The quotient of these two concentrations represents the actual dilution factor. However, applying this method requires additional expensive equipment (e.g. gas analyzers, hardware and software for data acquisition). In addition, when processing the tracer gas data, cross sensitivities, pressure and temperature influences, issues with water condensation and the soot contamination have to be considered.

In this work an alternative and relatively simple method is developed which allows the use of ejector diluters over a wide range of operating conditions by only measuring the pressures at the inlet and the outlet of the diluter and the sample temperature. The technique presented here is based on a simple stationary approach, but is shown to perform well also under transient conditions. Its performance was evaluated by particulate matter measurements made upstream of a DPF during transient operation of a diesel vehicle. The calculated time resolved dilution factors were checked against oxygen tracer gas measurements for both steady state and transient operation.

2. OPERATING PRINCIPLE OF EJECTOR DILUTERS AND MODELING

The work described in this paper was carried out using Dekati Ejector Diluters (DI-1000, Dekati Ltd, [14]) which are widely used in measuring exhaust aerosols. However, the basic principles and procedures explained in the following sections are generally applicable to all ejector diluters.

2.1 BASIC OPERATION

Figure 1 shows the design of a typical ejector diluter.

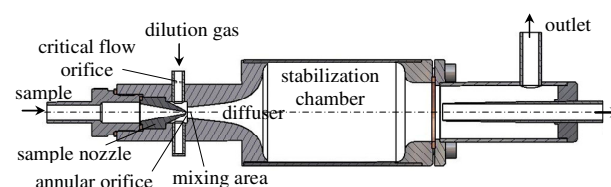


Figure 1: Schematic of a typical ejector diluter

The basis of all ejector-type diluters is the ejector pump which usually consists of a nozzle surrounded by an annular orifice and followed by a mixing area and diffuser. In the case of the Dekati ejector diluter, the central nozzle is connected to the sample probe and the dilution gas flows along the outside of the nozzle, through the annular orifice, and past the small orifice at the end of the nozzle. Attached to this pump-section is a stabilization chamber which feeds into the outlets of the diluter.

The operation of this type of diluter is based on Bernoulli's principle. The sample is drawn into the diluter by means of the energy of the working fluid (pressurized dilution gas). The strong acceleration of the expanding dilution gas as it passes through the annular orifice causes a pressure drop that draws the sample through the central nozzle. After passing through the nozzle/annular orifice, both flows enter the mixing area. Due to the transfer of momentum between the two gas streams, the dilution gas flow is decelerated whereas the sample flow is accelerated into this mixing zone. The gas mixture then passes into the diffuser which converts some of the kinetic energy into an increase in static pressure. Since the stabilization chamber is open to the atmosphere, the gas mixture reaches ambient pressure at the outlets of the diluter.

2.2 EJECTOR DILUTER TRANSFER FUNCTIONS

The aim of this work is to provide a straightforward, easy to use procedure for determining the dilution factor, with adequate accuracy for a wide range of applications in vehicle exhaust sampling and dilution. To account for changes in the ejector diluter sample flow rate due to elevated sample pressure and temperature, a simple

stationary model was developed. It is based on the following assumptions:

- The sample nozzle of the diluter can be treated as an orifice.
- The flow of the dilution gas ($Q_{dilution}$) is constant and known.
- The pressure at the outlet of the diluter (P_{outlet}) is near ambient pressure (± 10 mbar)
- The pressure difference across the diluter inlet and outlet can be used in place of the pressure drop across the diluter sample nozzle.
- Fluctuations in the sample temperature at the diluter inlet do not influence the temperature of the diluter body since both the diluter and dilution gas are heated to fixed temperatures (typically $\approx 200^\circ\text{C}$).

From fluid dynamics, it is necessary to consider the velocity and density of the gas when calculating the flow rate through the orifice. Density varies inversely with temperature, but varies directly with pressure. Gas velocity increases with pressure until it reaches sonic conditions (speed of sound), above which the velocity remains constant for higher pressures. Because of this change in behavior at "critical" flow conditions, two different flow regimes must be considered to calculate the sample flow as a function of the diluter operating conditions. The equations used to describe the behavior of these diluters are distinguished by their sample pressure dependence:

1. Non-critical flow regime, where $P_{sample} \leq 1.9 \times P_{outlet}$:

$$Q_{sample} = \frac{A_1}{\sqrt{T_{sample}}} \cdot \sqrt{(P_{sample} - P_{outlet}) - \Delta P_{min}} \quad (1)$$

2. Critical flow regime, where $P_{sample} > 1.9 \times P_{outlet}$:

$$Q_{sample} = \frac{A_2}{\sqrt{T_{sample}}} \cdot P_{sample} + B \quad (2)$$

Where P_{sample} and T_{sample} are the static pressure and absolute temperature at the inlet of the diluter, and P_{outlet} is the static pressure at the outlet of the diluter. A_1 , A_2 , B and ΔP_{min} are diluter specific parameters that must be determined during calibration. Once these parameters have been determined, Q_{sample} is calculated by measuring P_{sample} , P_{outlet} and T_{sample} while the diluter is in use. The calibration procedure is described in Section 3. A more detailed derivation of these equations and description of the parameters are presented in Section 5.

The dilution factor (DF) of the ejector diluter represents the reduction, by $1/DF$, in the concentration of the original sample and is calculated using the sample flow rate and the dilution gas flow rate:

$$DF = \frac{Q_{total}}{Q_{sample}} = \frac{Q_{sample} + Q_{dilution}}{Q_{sample}} \quad (3)$$

where Q_{sample} is the flow rate calculated by either transfer function (1) or (2), depending on the sample pressure, and $Q_{dilution}$ is the flow rate of the dilution gas. For the purpose of standardization, all flow rates will be reported in standard liters per minute (SLPM), where standard conditions are defined as 1013 mbar and 25°C . This unit is used so that it is not necessary to compensate for changes in gas density due to the temperature and pressure differences between the flow measurement location and the ejector diluter. Typical nominal dilution factors of ejector diluters are about 10.

3. EXPERIMENTAL

3.1 EXPERIMENTAL SETUP

The Dekati ejector diluters were calibrated using a gas flow manifold constructed to enable the gas pressures, temperatures and flow rates associated with the diluter to be controlled and monitored. The dilution factor was measured for sample pressures and temperatures in the range of 1 – 4 bar and 20 – 240°C respectively. A diagram of the system is provided in Figure 2.

The diluter is connected to controlled inputs for the sample and diluent gases. It is enclosed in a heating mantle (Model DH-1511) provided as an accessory by Dekati. This heater is generally set to a temperature of 240°C when vehicle exhaust is being sampled to avoid water vapor condensation and thermophoretic losses of PM. For laboratory tests, the diluter is also kept heated at this temperature. Nitrogen is used as the dilution gas due to the availability of UHP grade Nitrogen ($>99.999\%$) that can be used at the required pressures and flow rates. Either nitrogen or air can be used interchangeably to determine the flow characteristics of the diluter. The diluent passes through a single stage regulator into a mass flowmeter with a range of 0 – 100 SLPM. A pressure transducer is positioned downstream of the mass flowmeter so that any pressure drop across it does not influence the diluent delivery pressure of 30 psig. The temperature of the dilution gas is controlled by an inline heater (Model DH-1711) placed between the pressure gauge and the diluent inlet. The dilution gas is heated to 210°C , with the heater located downstream of the mass flowmeter to avoid changing its flow response by the heated gas. Some room temperature measurements, with both heaters turned off, were made to compare with data provided by the manufacturer.

The sample inlet of the ejector diluter is connected to a gas line system that is separate from the diluent gas line to prevent interactions between them. The sample gas

is either compressed zero air (UHP grade) or UHP nitrogen and can be delivered over a pressure range of 1 – 4 bar absolute. Because the ejector diluter can draw in a sample at lower than ambient pressures, it was necessary to have a means of reducing the delivery pressure at the diluter inlet down to 900 mbar. This is accomplished by having the pressurized sample gas flowing into the mass flowmeter in combination with a throttled vacuum pump (see Figure 2). The pump creates a small pressure drop below atmospheric pressure while still allowing a positive flow through the mass flowmeter. This made it possible to determine the maximum pressure drop at the inlet before sample flow stopped, which was found to be between 80 and 150 mbar below ambient. For sample pressures above 1 atmosphere, the pump is isolated from the system. One of two mass flowmeters with different ranges (0 – 10 SLPM and 0 – 50 SLPM) is used to monitor the sample flow depending on its actual flow rate. The pressure transducer to measure the sample pressure at the inlet is located downstream of the mass flowmeter to avoid a pressure drop across the flowmeter. The sample gas is heated with an in-line heater located between the flowmeter and the diluter inlet. A K-type thermocouple is placed in the gas stream at the diluter inlet. This thermocouple is used both to measure the temperature at the inlet and control the heater to maintain a constant temperature between 20 °C and 240 °C. The pressure at the outlet of the ejector diluter is monitored with a pressure transducer. For some of the tests, a throttling valve was connected to the diluter outlet to produce a back pressure in the diluter chamber, between 1000 and 1400 mbar.

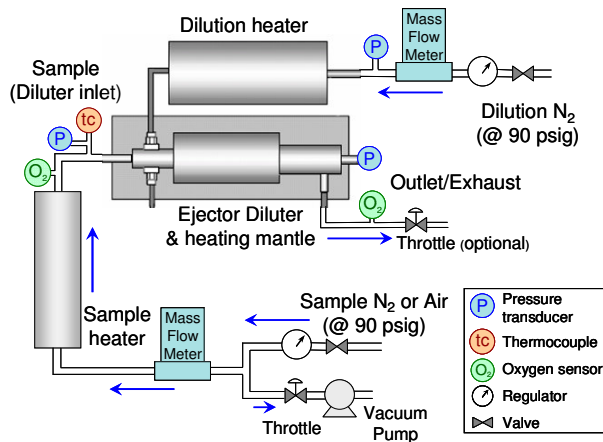


Figure 2: Laboratory flow manifold for calibrating an ejector diluter.

All of the mass flowmeters were calibrated with a Gilibrator-2 electronic bubble flowmeter (Sensidyne, Inc.). As such, they are internally self-consistent with each other. The pressure transducer readings were checked at two pressures: at vacuum (< 1 mbar) and at 1 atmosphere (≈ 1000 mbar) and were within 5 mbar of each other. The thermocouples were used without any additional calibration.

For some of the diluter flow measurements, oxygen sensors were incorporated into the system to provide an independent means of measuring the dilution factor (DF). The sensor is a Robert Bosch LSU Broadband λ sensor (LSU 4.9) with an LA4 Lambda Meter (ETAS GmbH), which is typically used to measure Air/Fuel ratio by analyzing vehicle exhaust gas. Since nitrogen is used to dilute the zero air sample, the ratio of oxygen content in the sample to the oxygen in the diluted gas gives the dilution factor as

$$DF = \frac{(\%O_2)_{inlet}}{(\%O_2)_{outlet}} \quad (4)$$

As these sensors measure the partial pressure of oxygen, the raw signals are corrected for differences in the absolute pressures at the two sensors. The influence of gas temperature is negligible as the sensor element is maintained at 750 °C.

Dilution factors obtained from measured flow rates are compared to oxygen concentration data in Figure 3. The correlation between the 2 methods is very good (average deviation was 0.75%).

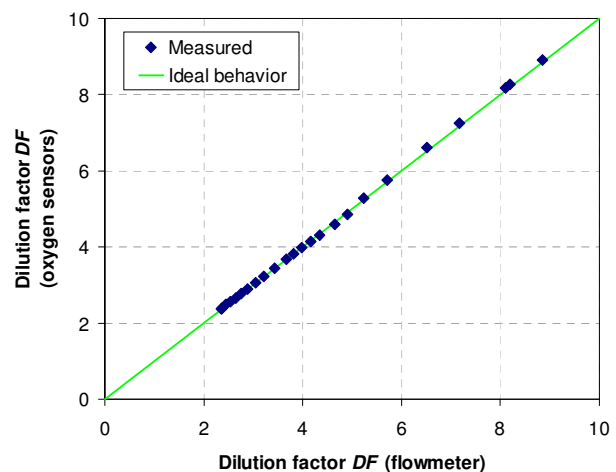


Figure 3: Comparison of flow measurement vs. tracer gas measurement.

3.2 VERIFICATION OF MANUFACTURER'S CALIBRATION

Flow measurements were carried out under the same conditions as the manufacturer's diluter calibration to verify the performance of the lab setup. Dekati calibrates their diluters by measuring the sample flow rate over a range of sample pressures from 910 – 1050 mbar with the outlet pressure at a constant 1013 mbar and keeping the diluter at room temperature. Figure 4 shows the calibration data for one of the ejector diluters along with the sample flow rate and dilution factor data obtained from our testing manifold.