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Abstract

Work done under this contract focused on two key improvements needed for the Simple Portable On-Vehicle Testing (SPOT) system. First, the probe geometry was to be significantly smaller such that it could be used with exhaust pipes smaller than 3 inches (7.62 cm). Secondly, enhancements were sought that may improve accuracy and signal to noise ratios. Several design iterations were investigated and two primary designs were built and tested. An optimized design based on a machined venturi with a ½ inch (1.27 cm) aspiration tube was built and tested. This led to the construction of several 2 inch exhaust probes for the SPOT program. The new design offers several advantages including ease of use with exhaust pipe diameters from 2 to 8 inches, compatibility with complex exhaust pipe geometries (such as teardrop exits, pipes with rain caps etc.), accuracy and precision comparable with the best laboratory grade engine test cell mass air flow measurement systems. The results of this work culminated with the assembly of a new 2-inch probe that was supplied under another contract to CARB with a SPOT unit.

Executive Summary

Background

The SPOT system is used to acquire long time-period emissions, duty cycle and ambient condition monitoring from non-road vehicles. It utilizes an exhaust probe that measures oxides of nitrogen, oxygen and total instantaneous exhaust mass flow. The development of this probe has undergone several iterations over the last 2 years in order to improve accuracy and for ease of use with a wide variety of vehicle types and exhaust configurations. CARB generated this contract to fund an effort to improve the exhaust probe into a configuration capable of being used on exhaust systems smaller than 3 inches. The previous configuration was approximately 4 inches in diameter, thus it could only be used with larger pipes (i.e., pipes larger than a 4-inch diameter).

Methodology

A new 2-inch exhaust probe was designed and built as a scaled version of the 4-inch version. It was initially based on the trumpet aspirator and was later revised to use an included venturi aspiration subsystem.

All of the work for design, machining and fabrication were conducted at AEI. Testing and evaluation was done both at the AEI flow laboratory facility and at the engine testing laboratories at the USEPA in Ann Arbor, Michigan.

Results

A two-inch probe based on the trumpet design was built and determined to perform satisfactorily. This design however was very difficult to build due to the small size and precision requirements. Another design was built based on a machined venturi. This system performed better than the trumpet design and was copied into five additional probes.

The new 2-inch exhaust probe achieves exhaust mass flow measurements with precision and accuracy approaching that capable in engine research test cell environments. In general, the system is accurate at any operating point within 2% and is capable of direct numerical scaling for pipe sizes from two to eight inches.

Conclusions

The objectives for designing and fabricating a 2-inch exhaust mass flow probe for use with the SPOT unit were achieved. The new probe is capable of acquiring exhaust mass flow from any engine with an exhaust pipe size between 2 and 8 inches. The new probe design offers several advantages in terms of ease of use, weight and flexibility with a wide variety of exhaust configurations.

1.0 Introduction

The Simple, Portable On-Vehicle Testing (SPOT) system has proven to be a very valuable tool in the quest of acquiring long-term emissions and duty cycle information from non-road and on-road vehicles. [Figure 1](#) shows this system as it was used during the summer of 2002 testing.



Figure 1 - The SPOT Unit

The 4-inch exhaust mass flow probe that was used with earlier SPOT systems performed very well for exhaust pipe sizes in excess of 4.0 inches diameter. This 4-inch probe, shown in [Figure 2](#), was ideal for use on larger vehicles having stack sizes up to 10 inches.

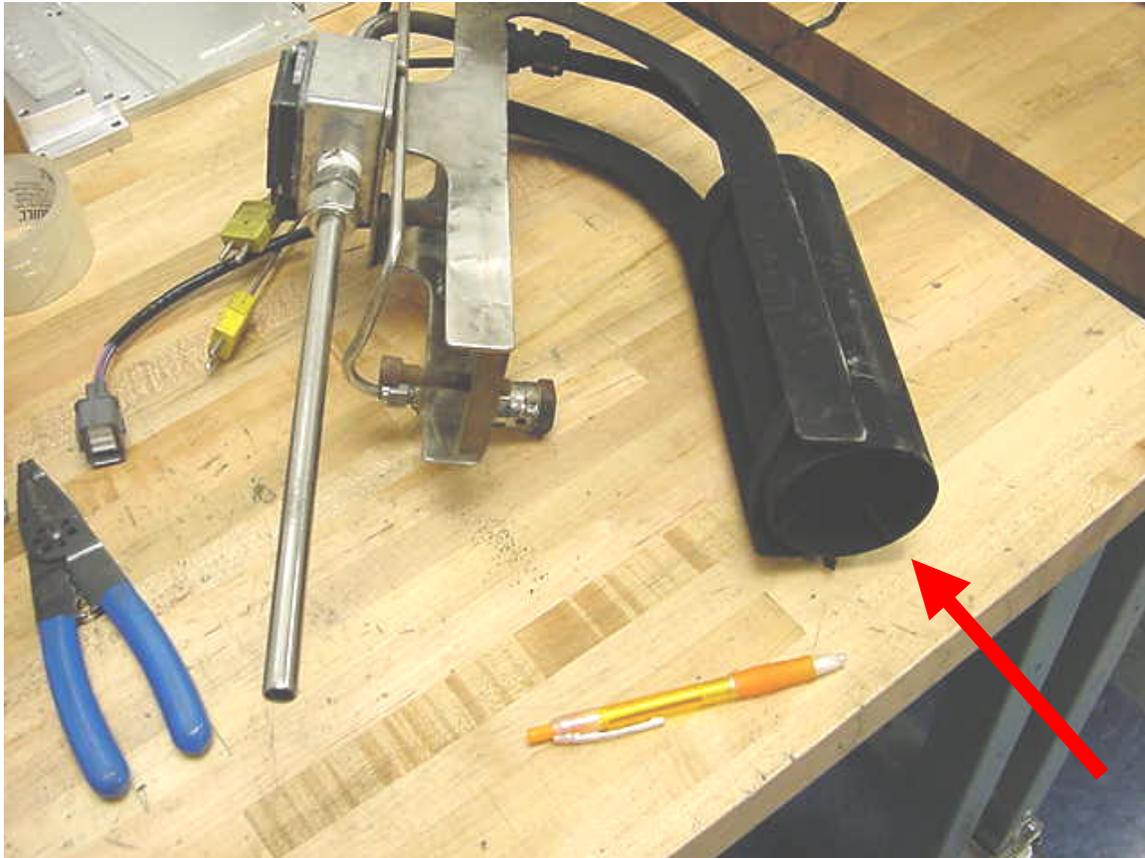


Figure 2 - 4 Inch Exhaust Probe (Induction Section Indicated by Arrow)

For sizes smaller than this, an exhaust pipe adaptation system was needed in order to make measurements. Moreover, the exhaust flow normally seen from diesel and SI engines with pipes smaller than 4 inches was on the low end of the turndown precision of the 4-inch probe, thus measurements were somewhat less accurate than desired.

1.1 Trumpet Operating Principle

The fundamental operating principle of the exhaust mass flow meter is based on gas entrainment. Inside a cylinder that is placed into the stack is a teardrop shaped obstruction. When exhaust gas passes over this teardrop shape, a rarified (low density, thus, low pressure) region is generated at the beginning of the taper. An annulus that surrounds the teardrop at this location is tied through an arrangement of tubes to a fresh air mass flow meter located on the bottom side of the probe in air. At the annulus position, fresh, ambient pressure air is captured by the rarified zone, thus resulting in a flow of air through said tube. Through experimentation, it is shown that there exists a predictable relationship between the entrained air mass flow and the passing exhaust

mass flow. Therefore, the instantaneous exhaust mass flow can be inferred by measuring the mass airflow of the entrained air. The principal advantages for this methodology are:

1. A hot wire type anemometer can be used to measure the mass flow. This would not be possible at exhaust temperatures.
2. A hot wire anemometer is inexpensive, thus this type of technology is affordable.
3. The fresh air measurement is far less sensitive to fouling than measuring exhaust, which is highly contaminated with particles, oil etc.
4. The entrainment zone at the trumpet is not sensitive to fouling due to large orifice sizes and high velocities.

A need existed for a smaller probe that could be mounted in tubes as small as 2 inches. To address this need, this project was initiated to design and construct a similar probe with smaller size for adaptation to exhaust pipes as small as two inches diameter.

1.2 Materials and Methods

The initial approach to accomplish the objective was to directly scale the 4-inch probe down to a 2-inch probe. This was done by fabricating a bulbous trumpet rarification module like that used in the 4-inch probe. [Figure 3](#) shows this device.



Figure 3 - Trumpet Rarification Module

The scaled module was named within AEI as the “tadpole” because of its very small size. This new teardrop shaped obstruction was approximately 3 inches in length and less than 1 inch in major diameter. The material of construction was 16-gauge 316 stainless steel. Because of the small size, this was a very difficult task to bend and roll such a small size with sufficient precision to accomplish the needed measurement accuracy and precision. After the first unit was completed however, it was integrated into a completed 2-inch probe assembly.

After testing the flow characteristics at AEI, the assembly was sent to the USEPA laboratories in Ann Arbor, Michigan. There, the probe was assembled into an exhaust stack from a 6-liter diesel engine. The test cell was equipped with a highly accurate intake air mass flow meter and fuel mass flow measurement system. The sum of the two equals the exhaust mass flow. By comparing the measurement signal from the exhaust probe to that of the test cell intake mass flow, a relationship is generated. AEI has developed a “normalized” methodology for calculating the flow rate as a function of output signal and the size of pipe that is being used. The output units are therefore pounds/hr/square inch. By multiplying this value by the cross sectional surface area of the measured pipe, the mass flow rate in pounds per hour is obtained.

Figure 4 shows the results of the first “tadpole” based 2-inch probe. This particular probe was serialized as 1-12 as part of a numbering system internal to AEI. There is no particular meaning associated with this number aside from being a serial number.

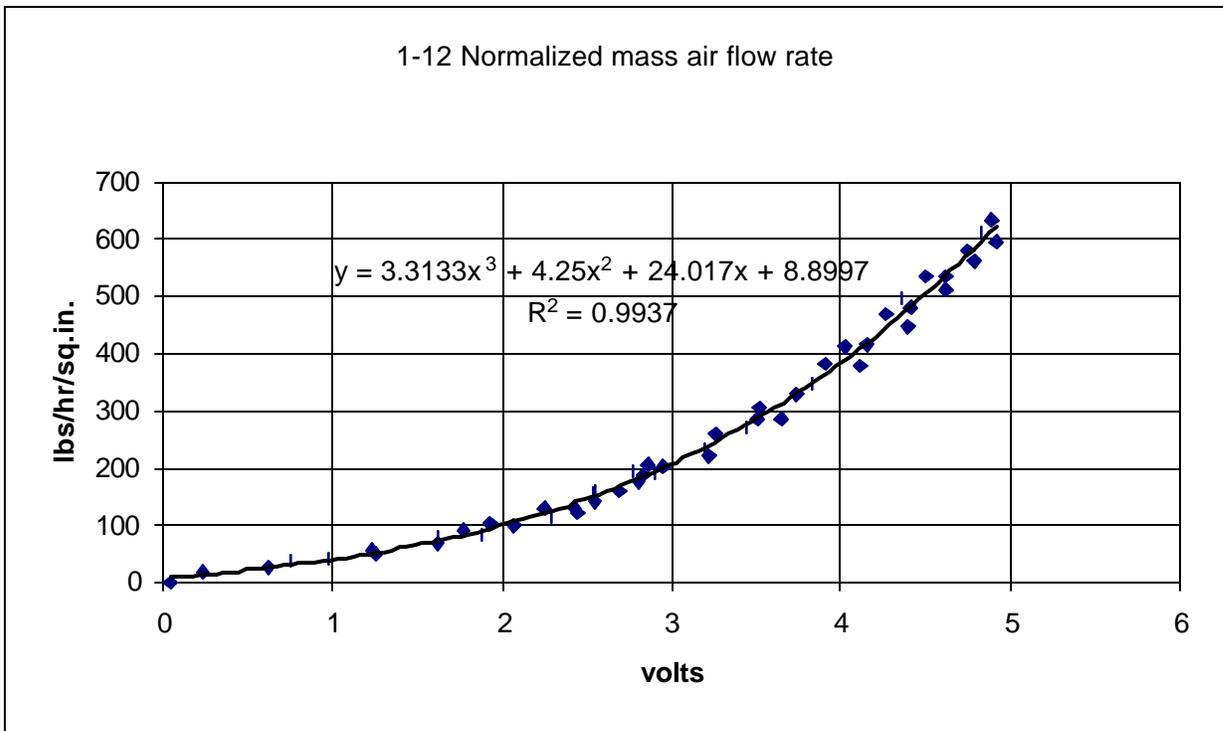


Figure 4 - Initial “Tadpole” Based 2 Inch Probe Flow Correlation

A third order relationship numerically defines the shape of the curve. As can be seen from the graph, the unit achieved an r-squared of 0.9937. Although this represented very good performance, AEI engineers believed that further improvement was possible with a more precise machining process for the rarification module.

Following this early work, it was proposed that a different entrainment mechanism be designed for inclusion into the 2-inch probe. This methodology is similar to that which is employed with the trumpet or tadpole entrainment module, however it is done on the inside diameter of a venturi shaped orifice instead of on the outside of a teardrop shaped obstruction. A rarified area is created by forming a constriction zone with a downstream expansion zone, generating subsequent fresh air entrainment. Utilizing the capabilities within the AEI research machining facility, a small venturi was developed that would fit within the 2 inch probe. [Figure 5](#) shows the assembled venturi.



Figure 5 - Small Venturi for the 2 Inch Probe

This two-piece module design allows exhaust gases to pass through the orifice (inside diameter of the module (indicated by arrow)) whereby subsequent expansion results in rarification. The term rarification, as applied to this system methodology, is a location in space, whereby the density of the air is significantly lower than the area around it, thus the air is “rarer”. This rarification allows for entrainment of atmospheric pressure gases, thus achieving the mechanism for fresh air entrainment. [Figure 6](#) shows another view of the rarification module.

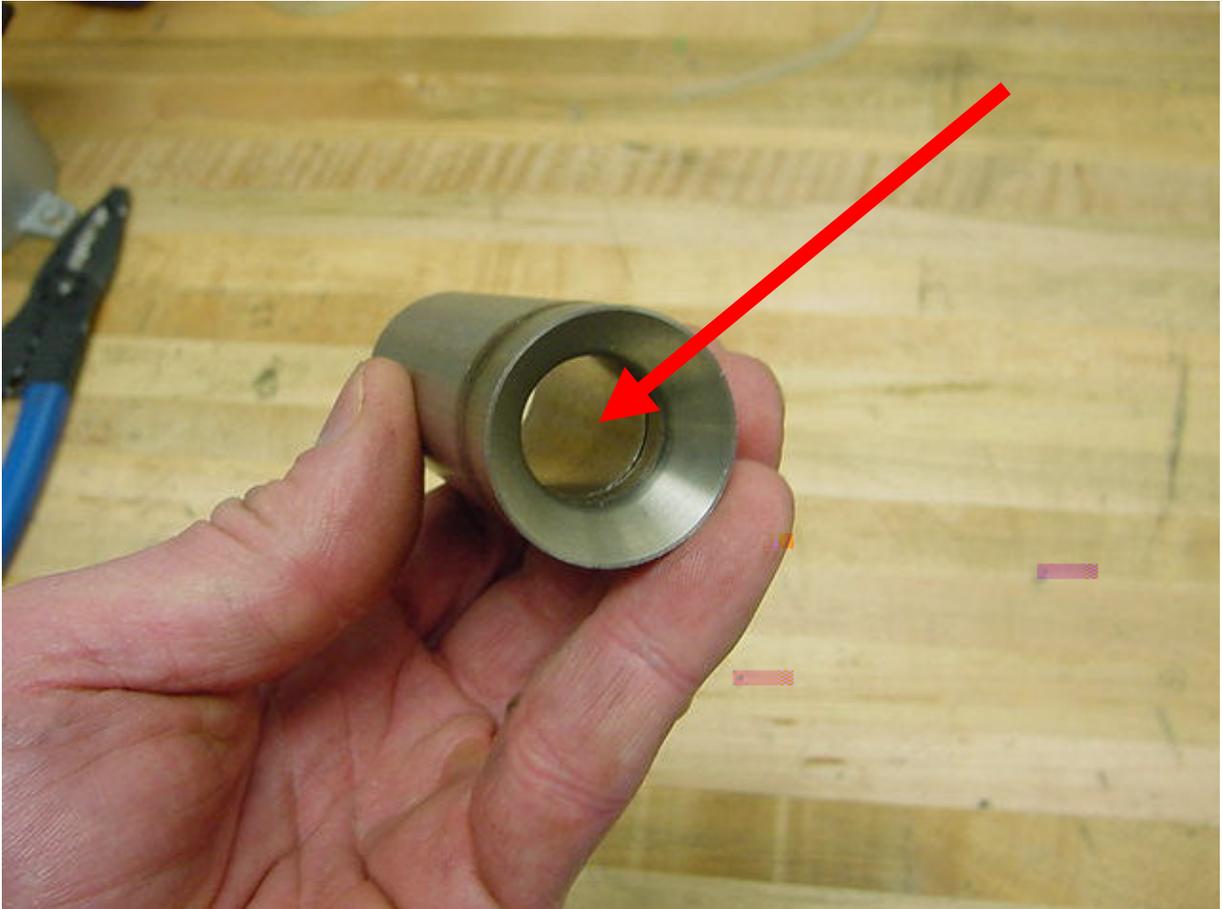


Figure 6 - Flow Through View of the Rarification Module

Initial flow measurements at AEI looked very promising with the assembled 2-inch probe venturi module. There was significant improvement in output voltage stability over the entire operating range. AEI attributed this improvement to the precision machining, which would be impossible to achieve with fabrication techniques necessary on the trumpet design. [Figure 7](#) shows the assembled venturi based rarification module.

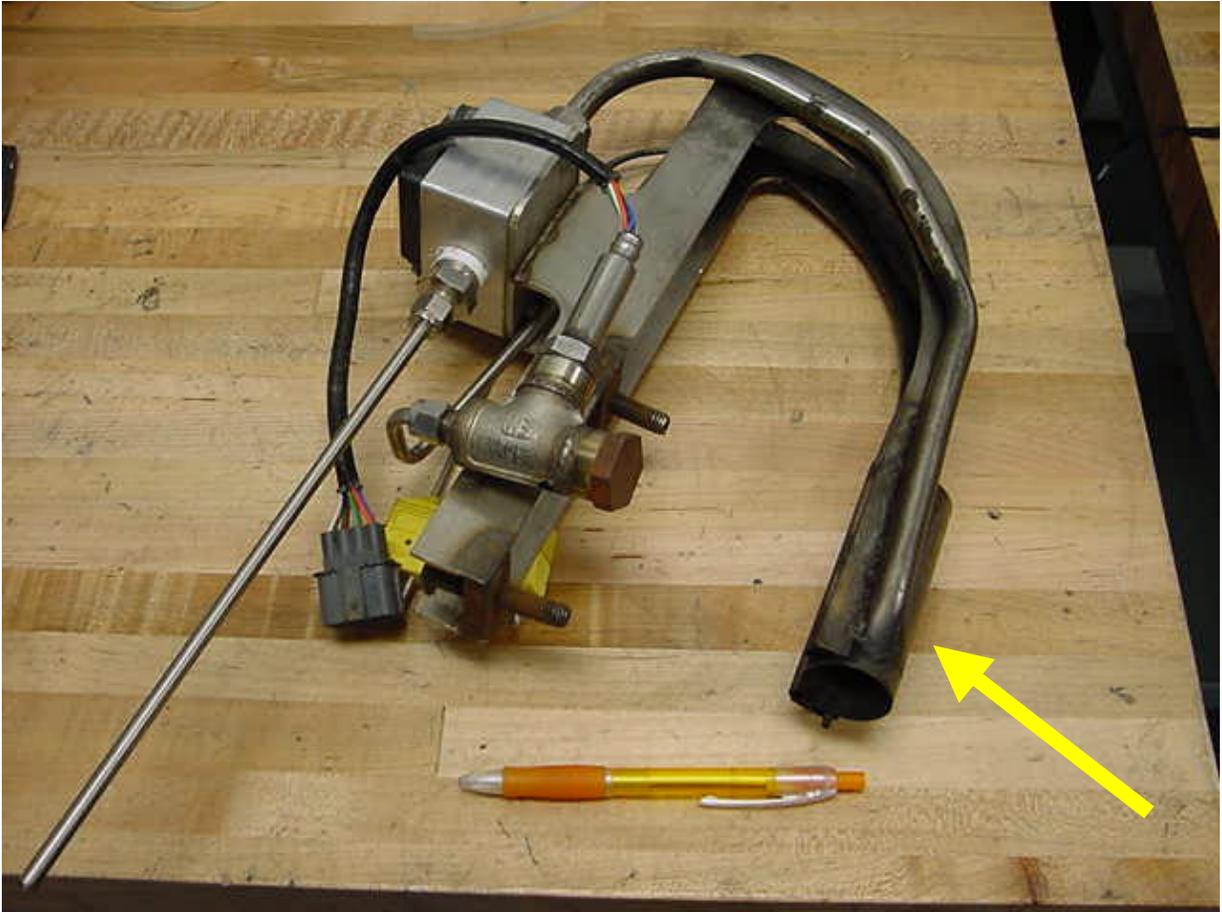


Figure 7 - Assembled 2 Inch Probe with Venturi Aspirator (Indicated by Arrow)

2.0 Results

AEI conducted exhaustive testing of the new assembly, with subsequent additional testing performed at the USEPA. The results of this new system were very favorable. Over the entire operating range of engines tested, the system was more stable, manifested lower drift and was generally more precise over all conditions including extreme temperature fluctuations.

Figure 8 shows the voltage to flow relationship for probe number 1-12 as tested at the USEPA. The system provided excellent correlation using a third order polynomial fit. This new measurement precision significantly improved the overall SPOT measurement system.

The black data points on the chart below are the initial testing data points. The yellow data points are validation testing performed the following day, and the magenta points are validation testing performed one week after the initial test.

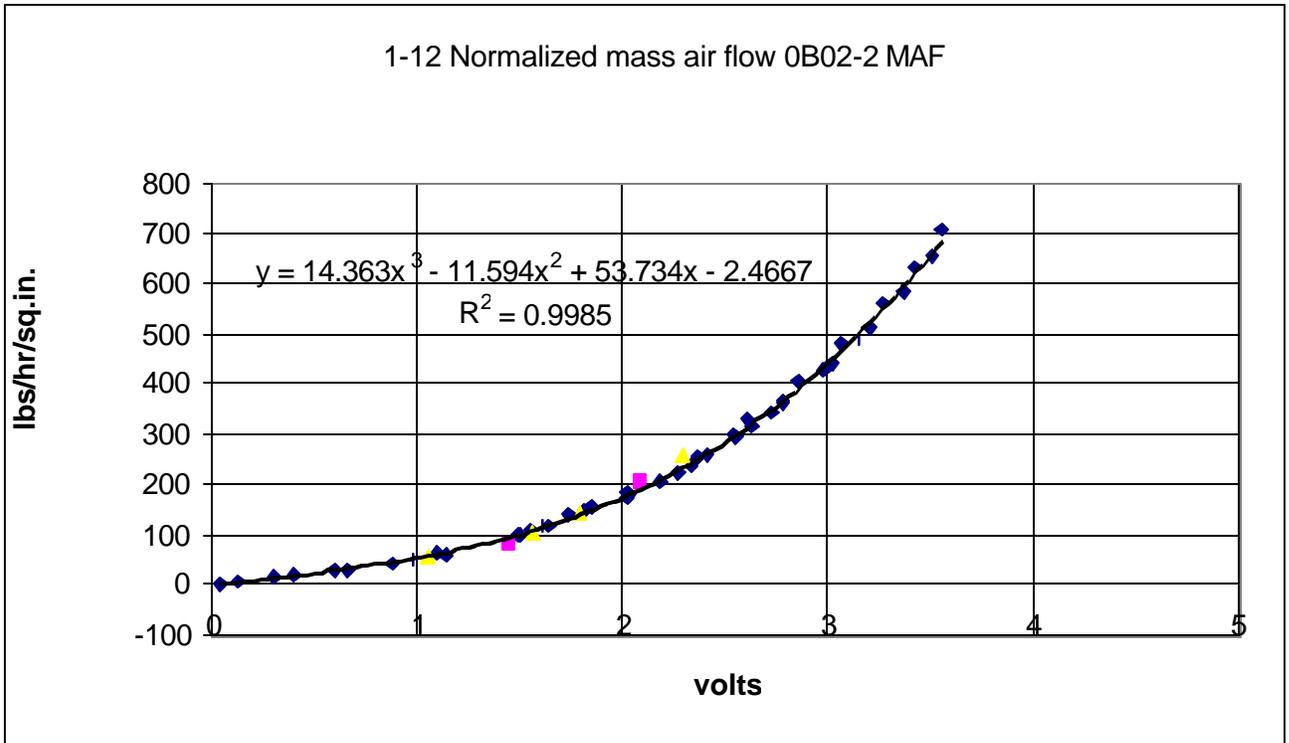


Figure 8 – 2” Probe Serial # 1-12 Voltage vs. Flow for the New Venturi System

The new system, with its decreased length and diameter, offered significant advantages in field application. First, the system worked equally well in exhaust stacks ranging from 2.0 inches up to 7 inches (the largest size usually encountered on vehicles) and second, it accommodates a wide variety of stack configurations, including stacks with sharp bends near the exit, those with teardrop exits and those with complex rain cap devices. [Figure 9](#) shows the relative size between the 2-inch and 4-inch probes.



Figure 9 – 2-inch and 4-inch Exhaust Probes

2.1 Follow-On 2 Inch Probe Work

Because of the success of this work, eight 2-inch probes were built based on the new design. In order to access the differences between probes, all were tested at AEI and the USEPA. The following Figures 10 through 19 illustrate the voltage to normalized flow relationships for each of the different probes. Some probes were tested with different hot wire anemometer serial numbers and are labeled accordingly. For all, the correlation is comparable to the initial prototype probe.

Throughout the following graphs (Figures 10 through 18), the black data points are the initial testing data points, the yellow data points are validation testing performed the following day, the magenta points are validation testing performed one week after the initial test, and the light blue points (when present) are validation testing performed the same day as the original testing.

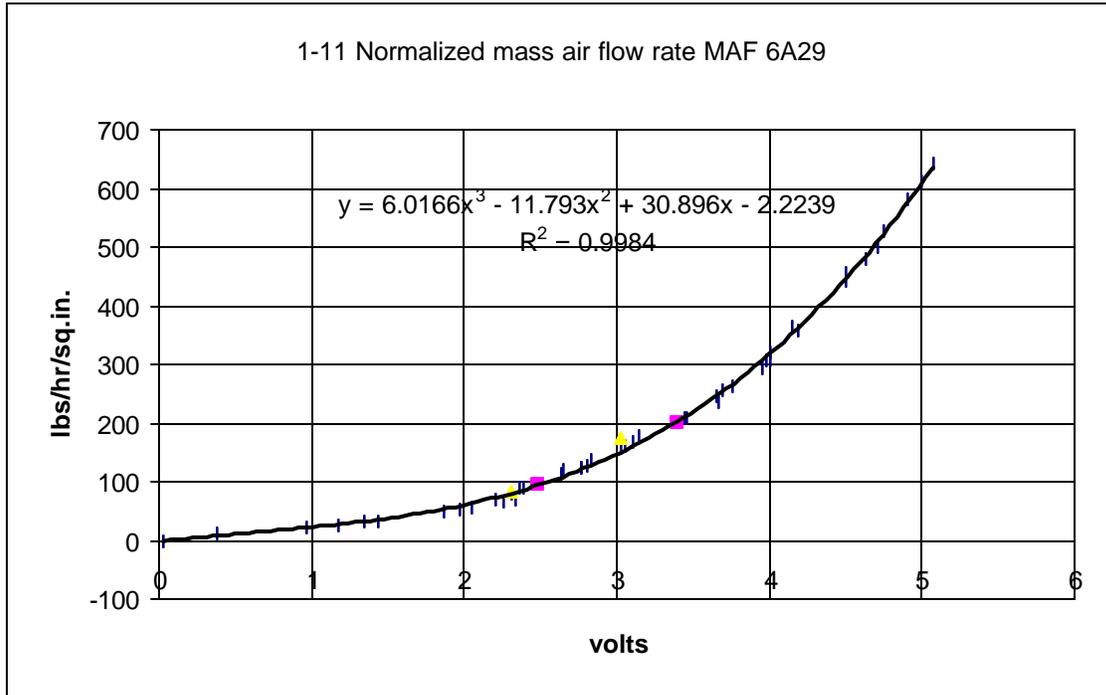


Figure 10 - Probe Serial #1-11 Correlation

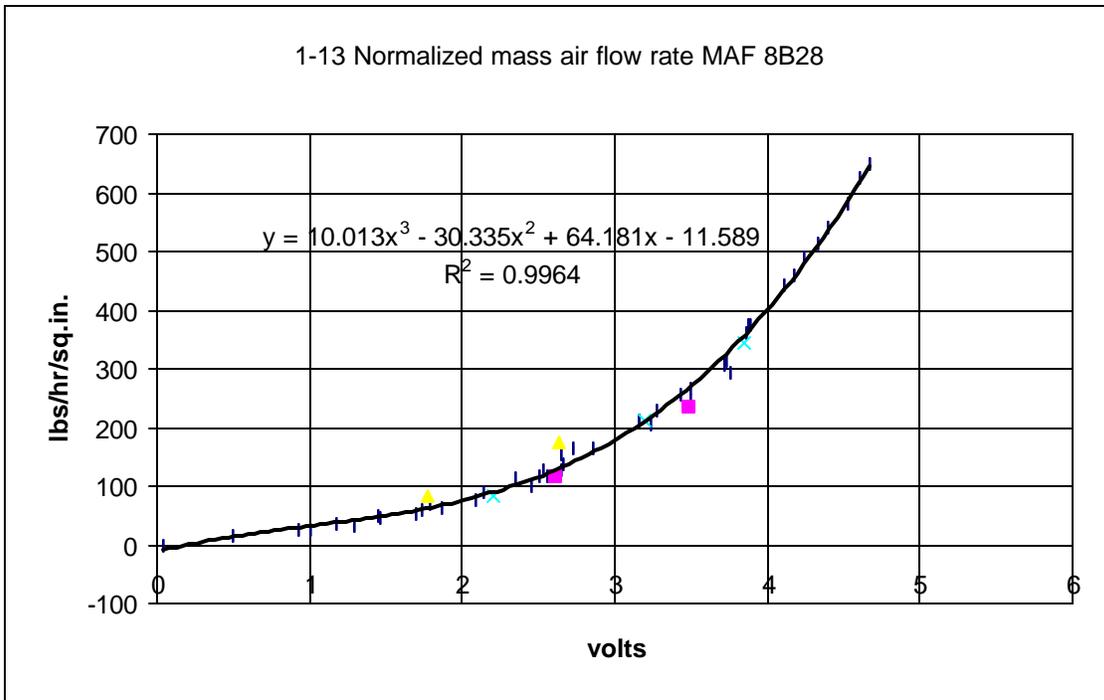


Figure 11 - Probe Serial #1-13 Correlation

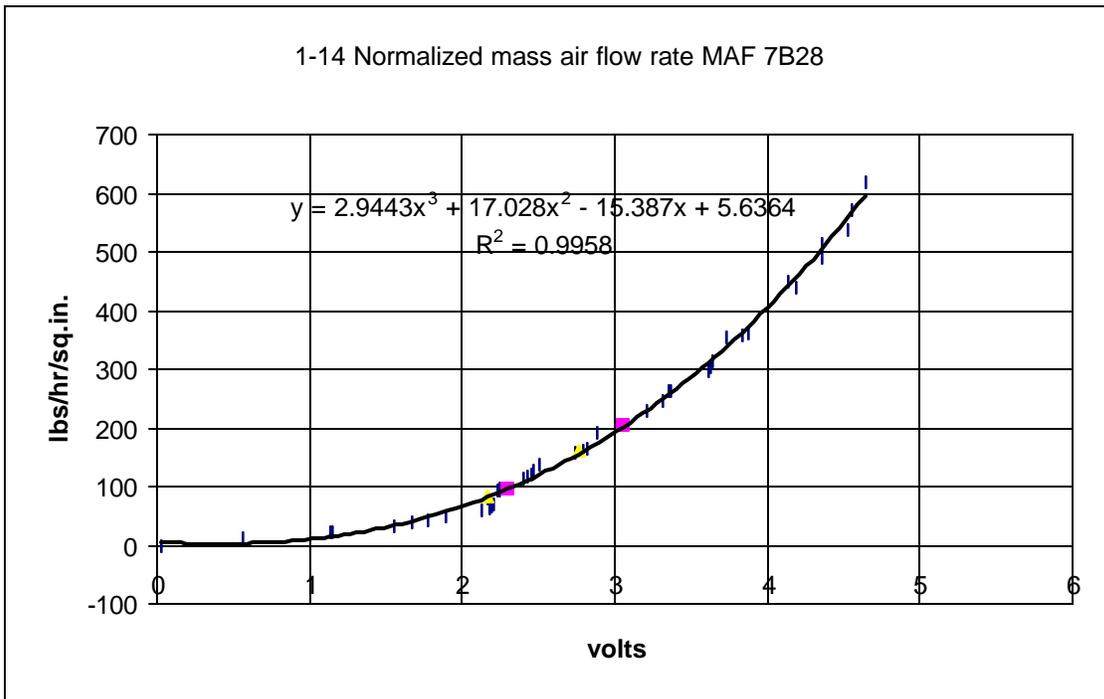


Figure 12 - Probe Serial #1-14 with 7B28 MAF Correlation

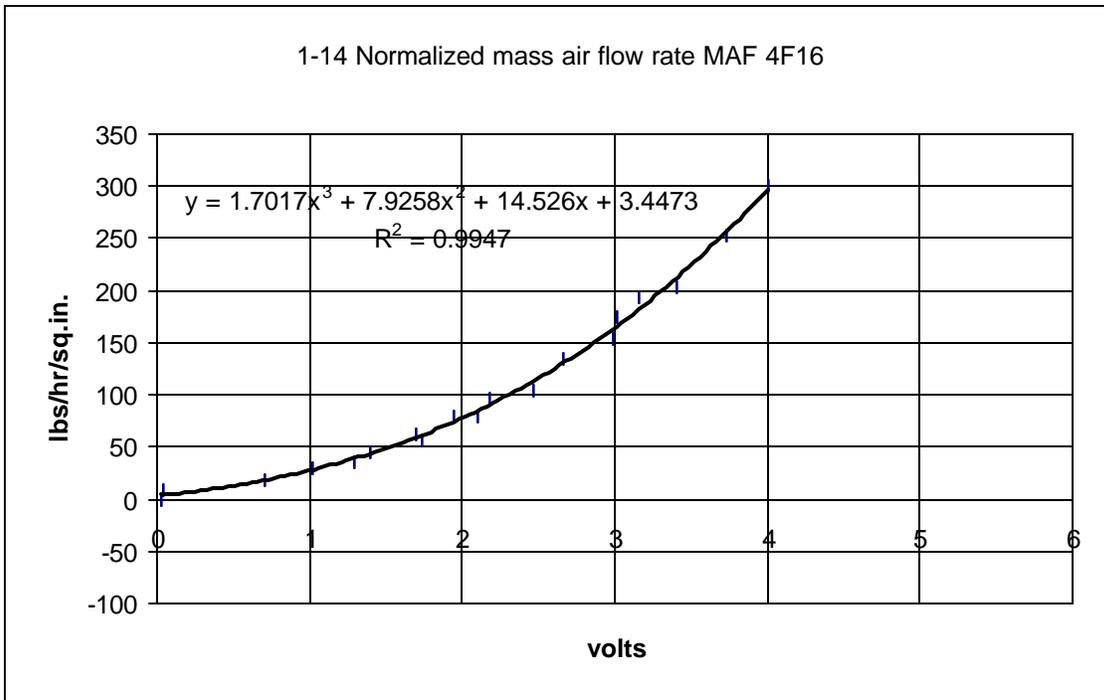


Figure 13 – Probe Serial #1-14 with 4F16 MAF Correlation

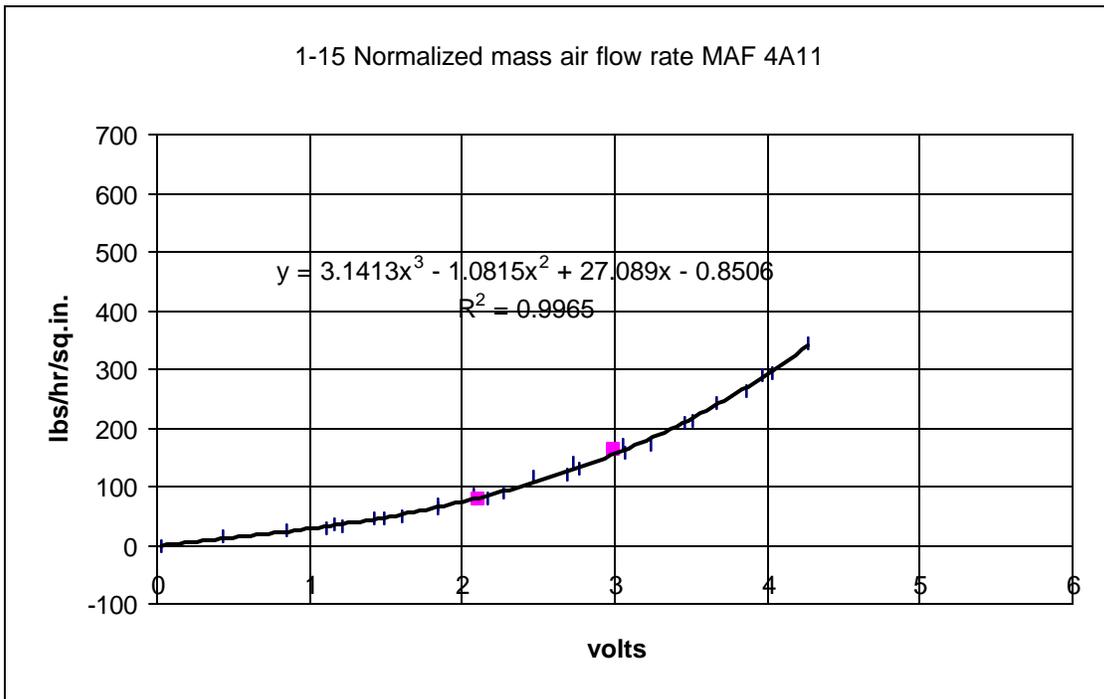


Figure 14 - Probe Serial #1-15 Correlation

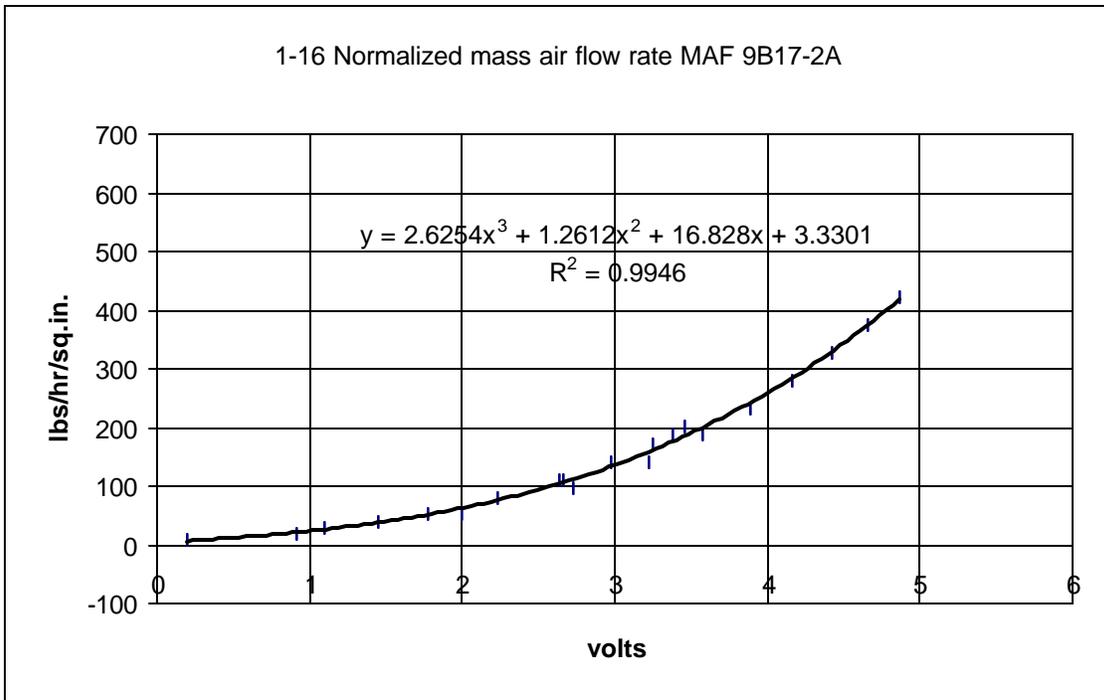


Figure 15 – Probe Serial #1-16 Correlation

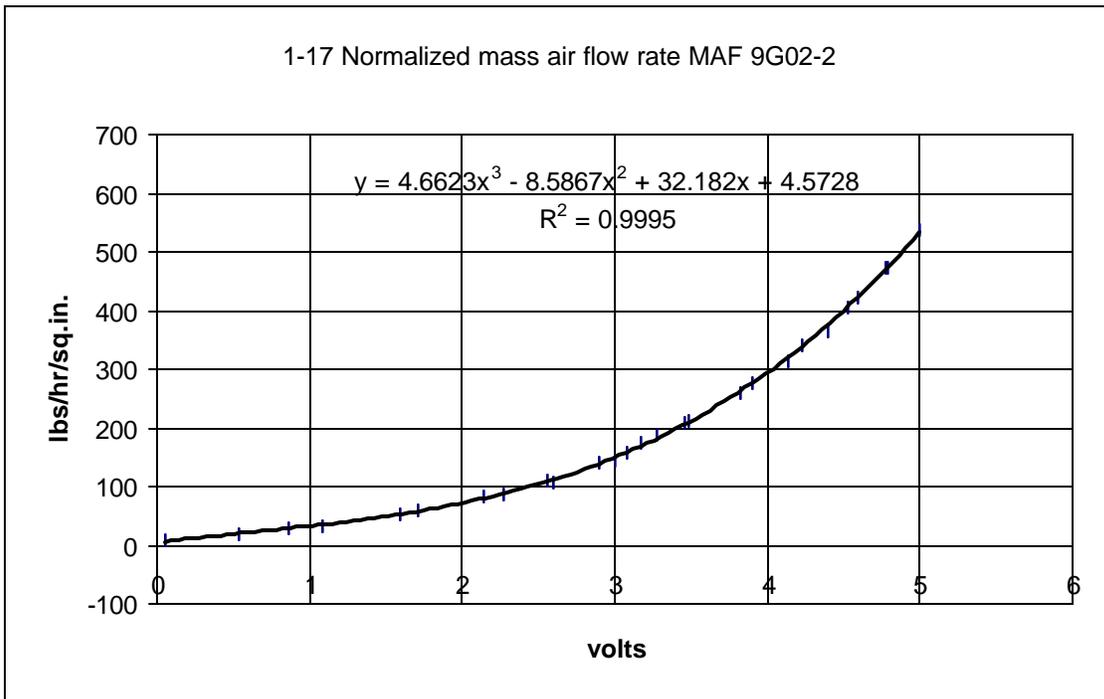


Figure 16 - Probe Serial #1-17 with 9G02-2 MAF Correlation

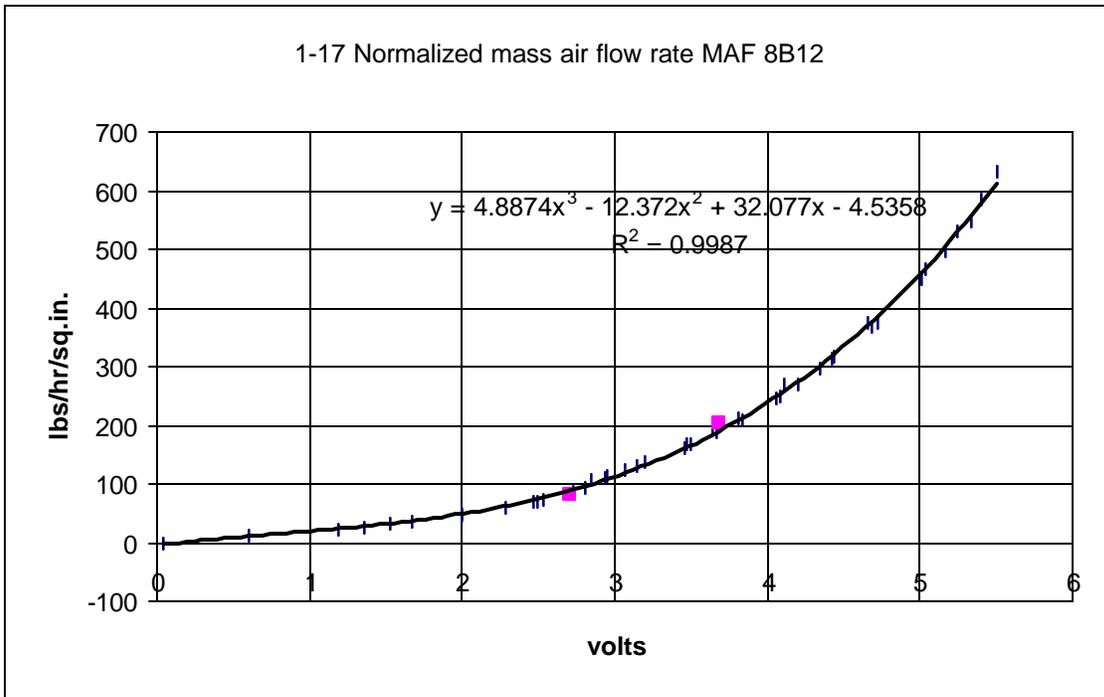


Figure 17 - Probe Serial #1-17 with 8B12 MAF Correlation

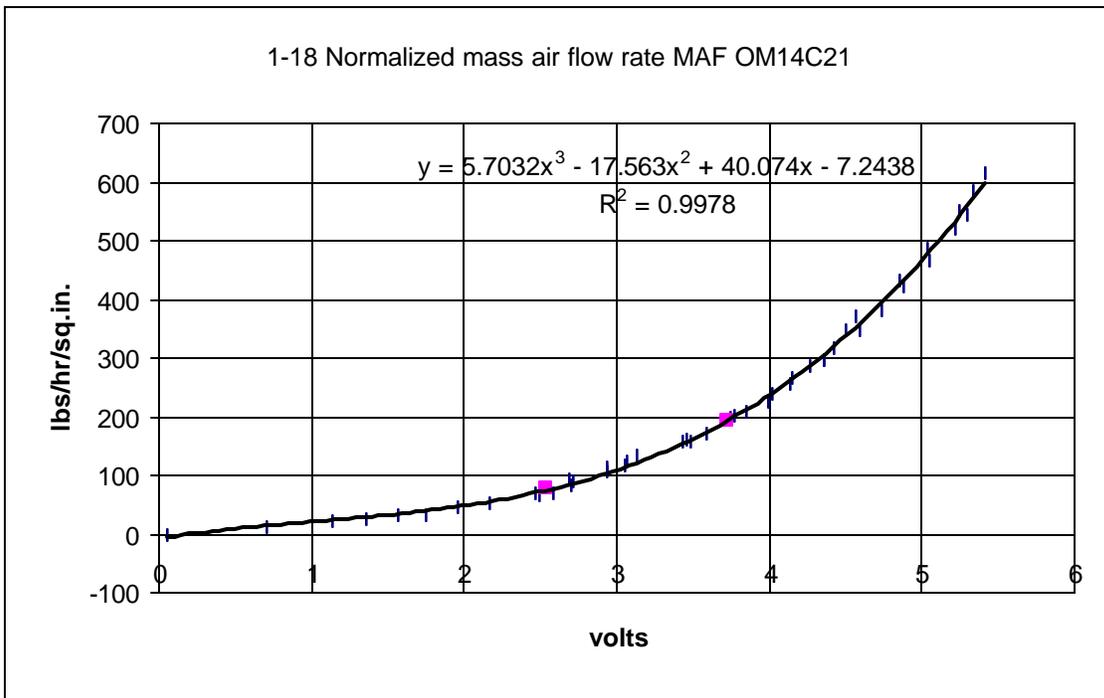


Figure 18 - Probe Serial #1-18 Correlation

3.0 Summary and Conclusions

An effort was initiated to design and develop a two inch exhaust probe for the SPOT system that could be used with vehicle exhaust sizes larger than 2 inches. Two design iterations were needed in order to achieve flow measurement precision better than the existing 4 inch probe. A venturi based rarification module was designed that replaced a trumpet design. The venturi based aspiration module in conjunction with a newly designed 2 inch probe resulted in exhaust mass flow measurement capability approaching that which can be accomplished in engine research test cell laboratories. AEI worked with the USEPA in Ann Arbor to establish correlative accuracy between the new 2-inch probe and laboratory systems.