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March 1978

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DEVELOPMENT OF AN OPTICAL CONVOLUTION VELOCIMETER FOR MEASURING STACK FLOW

Environmental Sciences Research Laboratory
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U.S. Environmental Protection Agency
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DEVELOPMENT OF AN OPTICAL CONVOLUTION VELOCIMETER FOR MEASURING STACK FLOW

by

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PREFACE

The work reported herein was performed under the auspices of Memorandum of Agreement (MOA) EPA-1AG-D6-F044, entitled, "Development of the Optical Convolution Velocimeter." This MOA was between the Air Force Flight Dynamics Laboratory located at Wright-Patterson Air Force Base, Ohio 45433, and the Environmental Sciences Research Laboratory of the U.S. Environmental Protection Agency (EPA) located at Research Triangle Park, North Carolina 27711. Mr. Gary A. DuBro was the technical monitor for the Air Force, and Mr. John Nader the technical monitor for the EPA.

This report was prepared by Bolt Beranek and Newman Inc., Cambridge, Massachusetts 02138, under USAF Contract F33615-76-C-3051. The objective of this investigation was to design and fabricate a prototype device based on optical convolution principles for the measurement of gas system velocities in emission sources and to test its applicability under simulated conditions. The program at Bolt Beranek and Newman Inc. was performed by Dr. Michael J. Rudd.

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ABSTRACT

A new type of instrument has been developed and tested for the measurement of stack flow velocities. The instrument is optical and generates a shadowgraph pattern of the wake from a small heater. This shadowgraph is projected on a mirror grating of precise dimensions and the reflected light detected by a photodiode. The output of the photodiode fluctuates at a frequency that is related to the velocity with which the turbulence is convected across the grating. By measuring this frequency, the flow velocity is determined.

A version of this optical convolution velocimeter (OCV), as it is called has been built to withstand a temperature of 200°C and combustion gases. This unit has been tested in both a wind tunnel and EPA's stationary source simulation facility (SSSF). The agreement with a pitot tube was close, 1% in the wind tunnel and 2 - 2.5% in the SSSF. Some difficulty in signal processing was found at high speeds and high temperatures or dust loadings, but this can be cured.

The OCV promises to be a much more accurate and easier to use instrument than the pitot tube, at little additional cost.

This report was submitted in fulfillment of interagency agreement MOA-EPA-IAG-DE-F044 by Air Force Flight Dynamics Laboratory, Dept. of the Air Force under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from July 1976 to February 1977, and work was completed as of February 1977.

CONTENTS

FIGURES

ACKNOWLEDGMENTS

The author wishes to gratefully acknowledge the help and suggestions from G. Dubro and D. Kim of the Air Force Flight Dynamics Laboratory of the Wright Aeronautical Laboratories since they were the original inventors of the Optical Convolution Velocimeter. The author also wishes to acknowledge the aid of J. Nader of the Stationary Source Emissions Branch, EPA, for the suggestion to use fiber optics in the stack OCV and for his support during the tests in the Stationary Source Simulation Facility.

SECTION 1

INTRODUCTION

THE OPTICAL CONVOLUTION VELOCIMETER (OCV)

The optical convolution velocimeter was conceived by DuBro and Kim* (U.S. Patent No. 3,953,126) as a noninvasive method for measuring aircraft speed that eliminates many of the problems encountered with the Pitot-static tubes currently used on board aircraft.

The OCV uses a light-emitting diode (LED) as its light source. The output of the LED is collimated by the lens, and projected through the turbulence onto a grating (see Figure 1). The turbulence is generated by the wake of an object placed in the flow. A mirror behind the grating returns the light through a lens onto a photodiode. As the light passes through the turbulence, it is refracted, and a "shadowgraph" pattern of bright and dark bands is formed on the grating. As the turbulence is convected with the mean flow, the shadowgraph pattern is convected over the grating. We can describe the light transmitted by the grating as

$$\int I(x-y)\ G(x)\ dx = F(y)$$

where $I(x-y)$ is the shadowgraph pattern that is convected in time by distance y, and $G(x)$ is the grating transfer function. The function $F(y)$ is the convolution of the shadowgraph and the grating. By Parseval's theorem, the spectrum of this convolution is equivalent to the product of the spectra of $I(x)$ and $G(x)$. If the spectrum of $G(x)$ is narrow, the spectrum of the convolution function $F(y)$ is narrow, and it will be sinusoidal with a frequency equal to that at which the turbulence crosses the grating. Hence, the velocity can be found by measuring this frequency.

The purpose of this report is to describe the development of the OCV for making in-stack velocity measurements. The OCV has a number of inherent advances over the pitot tubes which are currently employed. First, it is an absolute instrument and never needs recalibration once it has been set up. Secondly, it is unaffected by ambient conditions such as pressure and temperature. Thirdly, it just measures one component of the velocity. Fourthly, it can be given a digital readout very inexpensively: in fact, the whole OCV concept leads to a very inexpensive instrument. Thus the OCV promises to be a much more accurate and convenient to use instrument than the pitot tube, at very little additional cost.

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*D. Kim and G. DuBro, 1974, "The Optical Convolution Velocimeter" presented at the second Project Squid Workshop, Purdue University, Lafayette, IN, March 26-27.

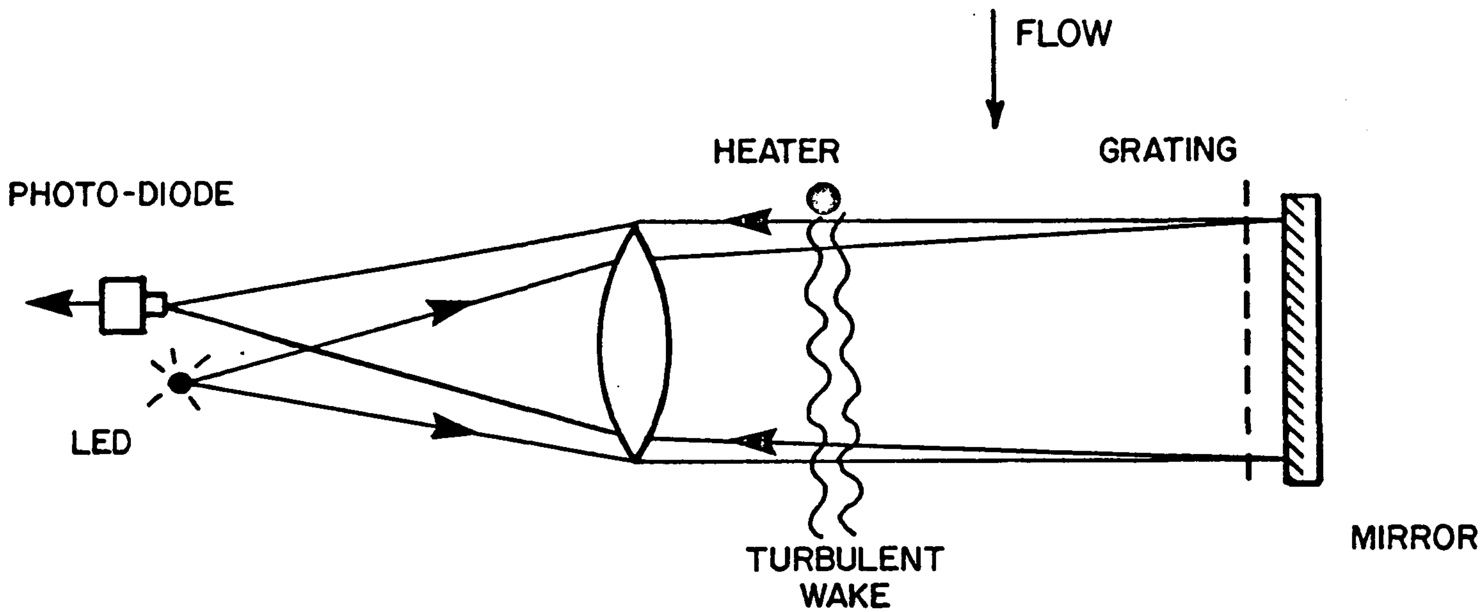

Figure 1. Principle of the Optical Convolution Velocimeter.

SECTION 2

CONCLUSIONS

An optical convolution velocimeter has been built which will successfully operate in the hostile environment of a stack. It operated in an environment of 200°C and 4000 mg/m^3 of dust loading with little difficulty. The general standard deviation of the differences between the OCV and the Pitot tube was 1% in the Bolt Beranek and Newman (BBN) wind tunnel and 2 - 2.5% in the SSSF.

The OCV had demonstrated itself as an accurate and easy to use flow measuring instrument for use in stacks.

SECTION 3

RECOMMENDATIONS

As a result of this program, a number of improvements to the OCV are suggested

1. Incorporate a high pass filter into signal processor. This will cure the difficulties encountered at high speeds with high temperatures and dust loadings.

2. Increase velocity range to 45 m/sec. The current unit was designed for 20 m/sec and with some modifications to the electronics this can be increased.

3. Combine signal processor and sensor head power supplies.

4. Calibrate against a Laser Doppler Velocimeter (LDV). An LDV is a more accurate instrument than a pitot tube and it provides a better and more reliable check on the calibration of the OCV.

One nice point about the operating principle of the OCV is that it is not restricted to making point measurements in the flow, but can be used to integrate across the whole stack. Such a system would have a collimated light source on one side of the stack and the grating and detector on the other. The development of such an instrument could consist of several stages.

a. Fabricate a cross-stack OCV.

b. Test the cross-stack OCV in the SSSF and investigate whether a marking heater was still required.

c. A theoretical and experimental investigation of the effects of a skewed velocity distribution in the stack on the OCV reading. This will determine whether the OCV can operate in one direction across the stack or must be used in both directions.

d. Design of a cross-stack OCV for field operation. This would include such features as an air curtain over the optical windows.

e. Reporting on the above activities.

This would generate a design for an OCV which would be capable of continuously monitoring the flow in a stack.

SECTION 4

DESIGN OF THE STACK OCV

At the request of the EPA, BBN has designed a high temperature version of the OCV which is suitable for insertion into a chimney stack. The main changes required for the instrument to operate under hot and corrosive conditions were to eliminate semiconductor devices from the hot end of the OCV, make it long enough to insert in the stack and use corrosion resistant materials. The main changes were:

1. Replace light emitting diode with a tungsten halogen lamp.

2. Move the photodiode into a cool area and couple it to the head with fiber optics.

3. A 2 m extension to insert the OCV into the flow.

4. Casing made from stainless steel instead of aluminum.

5. A high temperature grating.

We are greatly indebted to Mr. John Nader, of the EPA, whose suggestion it was to couple the cool photodiode to the hot region with fiber optics. A drawing of the OCV is shown in Figure 2 and views in Figures 3 and 4.

The grating was made by first photographically forming a Ronchi grating and removing the gelatin from the clear areas. The grating was then coated with vacuum deposited chromium in order to make it reflective. The grating was then bonded into its holder, chromised side on the back, with a high temperature silicone rubber.

The hot end of the stack OCV was required to be placed in a 200°C airstream. Accordingly, it was designed to withstand about 260°C. The tungsten halogen lamp likes an envelope temperature of more than 250°C, but the base temperature must not exceed 350°C. The high temperature stainless steel clad fiber optics from Dyonics was rated at 320°C (although we later found this to be optimistic). A Teflon holder for the lamp and fiber optics was employed. A Teflon washer also held the collimating lens in place.

At the cold end of the stack OCV, the body was made of anodised aluminum. The electronics was mounted on a circular printed circuit card and rated at

120°C. A 5-pin electrical connector couples the OCV head with the signal processor. The signal processor was the same as that which was used in the previous program with the U.S. Air Force and is described fully in Technical Report AFFDL-TR-76-132.* The processor is a special device for which BBN has applied for a patent and is called a "correlation discriminator." It measures accurately the frequency of a noisy and widely fluctuating signal.

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*Rudd, M.J., "Development of Prototype Optical Convolution Airspeed Sensor," Air Force Flight Dynamics Laboratory Report AFFDL-TR-76-132.

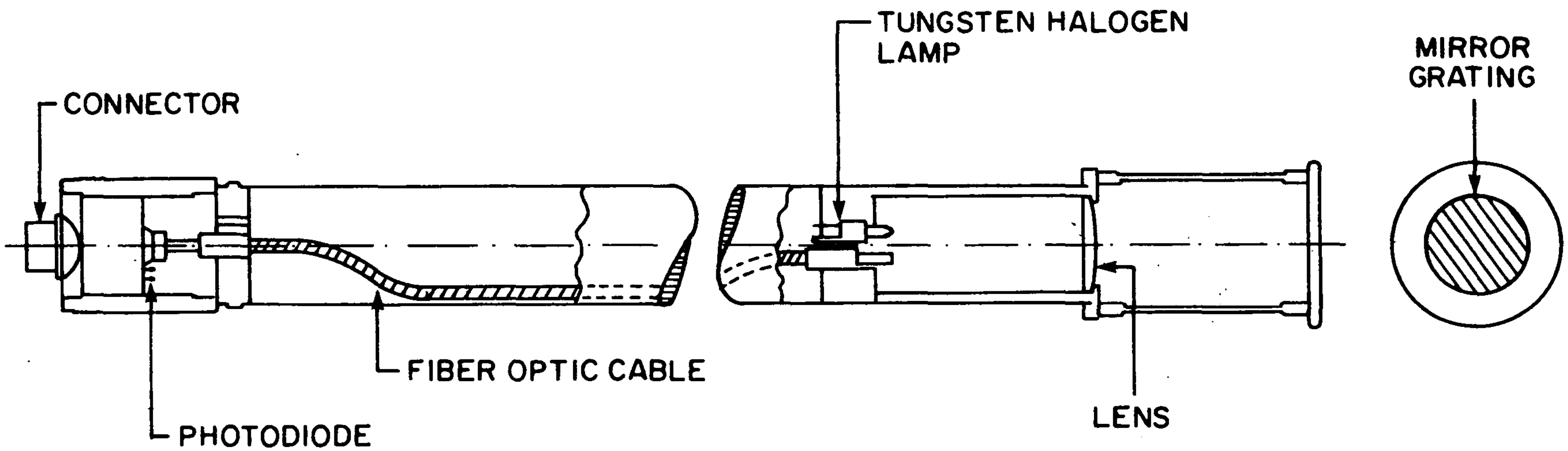

Figure 2. The Stack Optical Convolution Velocimeter.

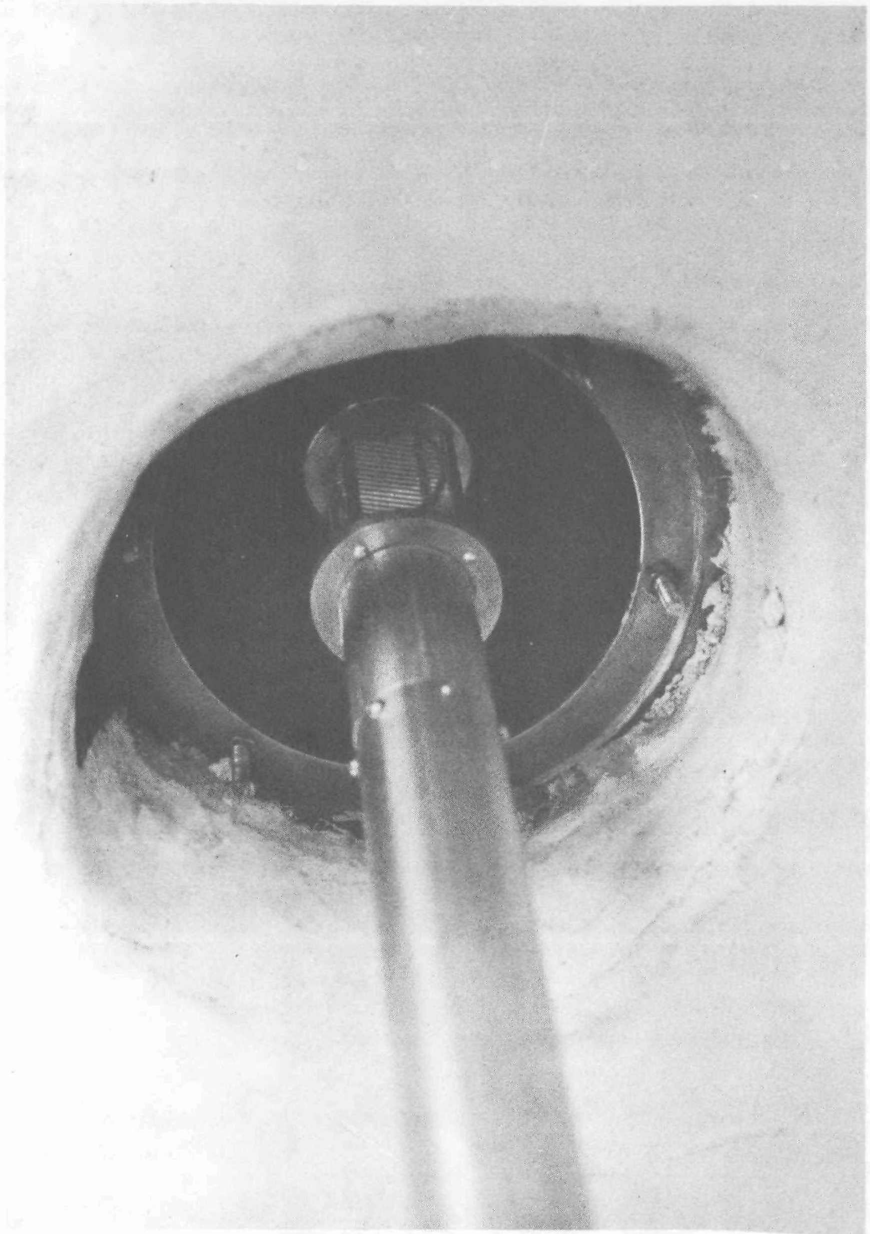

Figure 3. The Sensor Head of the Stack OCV.

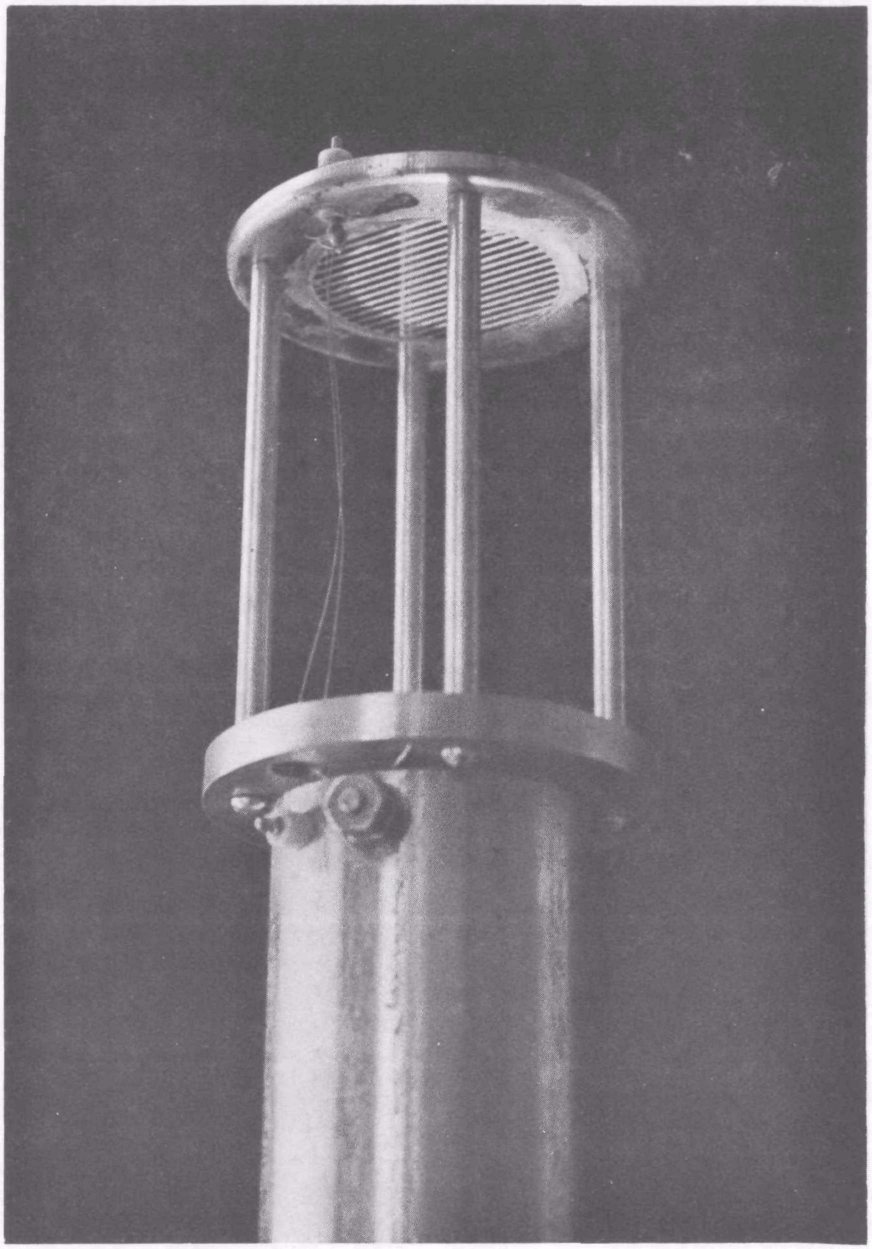

Figure 4. Close-Up of the Mirror-Grating of the Stack OCV.

SECTION 5

TESTING AND EVALUATION OF THE STACK OCV

PURPOSE OF TESTS

Tests have been performed to evaluate the performance of the stack OCV. These tests were of two types. First, the accuracy of the OCV was ascertained in BBN's own wind tunnel as a function of tunnel speed and angle of incidence. The second set of tests were performed at the EPA's Simulated Stationary Source Facility (SSSF) at Research Triangle Park and were to evaluate the performance of the stack OCV under adverse environmental conditions. These tests would show if, or how, hot and dirty flows would affect the accuracy of the OCV.

CALIBRATION OF TIME BASE

The OCV is inherently an absolute instrument in the sense that it does not need calibration. The grating lines on the OCV are each 1 mm wide and, therefore, a 10 kHz crossing frequency corresponds to a speed of 20 m/sec. In the OCV display, the frequency is counted for an appropriate period to give a number which corresponds to this speed. Thus, the time base of the counter was adjusted so that an input frequency of 10 kHz (from a signal generator) gave a reading of 20. This was the only adjustment made to the unit. All subsequent readings were taken without any further adjustments.

CALIBRATION OF OCV IN BBN WIND TUNNEL

The stack OCV was set up in the BBN low speed wind tunnel and compared with a pitot tube whose pressure was read on a slant tube manometer. Figure 5 compares the OCV readings with the pitot tube readings, which had to be corrected for atmospheric temperature and pressure. Two heater wire diameters were tested (.375 and .21 mm diameters) but no significant difference was found. There was no difference in the mean readings of the OCV and pitot tube and the standard deviations was 1.1%. The largest differences were at low speeds where the pitot tube was difficult to read.

The second series of measurements was to determine the sensitivity of the OCV to its angle of incidence. The OCV was rotated about its axis and the readings recorded at a constant tunnel speed. We would expect the OCV to vary as the *cosine* of the angle of incidence since it measures the velocity perpendicular to the grating lines. Figure 6 shows the results obtaining at four tunnel speeds. The root-mean-square difference between the measured result and the *cosine* response was computed for each speed and the results shown in Figure 6.

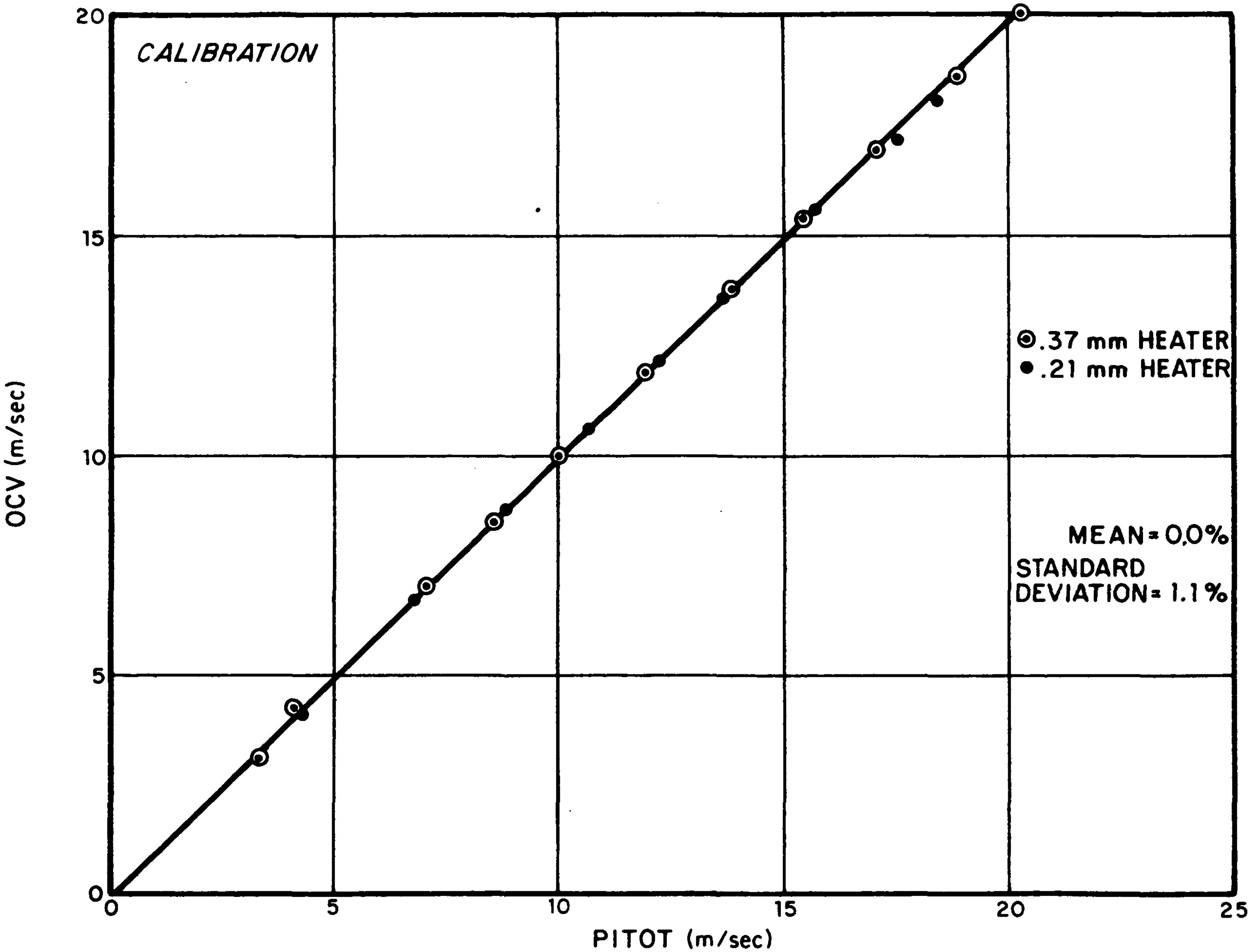

Figure 5. Calibration in BBN Wind Tunnel.

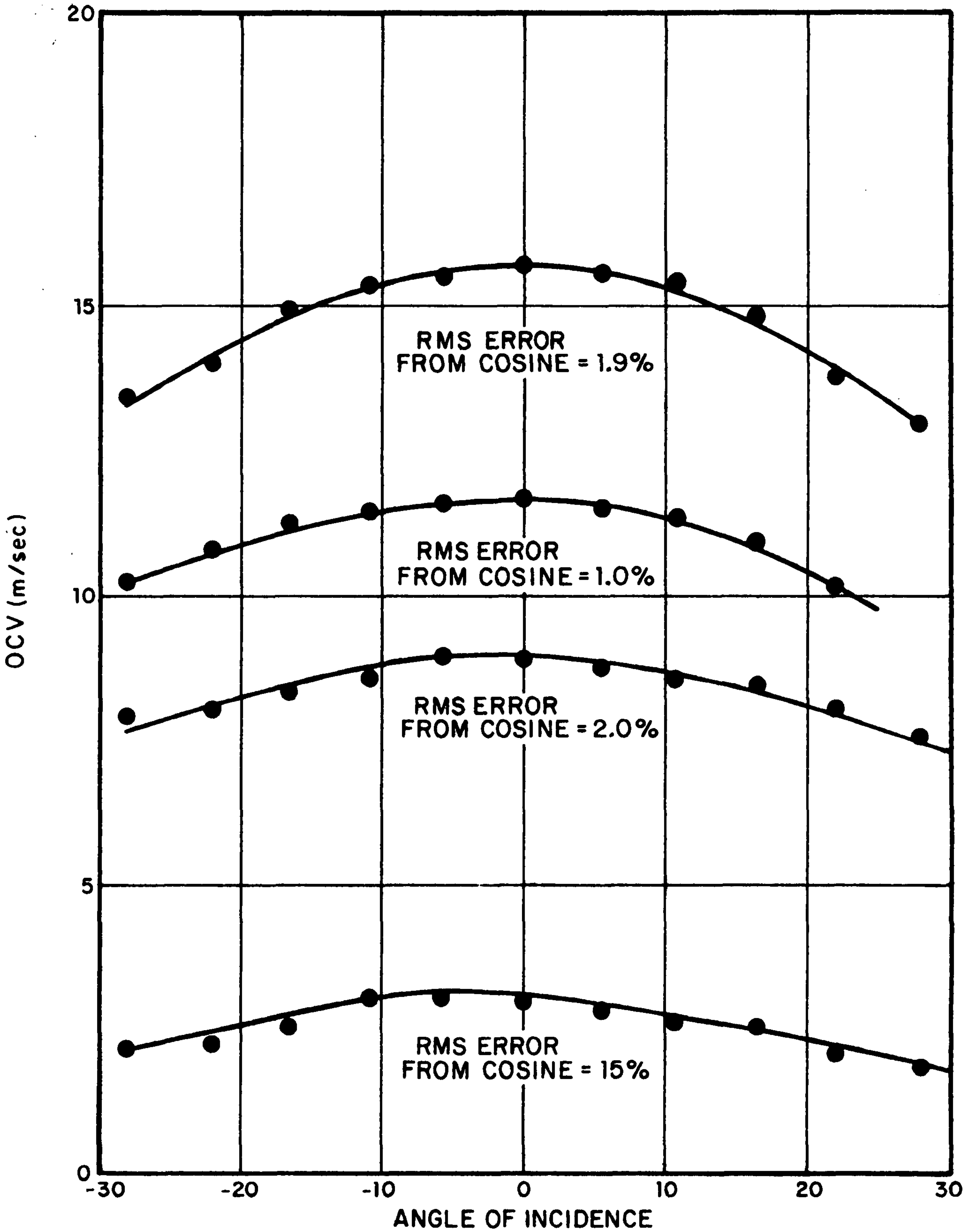

Figure 6. Angle of Incidence Sensitivity.

EVALUATION IN THE SSSF

After the stack OCV had been tested at BBN, it was shipped to the EPA laboratory at Research Triangle Park in North Carolina for tests in the SSSF. During these tests, the SSSF simulated combustion conditions with respect to temperature, humidity and dust. The OCV was inserted into the test duct through a port and located close to the center of the duct, where a pitot tube was also mounted, for comparison purposes. The pitot tube output was monitored with a "Magnehelic" instrument. The standard tunnel instrumentation was used to measure tunnel temperature and dust loading. Separate instrumentation was used to measure humidity. The equipment set up is shown in Figure 7.

Tests were performed under a wide range of conditions and these are summarized in Table 1. Twelve tests were conducted. The speed range covered was generally 3 - 20 m/sec except at elevated temperatures where the speed could not be allowed to drop below 11 m/sec or the electric heaters will become too hot.

TABLE 1. TEST MATRIX FOR SSSF.

Run No.	Temperature °C	Humidity % by Vol	Dust Feed Rate kg/hr	Dust Loading mg/m^3	Velocity Range m/sec	Comments
1	105	0.5	0	0	11 - 20	Warn
2	105	8.0(?)	0	0	11 - 20	Humid
3	105	14.9(?)	0	0	11 - 20	Very Humid
4	27	0.5	0	1400	3.5 - 20	Ambient
5	28	0.5	5-10	100-1400	3.5 - 20	Moderate Dust
6	28	0.5	23	600-4000	3 - 20	Heavy Dust
7	152	0.5	0	0	12 - 20	Hot
8	147	4.7	0	0	12.5 - 20	Combustion Gases
9	170	0.5	0	0	13.5 - 16.5	Hot
10	198	0.5	0	0	12 - 20	Hot
11	25	0.5	.7,1.4	20-200	3.5 - 20	Fine Dust
12	25	0.5	1.4	40-200	3.5 - 20	Electric Arc Furnace Dust

Figures 8 through 17 show the results of the tests. Each figure compares the OCV and pitot tube, computes the mean difference and the standard deviation of the differences. The pitot tube had to be corrected for the facility temperature and humidity (the dust loadings used should not have affected the

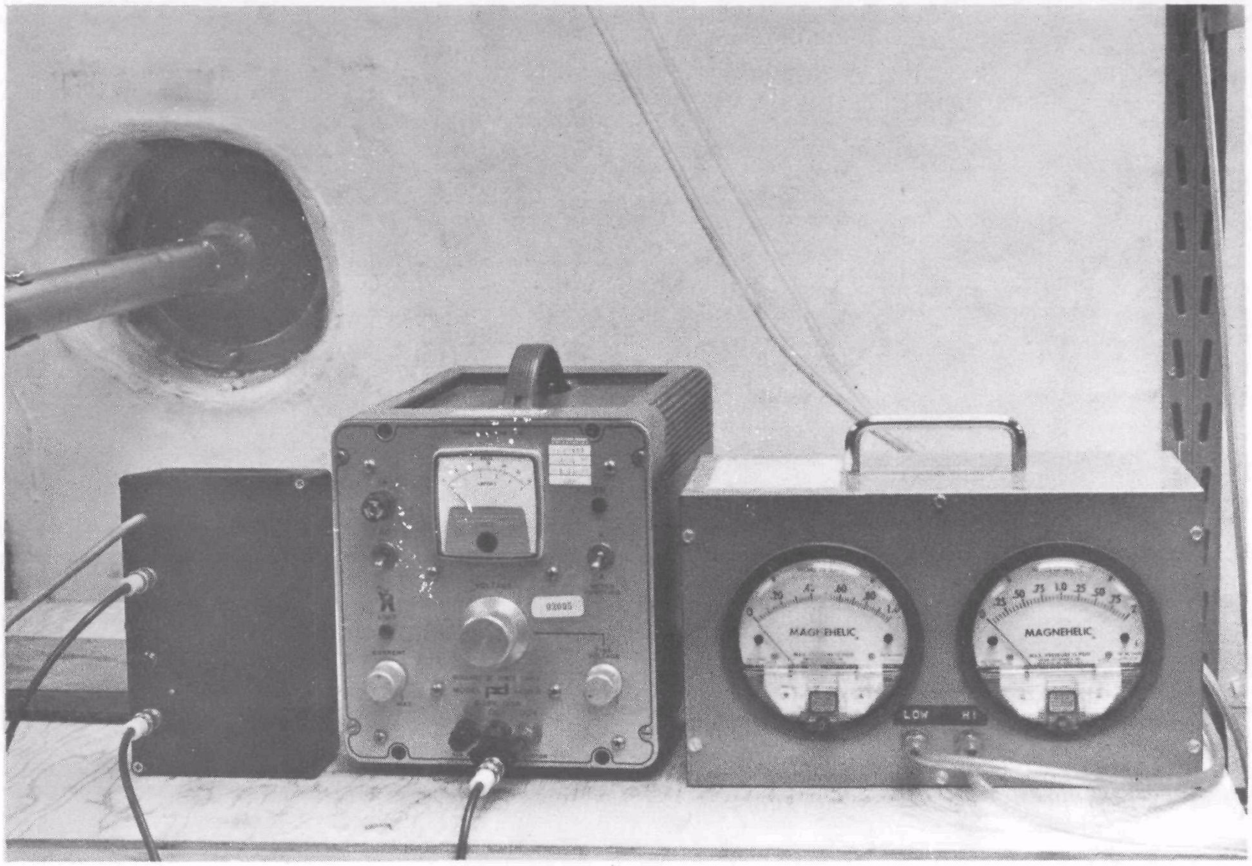

Figure 7. Stack OCV Set Up in the Stationary Source Simulation Facility (SSSF).

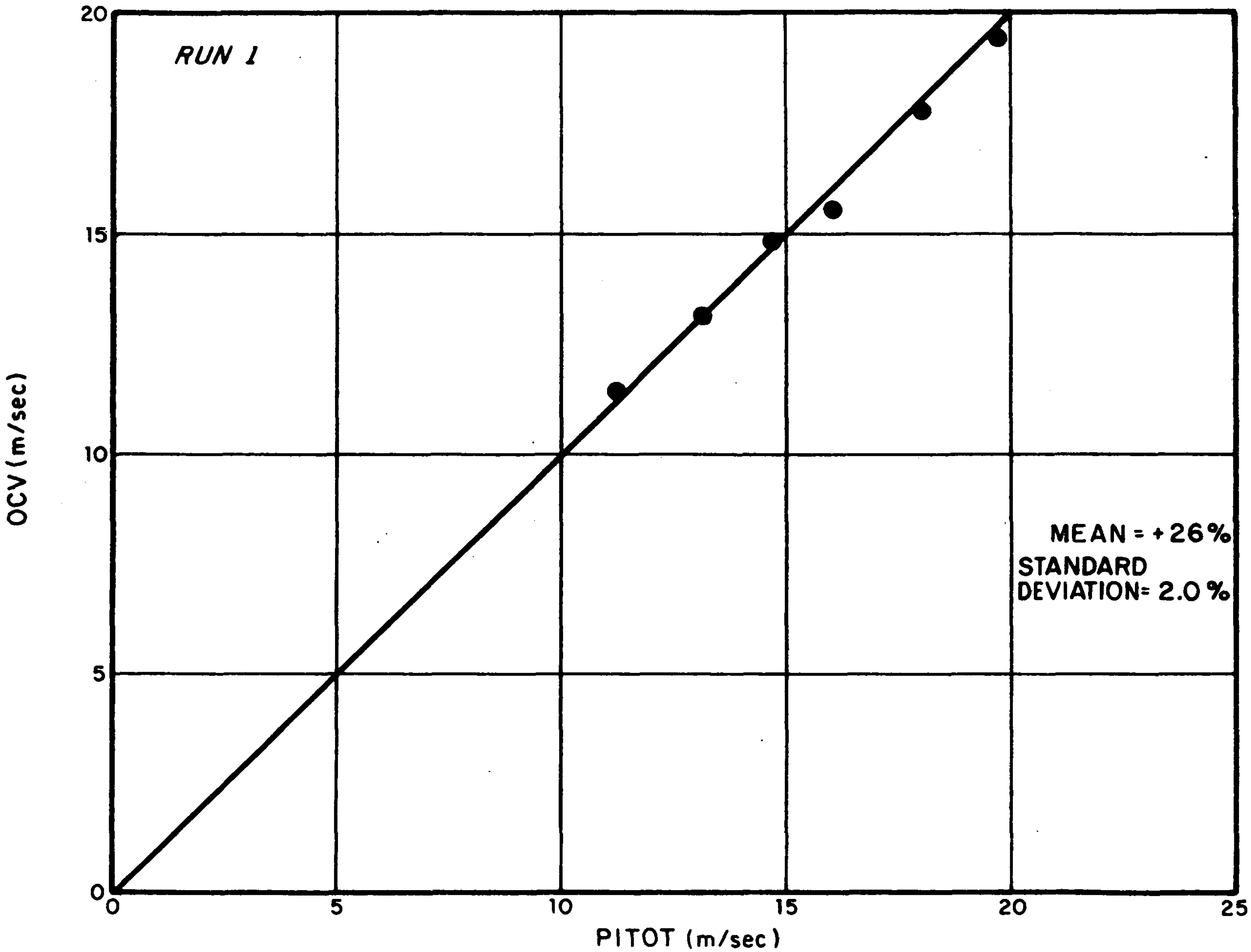

Figure 8. Run 1 — Warm 105°F.

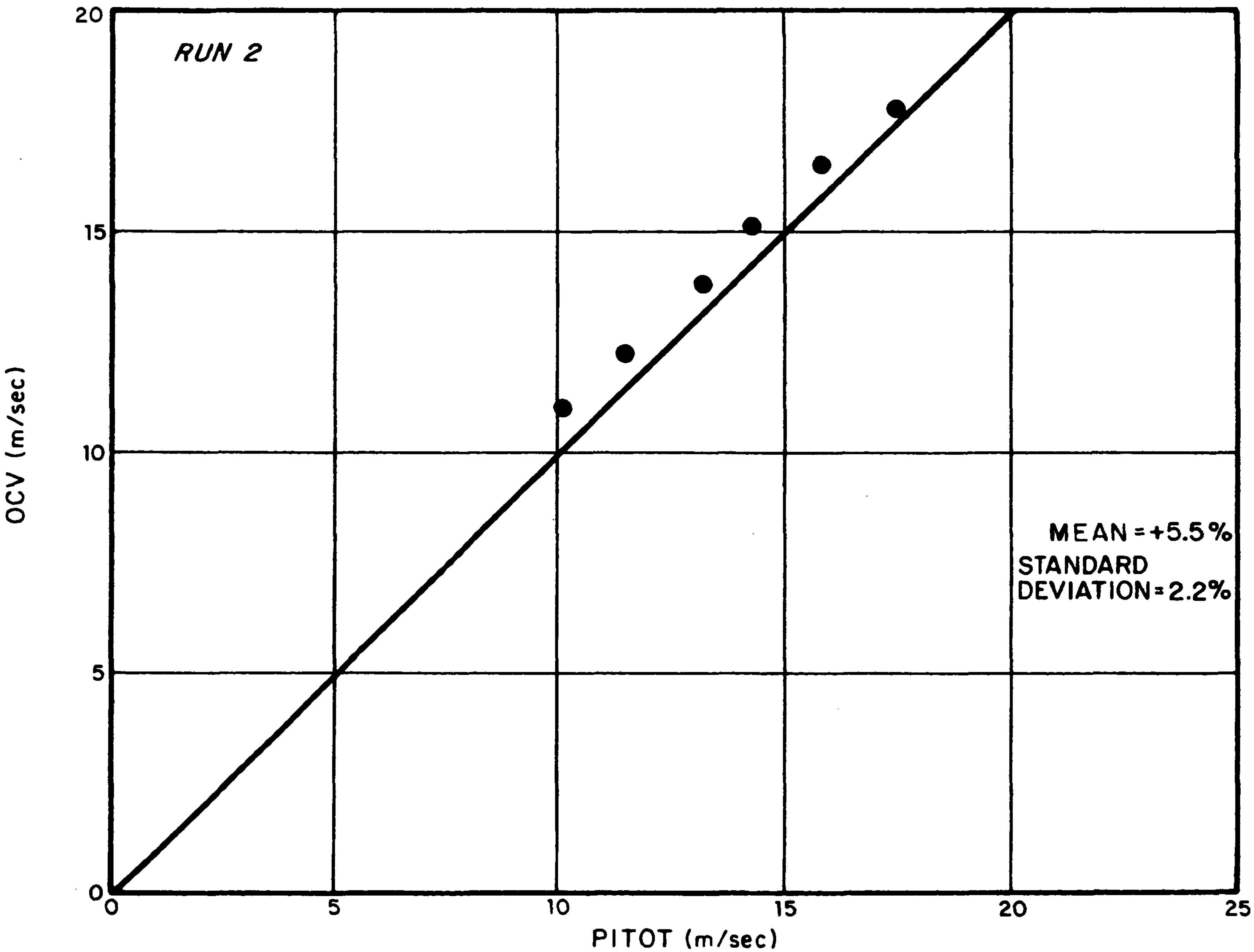

Figure 9. Run 2 — Humid, 8.0% H_2O and 105°C.

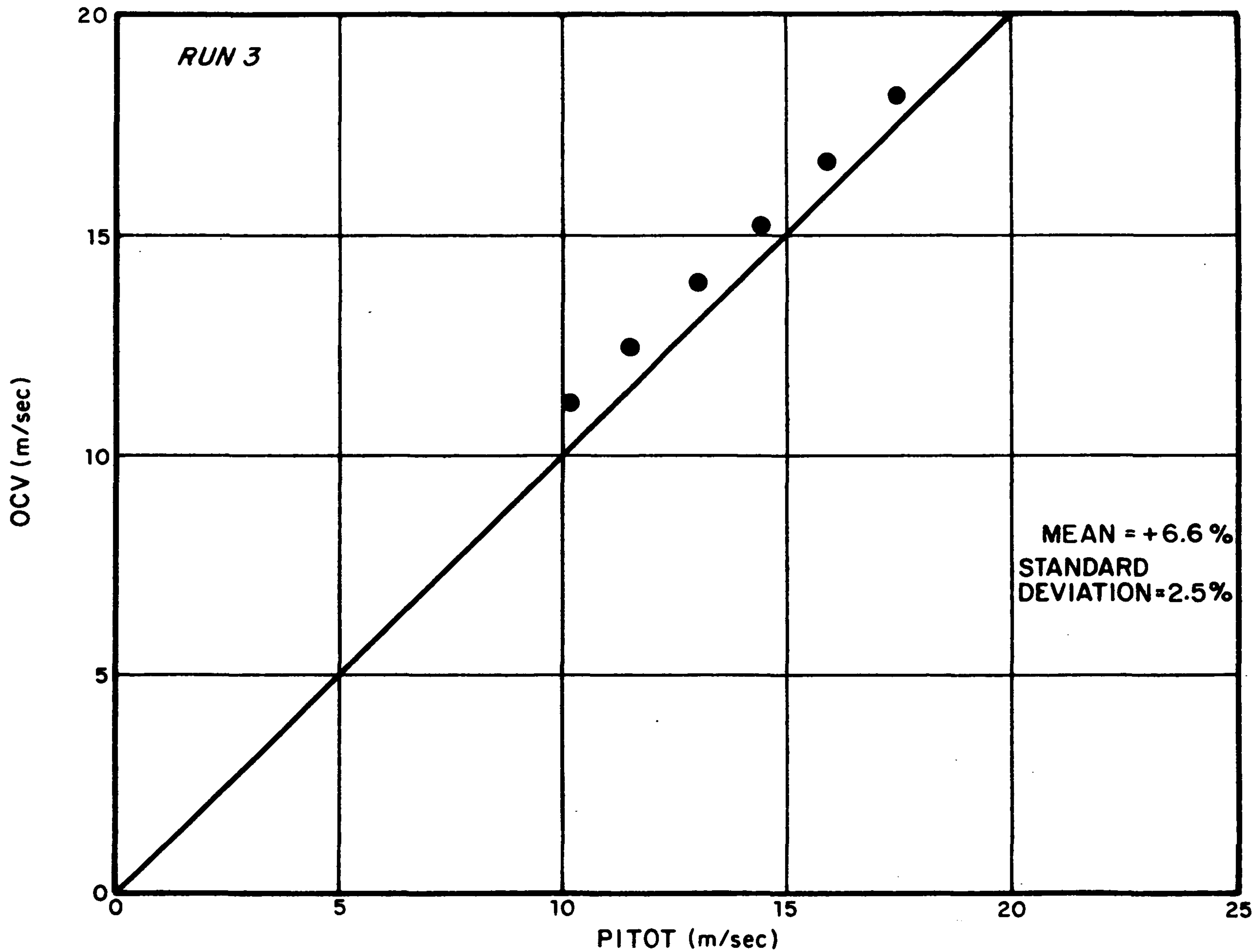

Figure 10. Run 3 - Very Humid, 14.9% H_2O and 105°C.

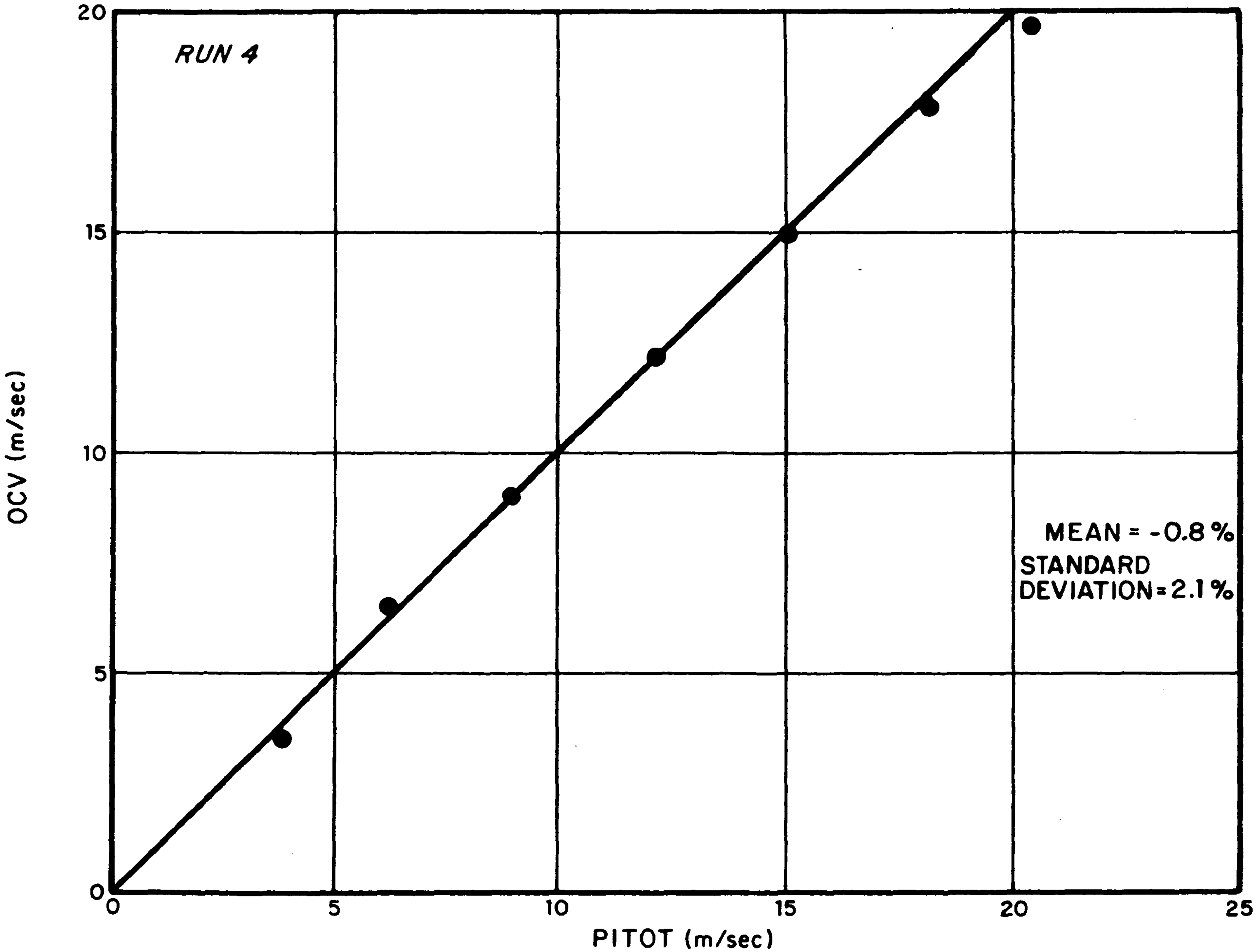

Figure 11. Run 4 - Ambient, 27°C.

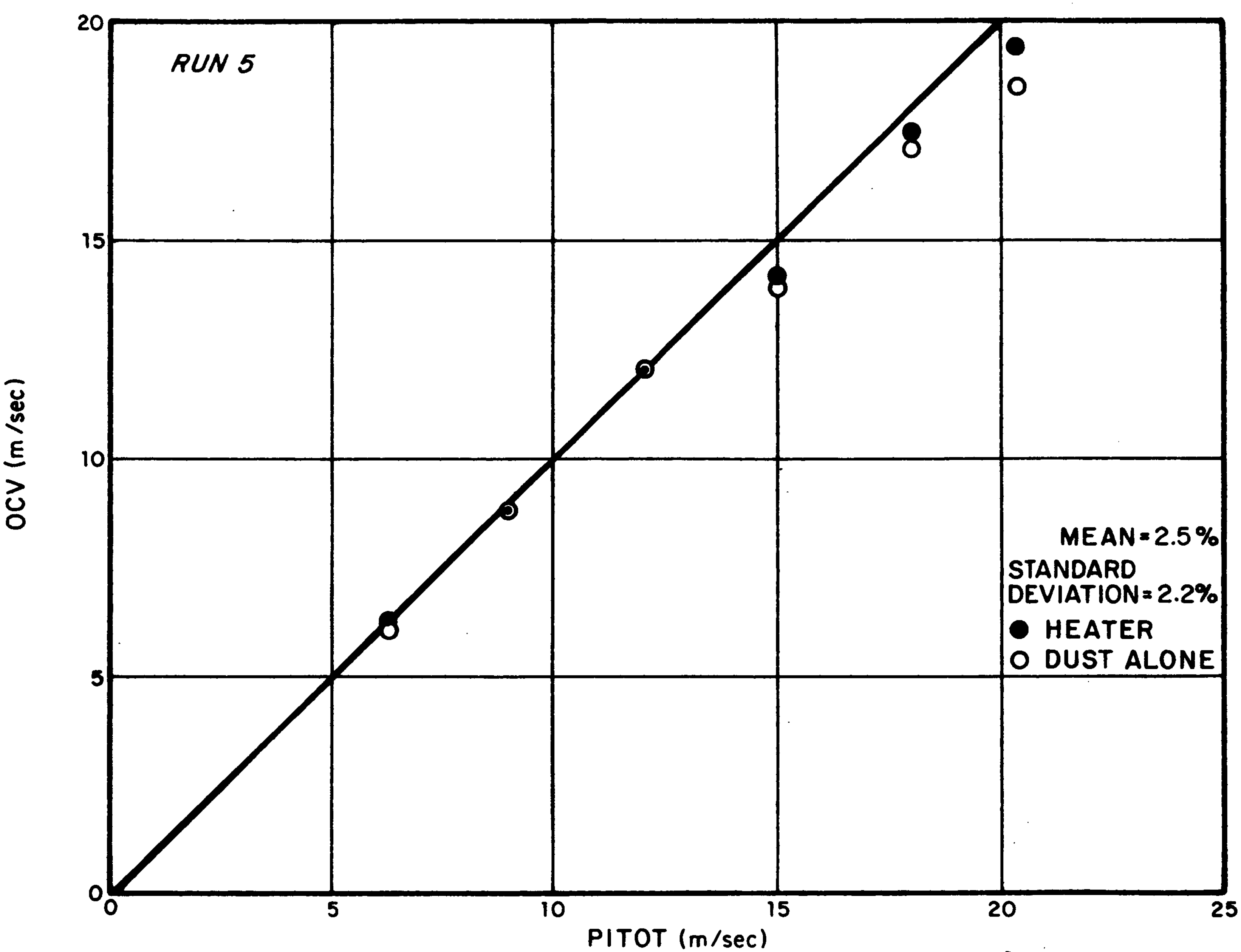

Figure 12. Run 5 - Moderate Dust Loading, 100 - 1400 mg/M^3

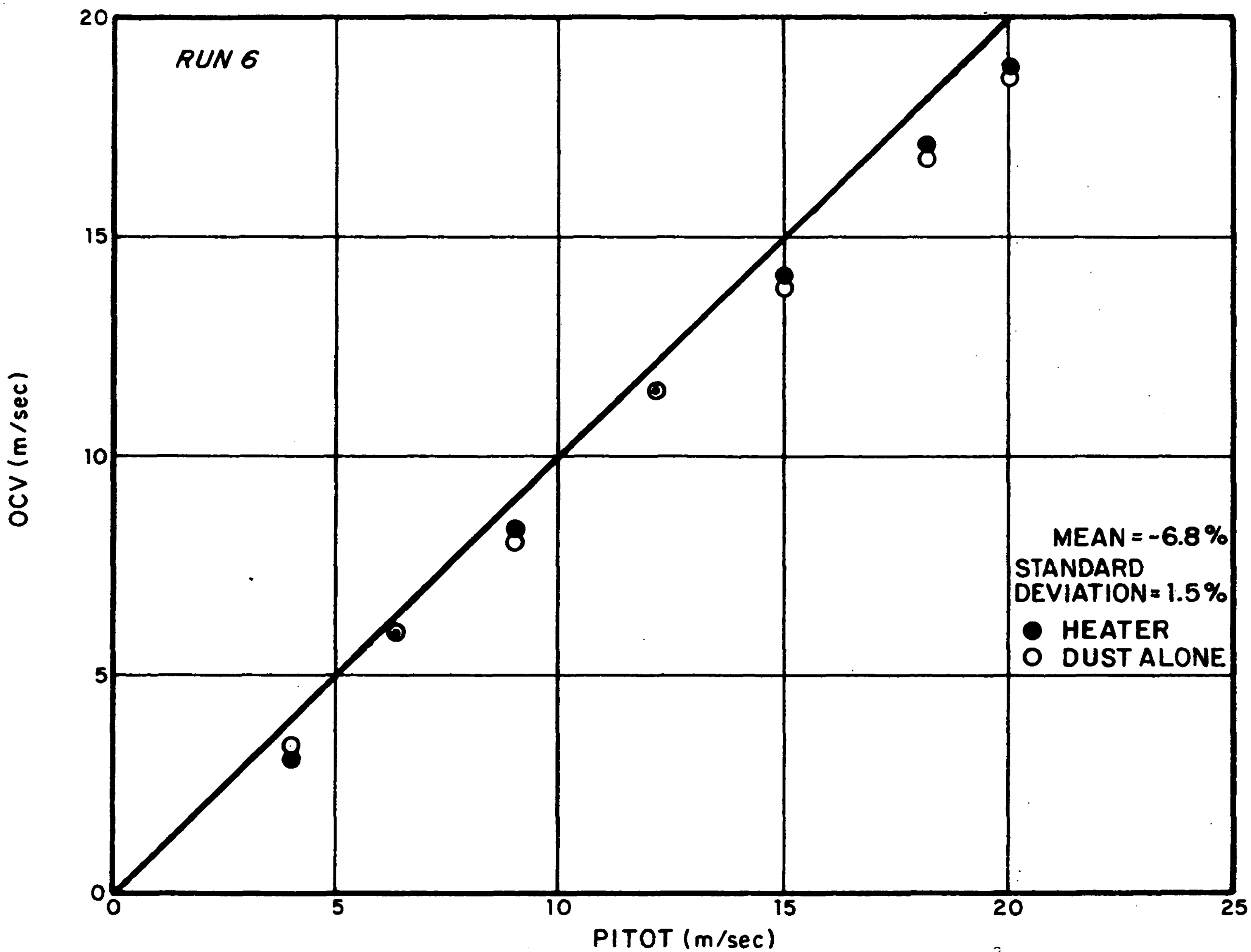

Figure 13. Run 6 - Heavy Dust Loading, 600 - 4000 mg/M^3

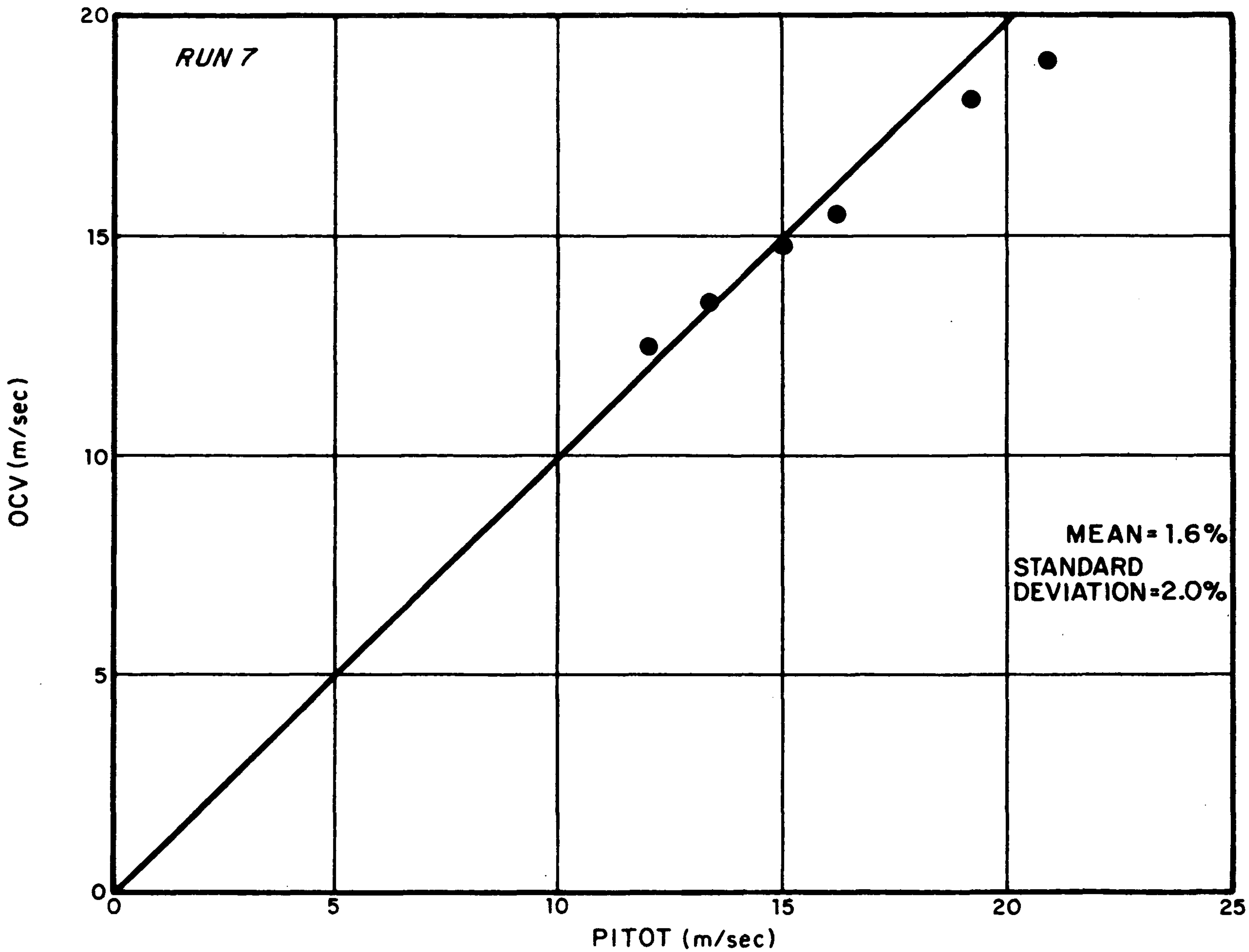

Figure 14. Run 7 - Hot, 152°C.

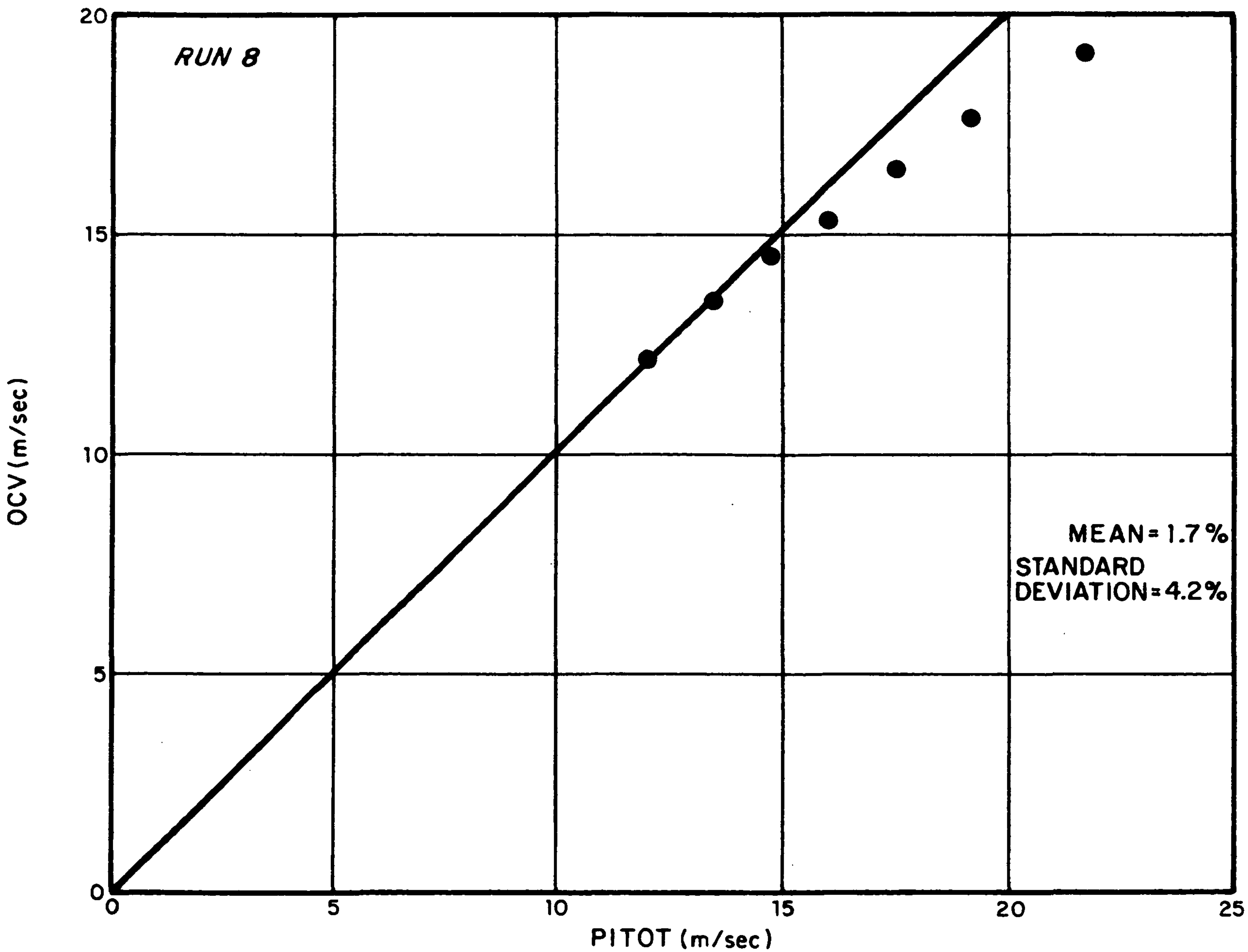

Figure 15. Run 8 - Combustion Products, 4.7% H_2O and 147°C.

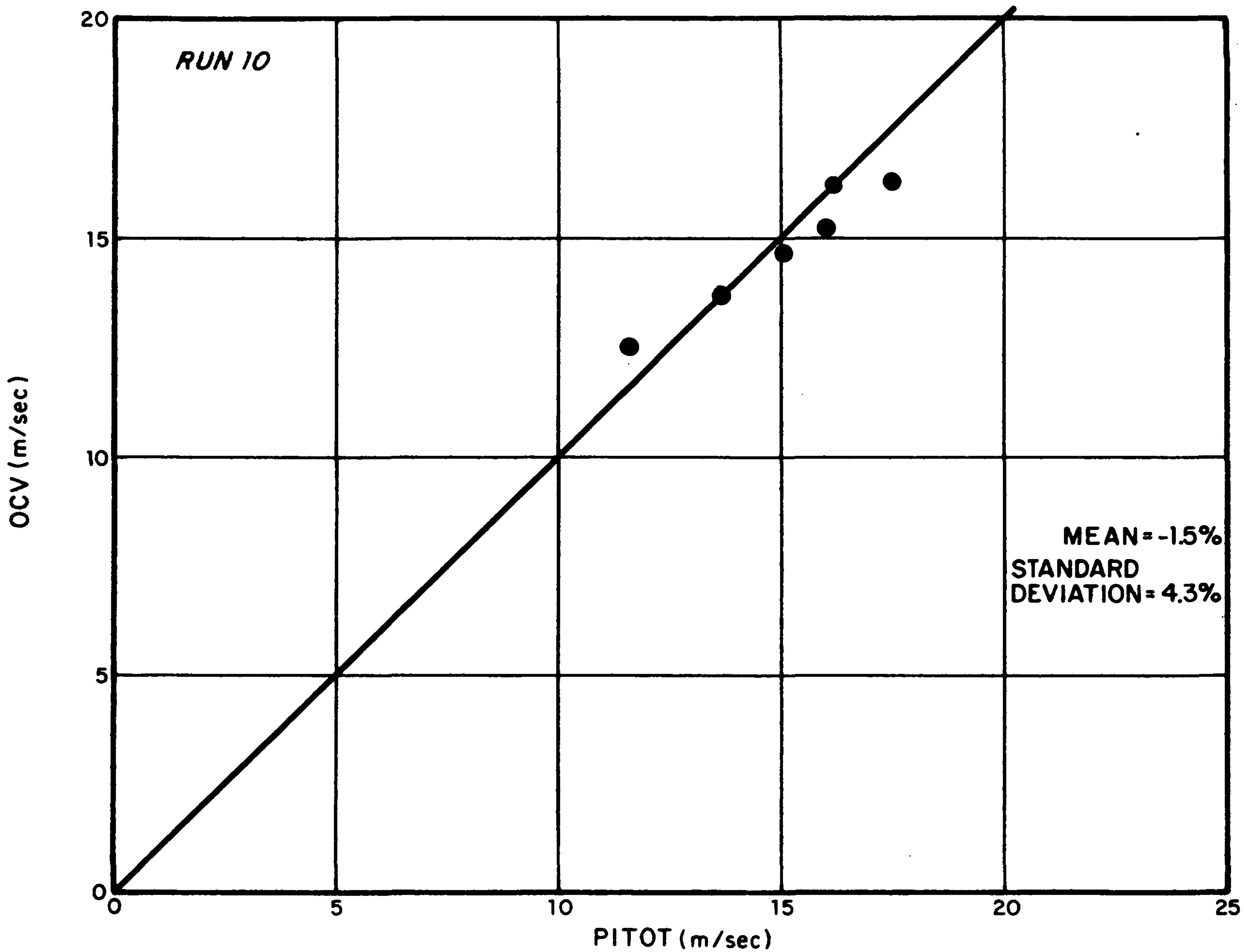

Figure 16. Run 10 - Very Hot, 170°C.

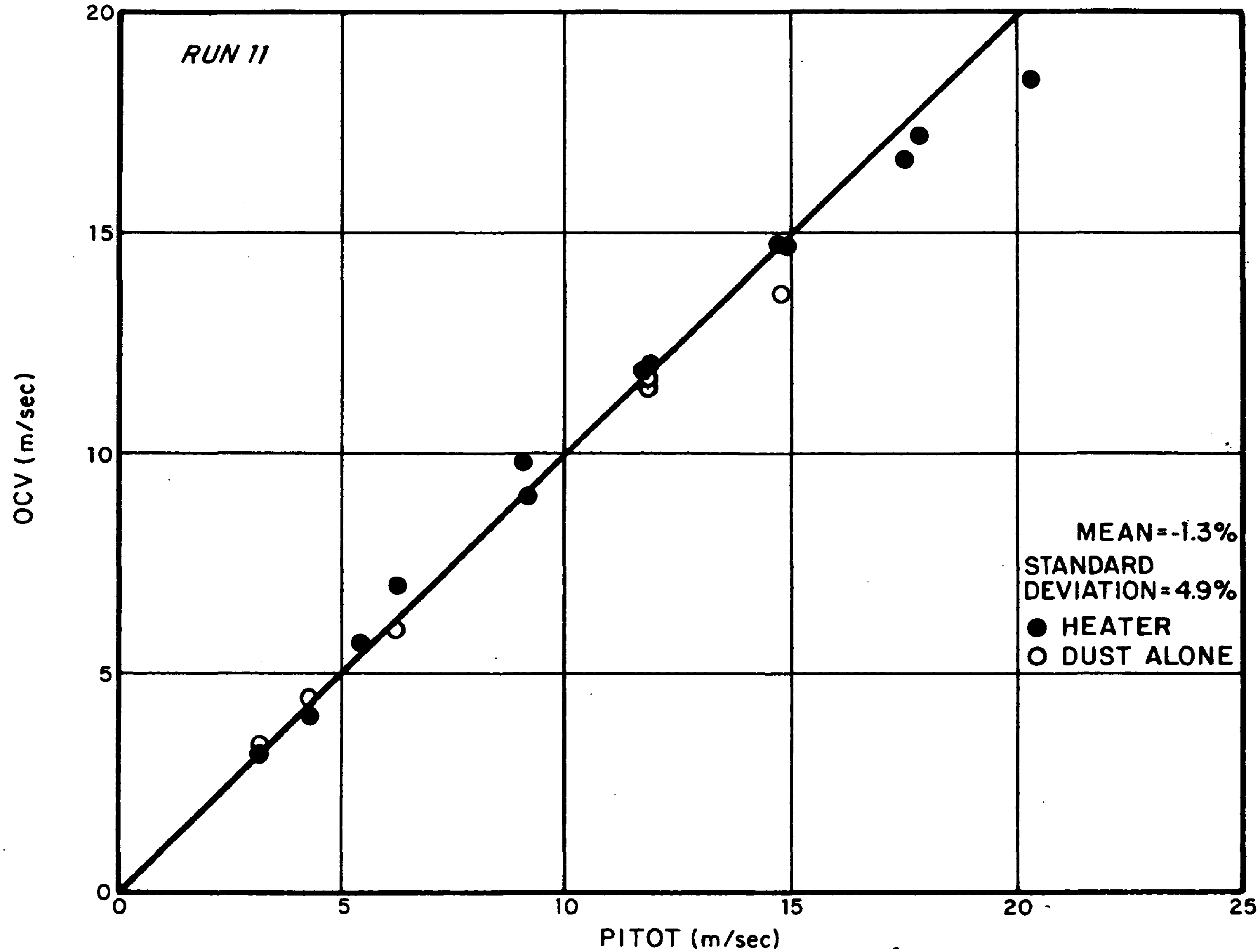

Figure 17. Run 11 - Fine Dust, 20 - 200 mg/M^3

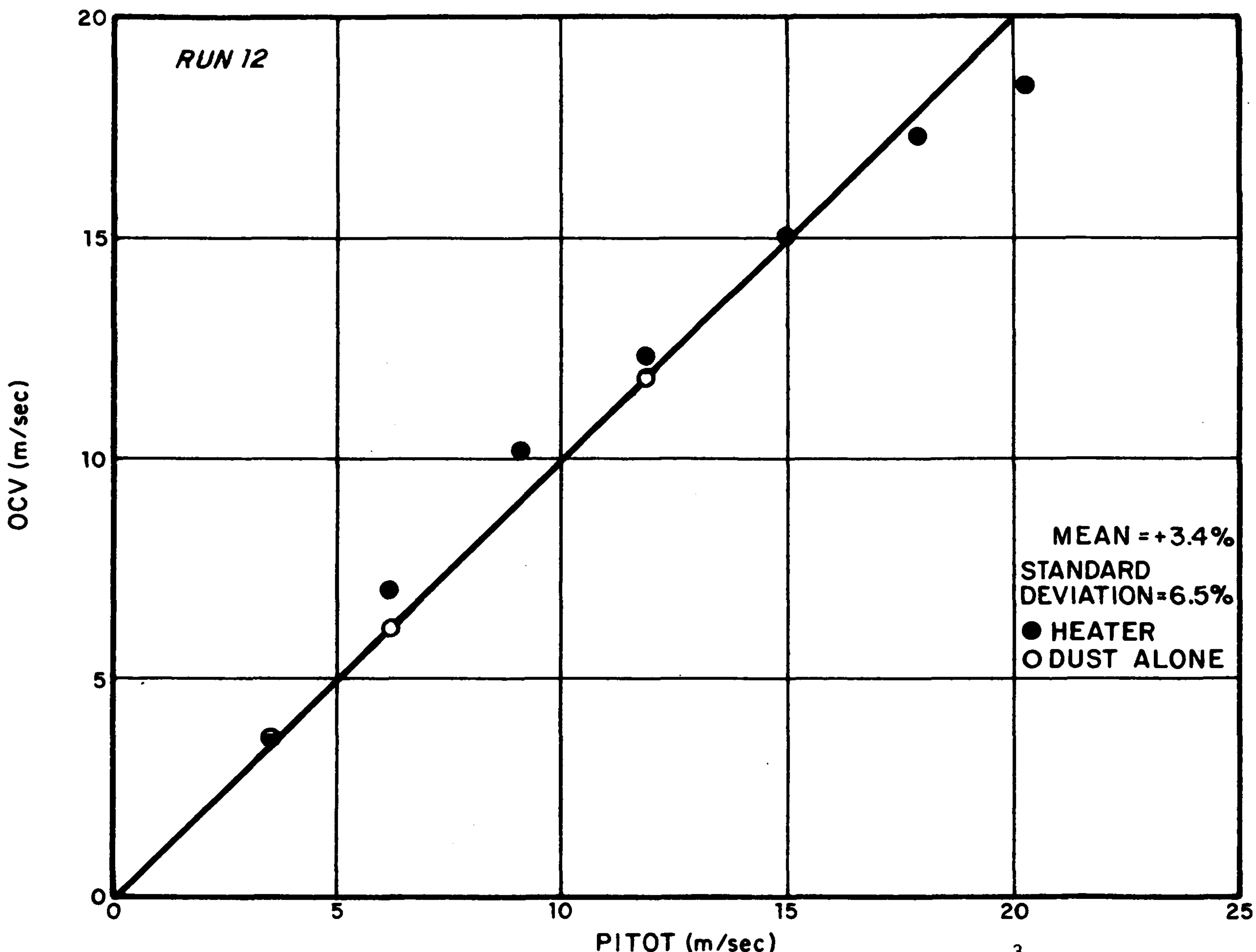

Figure 18. Run 12 - Electric Furnace Dust, 40 - 200 mg/M^3

pitot readings). The mean differences for the humid runs 2 and 3 of 5.5% and 6.6%, respectively, are larger than can be accounted for by statistical errors. However, the differences can be accounted for by humidities of 23% and 32.5% by volume instead of the 8% and 14.9% measured. This discrepancy could have arisen from condensation in the line to the humidity measuring instrument, causing an erroneously low reading for the humidity.

Run 6, heavy dust loading, had a mean difference of 6.8%. This probably arose from the large low frequency component of the signal from the OCV due to obscuration by dust. This is thought to cause distortion in the signal analyzer. However, this only occurred at very heavy dust loadings.

This same effect was noticed, to a lesser extent, at moderate dust loadings and elevated temperatures, particularly at higher tunnel speeds. The low frequency components in the signal tends to pull the signal processor down below the true frequency. These low frequency components arise from clouds of dust or refraction effects in the hot flow. These components could be removed by a high pass filter.

We also examined whether the dust was, by itself, sufficient seeding for the flow and whether or not a heater was required. To do this we rotated the OCV 180° so that the heater was downstream. The reading was then taken in that position as well as with the heater upstream. However, as Figures 12, 13, 17, and 18 show, the accuracy with dust alone was not as good as with the heater. The reason for this was probably the weaker signal with dust alone and the large low frequency component present. No significant difference in the accuracy was noted with the different size dust particles.

VISUAL INSPECTION

After all the tests had been completed in the SSSF, the stack OCV was dismantled to see if there was any significant deterioration. In fact, the inside of the OCV proved to be in very good condition. The teflon plastic lamp and fiber optic hold was in good condition and the electrical wiring showed no deterioration. However, the end of the fiber optic cable did show some blackening, indicating that the epoxy used to cement the ends of the fibers together had decomposed. This, however, did not interfere with the performance of the instrument.

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(Please read Instructions on the reverse before completing)

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A new type of instrument has been developed and tested for the measurement of stack flow velocities. The instrument is optical and generates a shadowgraph pattern of the wake from a small heater. This shadowgraph is projected on a mirror grating of precise dimensions and the reflected light detected by a photodiode. The output of the photodiode fluctuates at a frequency that is related to the velocity with which the turbulence is convected across the grating. By measuring this frequency, the flow velocity is determined.

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