U. S. DEPARTMENT OF COMMERCE

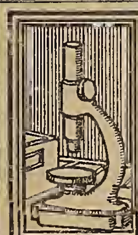
BUILDING MATERIALS AND STRUCTURES

REPORT BMS54

Effect of Soot on the Rating of an Oil-Fired Heating Boiler

by

RICHARD S. DILL
and PAUL R. ACHENBACH



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Foreword

This paper calls attention to an important factor which should be considered in the adjustment or testing of heating boilers or furnaces on the basis of a constant flue-gas temperature and in the design of chimneys. The paper describes the large effect on flue-gas temperature which can be expected from a comparatively light deposit of soot on heating surfaces. Some assurance is offered to users of heating boilers and furnaces that an increased flue-gas temperature due to soot deposition does not necessarily signify a great decrease in capacity or efficiency. Chimneys and smoke pipe should be able to withstand the relatively high temperatures that may occur if there is an extraordinary amount of soot deposited on heating surfaces during some period of improper combustion.

Lyman J. Briggs, *Director.*

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CONTENTS

ABSTRACT

It is shown that the rating of a boiler, obtained by a test method based on constant flue-gas temperature, can be seriously affected by soot on the heating surfaces, although the soot may be too slight in amount to affect greatly either the capacity or the efficiency at a constant firing rate. At constant firing rate the soot has a large effect on the flue-gas temperature.

I. INTRODUCTION

During trials of a proposed method for testing and rating oil-fired domestic steam boilers, some discrepancies appeared in the results which could not be readily accounted for; and, although the fact that the soot deposits were thin suggested at first that the effects noted were not to be attributed to soot, a series of runs was made, the results of which indicated that the soot did cause the discrepancies.

The test method under consideration, in common with some other methods proposed in the past, provides for testing boilers on a basis of constant flue-gas temperature and carbon dioxide content.

Information on the effect of soot on the capacity and efficiency of coal-fired boilers is available from other work.[1] In the present work, the point of interest is that a soot deposit causing a small decrease in efficiency results in a relatively large increase in flue-gas temperature. Then, when the flue-gas temperature is decreased to the point chosen for the test, by diminishing the firing rate, the delivery of the boiler is also diminished. In this way the delivery of the boiler, on which the rating is based, is affected.

II. TEST SPECIMEN AND EQUIPMENT

The boiler tested was a jacketed rectangular cast-iron boiler of four sections with a nominal rating of 280 ft^2 EDR.[2] The boiler and the gun-type oil burner used were made by the same manufacturer. Boiler and burner were erected for the tests in accord with the manufacturer's instructions, and testing equipment was applied in compliance with the test method under consideration. A potentiometer and thermocouple system were used for temperature measurements. An automatic float valve was provided to control the feed water. Oil consumption was measured by weight, and the carbon dioxide in the flue gas was measured with the Orsat apparatus. The thermostat and safety controls for the oil burner were installed in the conventional manner. The fuel was No. 2 fuel oil of 0.861 specific gravity and 19,500 Btu/lb higher heating value. Boiler output was determined from condensate weight. Draft in the firebox was maintained at 0.02-in. water gage.

[1] P. Nichols and C. E. Augustine, Effect of Soot on Heat Transmission in Small Boilers, U. S. Bureau of Mines, R. I. 3272.

[2] 1 ft^2 EDR is defined as the ability to emit 240 Btu/hr.

III. TEST PROCEDURE

The procedure during these tests consisted essentially in operating the boiler under the "stand-by" condition for several days and of observing the capacity, fuel consumption, etc., under test conditions once each day. Two series of runs were made, one at 10 percent of carbon dioxide and the other at 8 percent of carbon dioxide. During both series, the flue-gas temperature was adjusted to 600° F by setting the firing rate prior to each capacity determination. The setting then remained fixed until the next determination. The runs at 10 percent of carbon dioxide covered a period of 8 days and those at 8 percent of carbon dioxide, a period of 5 days.

At the end of each series, a run was made with the firing rate reset at the original value. The heating surfaces were then cleaned, and the performance of the boiler was observed to be substantially the same as it was before the deposition of soot began, which indicates that the results noted were caused by the soot.

IV. RESULTS

The results of the tests, shown in figures 1 and 2, indicate that soot can have a considerable effect on the rating of a boiler when such rating is based on a limiting flue-gas temperature, although the soot may be too slight in amount to seriously affect either the efficiency or the capacity at constant firing rate.

The results of the runs at 10 percent of carbon dioxide indicate that the effect of each day's deposition of soot is less than that of the preceding day's deposition and that the effect of the deposit approaches an upper limit with time. This effect is not clearly indicated by the results of the runs at 8 percent of carbon dioxide. The possibility of an error in the observation made on the second day in this series suggests itself, since it seems most reasonable that the function should be a curve such as that so strongly indicated by the results of the first series.

In the series of runs at 10 percent of carbon dioxide, the gross output of the boiler decreased from 136,000 to 70,850 Btu/hr, at the constant stack temperature of 600° F, owing to soot deposited during 8 days at the stand-by condition. With this soot deposit and the initial firing rate, the output was 127,400 Btu/hr and the efficiency was 63 percent instead of the initial 67 percent, whereas the flue-gas temperature was 790° F instead of the initial 600° F.

The soot deposited during the 8 days was estimated to be about 1/32 in. thick. A sample averaged approximately 10 mg/in.[2] of the heating surface from which it was scraped. These figures are not considered sufficiently precise to be a basis for calculations.

In the series of tests at 8 percent of carbon dioxide, the output of the boiler decreased from 115,400 Btu/hr to 84,230 Btu/hr owing to soot deposited during 5 days. With this soot deposit and at the initial firing rate, the output

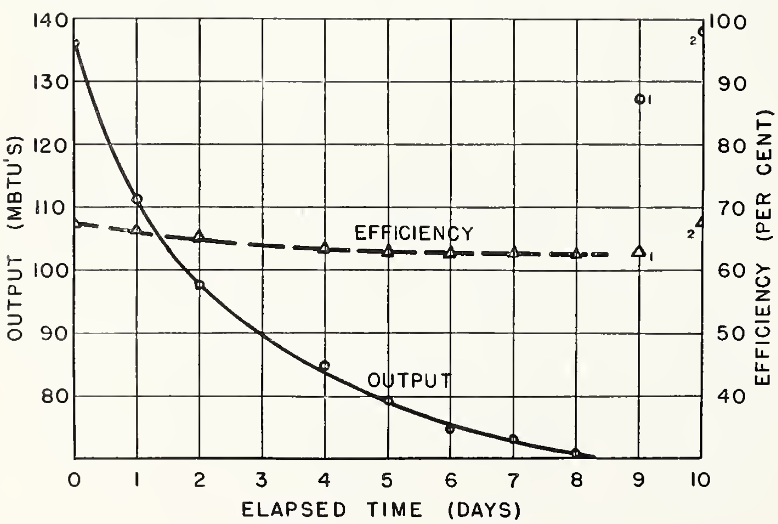
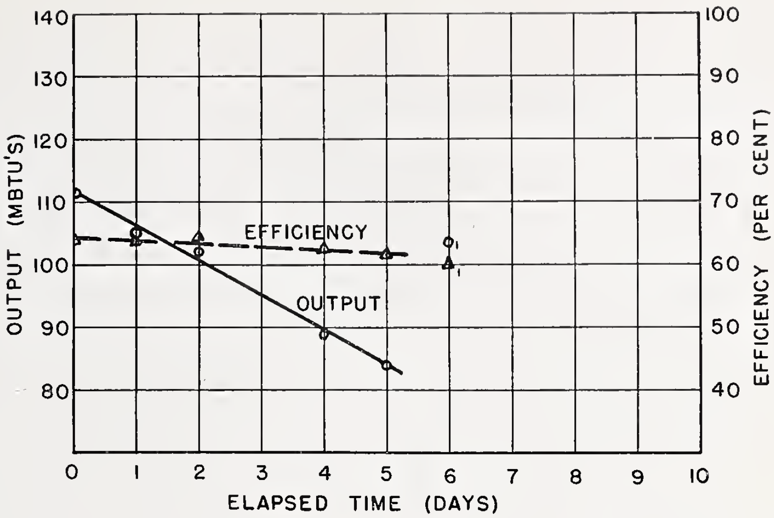


FIGURE 1.—*Effect of soot on boiler output at constant stack temperature (600° F).*

Soot was deposited by continuous operation at stand-by condition. Deposition of soot and daily observation of output were made with 10 percent of carbon dioxide in flue gas. Points with subscript "1" were obtained with initial oil rate with soot on heating surfaces. Points with subscript "2" were obtained with initial oil rate after cleaning soot from heating surfaces.

FIGURE 2.—*Effect of soot on boiler output at constant stack temperature (600° F).*

Soot deposited by continuous operation at stand-by condition. Deposition of soot and daily observation made with 8 percent of carbon dioxide in flue gas. Points with subscript "1" were obtained with soot on surfaces but with initial oil rate.



was 103,630 Btu/hr with an efficiency of 60 percent instead of the initial 65 percent and the stack temperature was 680° F instead of the initial 600° F.

No satisfactory method of specifying or measuring the amount of soot in a thin deposit on heating surfaces has been suggested. Soot is important primarily on account of its effect on heat transfer; and, since soot can vary in nature, a density determination, based on a measurement or estimate of thickness and weight deposited per unit area is of doubtful value. No attempt was made to measure the daily deposition of soot, but as a practicable expedient the effects of successive layers of soot deposited during successive 24-hr runs at constant conditions were observed.

V. DISCUSSION OF RESULTS

Assume a plant of 100,000 Btu/hr capacity in which the efficiency changes from 65 to 64 percent on account of the deposition of soot.

The heat liberated in the combustion chamber when the boiler was clean would be

$$\frac{100{,}000}{0.65}=153{,}800 \text{ Btu/hr.}$$

After the efficiency changed, the heat delivered to the house would be

$$0.64\times 153{,}800=98{,}430 \text{ Btu/hr.}$$

The difference, 100,000−98,430=1,570 Btu/hr, would appear largely as additional heat in the flue gas. Assuming the heat value of the fuel to be 20,000 Btu/lb and 20 lb of flue gas per pound of fuel, we have

$$\frac{153{,}800\times 20}{20{,}000}=154 \text{ lb of flue gas per hour.}$$

The specific heat of the flue gas may be taken as 0.25 Btu/lb deg.

The increase in flue-gas temperature due to the 1-percent change in efficiency would then be

$$\frac{1{,}570}{154\times 0.25}=41° \text{ F.}$$

If the initial flue-gas temperature were 600° F, the flue-gas temperature with sufficient soot on the heating surfaces to change the efficiency 1 percent might be as high as 640° F.

A change of 41 degrees F in flue-gas temperature would probably be unimportant, but greater changes than 1 percent in efficiency due to soot are likely to occur in service and to result in greater changes in flue-gas temperature. If the relation is linear, a change in efficiency from 65 to 60 percent would result in a 205 degree F change of flue-gas temperature, so that, at constant firing rate, flue-gas temperature may become excessive due to a soot deposit capable of causing a small change in efficiency.

The results of the tests at 10 percent of carbon dioxide show that sufficient soot to reduce the efficiency from 67.3 to 63.0 percent at constant firing rate was sufficient to reduce the output from 136,137 Btu/hr to 70,840

Btu/hr at constant flue-gas temperature. This amounts to

$$\frac{136,140-70,840}{67.3-63.0}=15,200 \text{ Btu/hr for each percent of efficiency,}$$

or

$$\frac{15,200}{136,140}\times 100=11.15 \text{ percent of capacity for each percent of efficiency.}$$

For the tests at 8 percent of carbon dioxide, the same figures are

$$\frac{111,540-84,230}{64.0-60.0}=6,826 \text{ Btu/hr for each percent of efficiency,}$$

or

$$\frac{6,826}{111,540}\times 100=6.12 \text{ percent of capacity for each percent of efficiency.}$$

If, after a boiler has been in service for a time, a layer of soot gathers on the heating surfaces, the flue-gas temperature will be higher than it was when the boiler was new and clean. Then, if an attendant or inspector resets the oil rate to maintain the initial flue-gas temperature, measured with a thermometer, in order to comply with some specification or safety regulation, the capacity of the boiler may be so seriously reduced that it cannot heat the house satisfactorily.

An increase in flue-gas temperature, whether due to a soot deposit or some other cause, will result in an increased draft, and this may affect the operation of the heating plant. For those types of oil burners which rely upon blowers for draft, only a small or negligible effect on operation would be expected, but the effect on the operation of those types of water heaters and heating devices which rely upon chimney draft might be important. Natural draft oil-burning devices are sometimes connected to existing chimneys which do not furnish sufficient draft. The effect of the soot deposit is, in such cases, in the right direction to increase the draft, and this may be a reason why the soot deposit ceases to increase after attaining a certain thickness.

In these tests, draft was obtained by means of an induced-draft fan; and, since the draft was maintained at 0.02-in. water gage, data on the effect of temperature change on chimney draft were not obtained.

It is realized that a boiler-burner combination will generate and deposit less soot under some operating conditions than under others, that some combinations may be in general better than others in this respect, and that some combinations, if properly adjusted, may not generate or deposit perceptible soot. Nevertheless, these observations indicate that it would be well for chimneys intended for use with oil-burning furnaces or boilers to be designed to withstand reasonably high temperatures, since such high temperatures may be reached on account of soot deposited during some period of maladjustment.

This work emphasizes the importance, during tests of a boiler by any method based on a constant flue-gas temperature, of assuring either that no soot exists on the heating surfaces or that the soot deposit has reached an equilibrium condition by operating the boiler under the test condition for a time preceding the observations.

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