A Study of Smokeless Furnaces
Suitable for Stationary Steam Boilers

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A STUDY OF SMOKELESS FURNACES SUITABLE FOR STATIONARY STEAM BOILERS

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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STATIONARY STEAM BOILERS.

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE

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A STUDY OF SMOKELESS FURNACES SUITABLE FOR
STATIONARY STEAM BOILERS.

1. CONCLUSIONS.

1. Boilers which were equipped with mechanical stokers operated with practically no smoke. This was true in single units of 210 H.P. to units placed in a battery amounting to 1370 H.P.

2. Water tube boilers in small units hand fired operated with less smoke than fire tube boilers similarly fired.

3. In all of the tests made the fire tube boilers showed a higher average per cent of smoke than the water tube boilers when operating under normal conditions. None of the fire tube boilers tested were equipped with mechanical stokers.

4. Hand fired boilers can be operated with less smoke than is generally the case, if the furnaces are suitably designed and the fireman exercises care in firing the boilers.

II. INTRODUCTION.

1. GENERAL DISCUSSION.

(a) Historical.

The question of smoke prevention is not by any means one that has been confined to recent years. From the time coal was first used in this country the evils attending the emission of black smoke from imperfect combustion have been recognized. No entirely satisfactory method of eliminating smoke or otherwise escaping the evils attendant upon its production has as yet been developed. The black smoke in our atmosphere is for the most part produced by the
combustion of coal, either in domestic fires or in fires and furnaces devoted to commercial work.

The exact time of the introduction of coal into this country is not known, but it is probable that it was in the early part of the seventeenth century. As early as 1750 - 1755, when coal first began to come into common use, we find governing bodies trying to enforce laws against the prevention of smoke. From the year 1820 to the present day various acts have been passed or amendments made especially referring to smoke prevention. In spite of all this the evil has been growing year by year, the laws having to a great extent failed to affect any real improvement. The legal aspect, however, is not to be treated with in this paper. For the present it is sufficient that, it is generally conceded that the large quantities of black smoke emitted from factory and power plant stacks constitute a nuisance which it behooves all classes of society to do their utmost to eliminate.

The subject of smoke admits of a wider treatment than is usually accorded to it. The whole question of combustion of coal and smoke prevention is one of national importance. It is not necessarily true that a smokeless fire is an economical fire for in many cases fires are smokeless but still very wasteful. On the other hand a fire may be smokeless and at the same time an efficient fire, in fact most of those things which produce a smokeless fire will also give improved combustion.

(b) Purpose.

It is the intention of this paper to discuss the fundamental principles as applied to the combustion of coal in the various types of boilers, and their settings, without regard as to the
capacities under which they were operated. Practically all of the coal burned under the various boilers tested came from the Electric Mine of Danville, Illinois. This coal was mined from seam 6, Vermilion County. A proximate analysis of the coal used was made for each test. These analyses are given in Table 1, page 4.

The writers will endeavor to describe several local boilers as to their settings, firings, and the resulting smoke records as taken during actual operation. These boilers having been tested in actual operation give good examples of the smoke performances under ordinary running conditions.

Table 1, in addition to the analyses already noted presents data relative to the time and the place of making the tests, and the character of the coal. It also gives the number of the pages in the appendix upon which will be found smoke chart, drawing of the boiler setting, and the photograph of the stack for each test.

III. DATA AND RESULTS.

1. WATER TUBE BOILERS.

In the drawings shown on pages 23, 25, 26, 29, 31, 33, and 36, are represented three types of water tube boilers, namely; the Heine, the Stirling, and the Babcock and Wilcox, with their settings and a few principal dimensions. These boilers were tested by the writers under every-day operating conditions. Some of these boilers were hand fired and some were automatically fired. The capacities of the water tube boilers ranged from 210 H.P., in a single unit to 1370 H.P. in a battery of single units.

(a) Firings.

The hand fired water tube boilers were of capacities ranging from a single unit of 375 H.P. to a battery of two units amount-
<table>
<thead>
<tr>
<th>No. of Test</th>
<th>Plant Where Test Was Made</th>
<th>Date</th>
<th>Proximate Analyses</th>
<th>Name of Mine and Kind of Coal</th>
<th>Pages of Appendix on Which Are:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fixed Carbon</td>
<td>Volatile Matter</td>
<td>Moist.</td>
</tr>
<tr>
<td>1</td>
<td>Mech. Eng. Lab of Univ. of Ill.</td>
<td>Mar. 1909</td>
<td>38.57</td>
<td>36.11</td>
<td>12.80</td>
</tr>
<tr>
<td>2</td>
<td>Univ. of Ill. Power Plant</td>
<td>Dec. 2009</td>
<td>36.96</td>
<td>35.10</td>
<td>12.25</td>
</tr>
<tr>
<td>3</td>
<td>Champaign-Urbana Elect. Power Plant</td>
<td>Dec. 2909</td>
<td>36.82</td>
<td>35.00</td>
<td>12.34</td>
</tr>
<tr>
<td>4</td>
<td>Same Plant as Test No. 3</td>
<td>Dec. 2909</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>5</td>
<td>Same Plant as Test No. 3</td>
<td>Dec. 2909</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>6</td>
<td>Urbana Light Heat Power Plant</td>
<td>Mar. 909</td>
<td>36.37</td>
<td>34.49</td>
<td>14.44</td>
</tr>
<tr>
<td>7</td>
<td>Champaign-Urbana Water Works</td>
<td>Dec. 3109</td>
<td>42.68</td>
<td>31.67</td>
<td>11.56</td>
</tr>
<tr>
<td>8</td>
<td>New York Central Power Plant</td>
<td>Mar. 609</td>
<td>36.04</td>
<td>31.30</td>
<td>15.87</td>
</tr>
<tr>
<td>9</td>
<td>Same Plant as Test No. 8</td>
<td>Mar. 2309</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>10</td>
<td>Univ. of Ill. Horticultural Plant</td>
<td>Mar. 2009</td>
<td>36.61</td>
<td>36.02</td>
<td>14.36</td>
</tr>
<tr>
<td>11</td>
<td>Twin City Ice &amp; Cold Storage Plant</td>
<td>Mar. 1309</td>
<td>34.73</td>
<td>34.21</td>
<td>15.59</td>
</tr>
</tbody>
</table>
The coal was generally fired first in one door then in the other one by the spreading method, and in quantities of fourteen to eighteen shovels full at one firing. The boilers operated at full load and generally produced considerable smoke. The density of the smoke increased when firing took place then decreased to, or nearly to, no smoke; only to increase again when the next firing took place. The two Stirling boilers of the Chamapign Electric Power Plant gave an unusually high per cent of smoke throughout the entire test. This may be explained by the fact that these boilers were operating with considerable overload. In this case it was said that it was difficult to cut down the smoke on these two Stirling boilers even under normal conditions. The three Babcock and Wilcox boilers tested at the same power plant were a trifle better than the two Stirling boilers, although they produced a somewhat high per cent of smoke.

The mechanical stoker fired boilers were of capacities ranging from a single unit of 210 H.P. to a battery of several units amounting to 1370 H.P., and in all cases practically no smoke was produced during the duration of the test. The average density of the smoke of the mechanical stoker fired boilers was about sixteen per cent, while the average density of the smoke of the hand fired boilers was about seventy per cent. This shows the great preventive action of the mechanical stoker. The only time that the stoker fired boilers really produced smoke was when the fire was sliced or poked. This did not amount to a very high per cent. Water tube boilers when operating above their rated capacities are very apt to have a higher per cent of smoke than when operating under normal conditions even when equipped with mechanical stokers. The average thickness of
the fires in the furnaces of the stoker fired boilers ranged from five to six inches, while the thickness of the fires in the furnaces of the hand fired boilers ranged from five to nine inches. The thinner fires in the stoker fired furnaces was one of the chief reasons why the stoker equipped boilers operated with a lower per cent of smoke than the hand fired boilers. A thick fire is a very great hindrance to thorough combustion, consequently in the hand fired boilers combustion was not as complete as it should have been, and much of the fuel passed up the stack in the form of smoke. This was practically eliminated in the case of the thinner fires of the stoker fired boiler furnaces.

(b) Settings.

The settings of the water tube boilers that were tested are shown on pages 23, 25, 26, 29, 31, 33, and 36, with the general arrangement of arches, baffles, etc. The combustion chamber is represented in each of the drawings. The settings for the boilers of the University of Illinois Power Plant shown on pages 26 and 27, and the test boiler in the Mechanical Engineering Laboratory shown on page 23, are especially designed to operate without smoke. The battery of six boilers tested in the University of Illinois Power Plant is made up of three Babcock and Wilcox boilers and three Stirling boilers. None of the boilers tested in actual commercial practice were especially designed to operate without smoke, although the two Heine boilers of the Champaign Electric Power Plant equipped with chain grate stokers were found to operate with only twenty per cent of smoke. This value for a commercial boiler is a good showing, taking into account that the boilers were operating at full load during the entire duration of the test. They may have actually operated with a
small per cent overload.

(c) Smoke records.

The smoke records of all the tests were made in accordance with Professor Ringelmann's smoke charts. These smoke charts are described in detail on page 21. The observation of the smoke issuing from the stack was made continuously for a period of three hours and a reading taken every minute. These readings were recorded in the form shown in Table 11, page 8. From the complete smoke record of a test there was obtained an average smoke value for the entire duration of the test of three hours. The smoke charts as made from the records of the tests from water tube boilers are shown on pages 24, 27, 30, 32, 34, and 37, while the average smoke chart is shown on page 50.

2. HORIZONTAL TUBULAR BOILERS.

In the drawings shown on pages 39, 44, and 47, are represented three types of horizontal return tubular boilers, namely; the Chandler and Taylor, the Murray, and a specially designed boiler, with their settings and a few principal dimensions. These boilers were tested by the writers under every-day operating conditions. All of these boilers were hand fired.

The horizontal return tubular boiler is better known as the fire tube boiler by which name it has been previously called, and will also be so called in the remaining pages of this paper. The chief advantage of the fire tube boiler is its cheapness and its economical operation with all grades of coal, especially those containing a high fixed carbon content. The coal used during the tests could possibly be burned under a fire tube boiler without smoke, although the result is very doubtful. Special methods or settings are
Table 11.
Smoke records as taken from the test of the Murray fire tube boiler at the Twin City Ice and Cold Storage Power Plant. Two hours.

<table>
<thead>
<tr>
<th>Time</th>
<th>Smoke</th>
<th>Time</th>
<th>Smoke</th>
<th>Time</th>
<th>Smoke</th>
<th>Time</th>
<th>Smoke</th>
<th>Time</th>
<th>Smoke</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30</td>
<td>1</td>
<td>8:31</td>
<td>0</td>
<td>8:32</td>
<td>0</td>
<td>8:33</td>
<td>0</td>
<td>8:34</td>
<td>0</td>
</tr>
<tr>
<td>8:35</td>
<td>0</td>
<td>8:36</td>
<td>0</td>
<td>8:37</td>
<td>0</td>
<td>8:38</td>
<td>0</td>
<td>8:39</td>
<td>0</td>
</tr>
<tr>
<td>8:40</td>
<td>0</td>
<td>8:41</td>
<td>0</td>
<td>8:42</td>
<td>0</td>
<td>8:43</td>
<td>0</td>
<td>8:44</td>
<td>0</td>
</tr>
<tr>
<td>8:45</td>
<td>0</td>
<td>8:46</td>
<td>0</td>
<td>8:47</td>
<td>0</td>
<td>8:48</td>
<td>0</td>
<td>8:49</td>
<td>0</td>
</tr>
<tr>
<td>8:50</td>
<td>0</td>
<td>8:51</td>
<td>0</td>
<td>8:52</td>
<td>0</td>
<td>8:53</td>
<td>0</td>
<td>8:54</td>
<td>0</td>
</tr>
</tbody>
</table>
necessary to secure improvement in the smoke conditions of these boilers. A special setting purposely designed for the prevention of smoke is shown on page 44. This type of setting combined with more careful firing is supposed to operate without smoke. In the test run on this boiler by the writers the boiler did operate without a very high per cent of smoke under normal conditions, but when fired the per cent of smoke increased rapidly only to decrease again to its former condition.

(a) Firings.

All of the fire tube boilers tested were hand fired, none with mechanical stokers having been tested. These boilers were of capacities ranging from a single unit of 60 H.P. to a battery of six 100 H.P. units making the total of the battery 600 horse power. The coal was generally fired first in one door then in the other one by the spreading method, and in quantities of fourteen to twenty shovels full at one firing. The fire tube boilers tested were as a rule great smoke producers, with the exception of the specially designed boiler at the University of Illinois Horticultural Heating Plant. This boiler was not, however, operating up to its rated capacity hence the facts concerning it under full load cannot be given. In the writers opinion this boiler would smoke about twenty per cent if operated with more load than it was carrying on the day on which the test was conducted. The Chandler and Taylor boilers operated with about as high a per cent of smoke in single units as they did when placed in battery. The Murray boiler operating at full load produced an average of about 23 per cent smoke, which was low considering the careless way it was fired.
(b) Settings.

The settings of the fire tube boilers that were tested are shown on pages 39, 44, and 47, and the general arrangement of arches, height of furnace, and several dimensions are also given. The settings of these boilers are in all cases except one designed without regard to smoke prevention. The only setting of a fire tube boiler especially designed for smokeless combustion is the sixty horse power boiler in the Horticultural Heating Plant at the University of Illinois. This boiler has several arches and walls that are different from those commonly found in settings. The arrangement of these special parts can be seen in the drawing of the boiler setting on page 44.

(c) Smoke records.

The smoke records for the tests with the fire tube boilers were made in the same manner as those for the water tube boilers, that is, the observation of the smoke was made for a period of three hours and a record made every minute according to Professor Ringelmann's smoke charts. A description of the method employed will be given later.

IV. DISCUSSION OF DATA AND RESULTS.

1. GENERAL.

(a) Combustion.

The principle involving complete combustion is one of the greatest importance to a Mechanical Engineer. As a basis for the thorough understanding of the problems of smoke prevention, a brief review will prove interesting here. The problem in connection with smokeless boilers is to provide furnaces, so constructed and capable of operation such as to make combustion as near perfect as pos-
sible, thereby eliminating smoke, smoke being products resulting from incomplete combustion.

Combustion is a rapid chemical combination resulting in heat and light. The combining elements are oxygen, which is usually derived from the atmospheric air; and either carbon or hydrogen, or a compound of the two. Sulphur sometimes appears with the carbon and the hydrogen, and also combines with the oxygen. The substance that is formed by the chemical union is called the product of combustion; and the heat that is produced by the combustion of a unit weight (one pound) of the fuel is called the heat of combustion. This is usually measured in British thermal units. One British thermal unit is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. Table III immediately following relates to the complete combustion of hydrogen, carbon, and sulphur:

<table>
<thead>
<tr>
<th>Element</th>
<th>Chemical Symbol</th>
<th>Name</th>
<th>Chemical Symbol</th>
<th>Heat of Comb'stn B.t.u. per lb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H</td>
<td>Water</td>
<td>H₂O</td>
<td>62000</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>Carbon Dioxide</td>
<td>CO₂</td>
<td>14500</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>4400</td>
</tr>
<tr>
<td>Sulphur</td>
<td>S</td>
<td>Sulphur Dioxide</td>
<td>SO₂</td>
<td>4000</td>
</tr>
</tbody>
</table>

Table III.

In the complete combustion of carbon, the product of combustion, it will be observed, is carbon dioxide (CO₂). Each atom of carbon combines with two atoms of oxygen. If sufficient oxygen
is not provided, it may happen that each carbon atom will combine without one oxygen atom, thus forming carbon monoxide (CO). As a result of this incomplete combustion, the heat developed is only 4400 B.t.u. The carbon monoxide may combine with oxygen, according to the formula

\[ \text{CO} + \text{O} = \text{CO}_2 \]

and the heat developed will be the difference, \(14,500 - 4400 = 10,100\) B.t.u. per pound of carbon in the carbon monoxide.

A knowledge of the relative weights of these elementary atoms gives a correct means of computing the amount of oxygen required for combustion. The weights are as follows:

- H ............. 1
- O ............. 16
- C ............. 12
- S ............. 32

In the burning of the oxygen to \(\text{H}_2\text{O}\), two atoms of hydrogen each of weight 1 combine with one atom of oxygen, weight 16; hence the ratio of oxygen to hydrogen is \(16:2 = 8:1\), i.e., 8 lb. of oxygen are required for the combustion of 1 lb. of hydrogen, and there results \(8 + 1 = 9\) lb. of water. This combustion with others is shown in the following table:

<table>
<thead>
<tr>
<th>Elements</th>
<th>Chemical Equation</th>
<th>Relative Weights</th>
<th>Weights pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen to (\text{H}_2\text{O})</td>
<td>(2\text{H} + \text{O} = \text{H}_2\text{O})</td>
<td>((2 \times 1) + 16 = 18)</td>
<td>(+ 8 = 9)</td>
</tr>
<tr>
<td>Carbon to (\text{CO}_2)</td>
<td>(\text{C} + 2\text{O} = \text{CO}_2)</td>
<td>(2 + (2 \times 16) = 44)</td>
<td>(+ \frac{22}{3} = 3 \frac{1}{3})</td>
</tr>
<tr>
<td>Carbon to (\text{CO})</td>
<td>(\text{C} + \text{O} = \text{CO})</td>
<td>(12 + 16 = 28)</td>
<td>(+ \frac{14}{3} = 2 \frac{2}{3})</td>
</tr>
<tr>
<td>Sulphur to (\text{SO}_2)</td>
<td>(\text{S} + 2\text{O} = \text{SO}_2)</td>
<td>(32 + (2 \times 16) = 64)</td>
<td>(+ 1 = 2)</td>
</tr>
<tr>
<td>Methane cr</td>
<td>(\text{CH}_4 + \text{O} = \text{CO}_2)</td>
<td>((12 + 4) + (4 \times 16) = )</td>
<td></td>
</tr>
<tr>
<td>Marsh Gas</td>
<td>(\text{CO}_2 + 2\text{H}_2\text{O})</td>
<td>(12 + (2 \times 16) + 2(2 + 16))</td>
<td>(+ 4 = 5)</td>
</tr>
</tbody>
</table>
When the oxygen needed for the combustion is taken from the atmosphere, the nitrogen always present must be taken into consideration. Nitrogen takes no part in the combustion but mingles with the products of combustion, absorbs heat from them and passes away with them. Approximately, it takes 4.25 pounds of air to furnish 1 pound of oxygen; the remaining 3.25 pounds are nitrogen. When the combustion of the different elements takes place in air the resulting relative weights are modified on account of the nitrogen. This is exhibited below.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Chemical Equation</th>
<th>Relative Weights</th>
<th>Weights pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon in Air</td>
<td>C + Air=</td>
<td>12 + (2 x 4.25 x 16)=</td>
<td>1 + 11.33=</td>
</tr>
<tr>
<td></td>
<td>CO₂ + 7.43N</td>
<td>44 + 104</td>
<td>3.67 + 8.66</td>
</tr>
<tr>
<td>Marsh Gas in Air</td>
<td>CH₄ + Air=</td>
<td>(12+4)+(4 x 4.25 x 16)=</td>
<td>1 + 17=</td>
</tr>
<tr>
<td></td>
<td>CO₂+2H₂O+14.8N</td>
<td>44+(2 x 18) + 208</td>
<td>18</td>
</tr>
</tbody>
</table>

It will be seen from the above table that to burn 1 pound of carbon 11.33 pounds of air must be supplied. The 8.66 pounds of nitrogen contained in the weight of air pass away with the 3.67 pounds of carbon dioxide (CO₂) formed by the combustion. For the complete combustion of 1 pound of marsh gas, 17 pounds of air are required. Chemical combinations of carbon and hydrogen, the so-called hydrocarbons, play an important part in the burning of coal, particularly those coals of large volatile content. The most important hydrocarbons are methane or marsh gas, ethylene or olefiant gas, and acetylene.

At the ordinary temperature and atmospheric pressure, a pound
of air has a volume of about 13.1 cubic feet. Using this value, the following are obtained for the theoretical amount of air required for the complete combustion of various fuels:

<table>
<thead>
<tr>
<th>Kind of fuel.</th>
<th>Carbon</th>
<th>Hydrogen</th>
<th>Sulphur</th>
<th>Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of air (lb.)</td>
<td>11.33</td>
<td>34</td>
<td>4.25</td>
<td>17</td>
</tr>
<tr>
<td>Volume of air (cu. ft.)</td>
<td>150.00</td>
<td>445</td>
<td>55.00</td>
<td>220</td>
</tr>
</tbody>
</table>

The heat developed by the combustion is absorbed by the products of combustion, and as a result, the temperature of these gases rises in a marked degree. Thus when carbon is burned in air, the 14,500 B.T.U. developed should heat the 3 2/3 pounds of CO₂ and 8 2/3 pounds of nitrogen from an initial temperature of perhaps 60° to a final temperature of 4500°. The actual final temperature is considerably lower than 4500°. The products of combustion act as a vehicle, carrying the heat developed by combustion to its final destination.

2. RELATION BETWEEN FIRINGS, SETTINGS, AND SMOKE RECORDS OF WATER TUBE BOILERS.

The smoke records as taken from actual operation of the water tube boilers made plain the fact that when a boiler was being fired by hand, the density of the smoke increased from at or near no smoke to one-hundred per cent, but after a short interval the density gradually decreased to its former condition. This state of affairs continued with a certain regularity throughout the duration of the test. The above was true with practically every boiler tested, and this can be readily seen by reference to the smoke charts on pages 24, 27, 30, 32, 34, and 37.
The settings of the various water tube boilers were in general much alike. The general plan and dimension of each boiler tested can be seen by reference to the drawings on pages 23, 25, 26, 29, 31, 33, and 36. Practically no smoke was produced with any of the boilers stoker fired, which result was due to the fact that the coal was fed into the hot furnace at a uniform speed and in a uniform amount. The arrangement of the baffles was such that the hot gases were kept away from the cold tubes until perfectly, or nearly perfect, combustion had taken place. The cause of the hand fired water tube boilers smoking as they did was that the coal was fed irregularly, and in varying and incorrect amounts. The feeding of the coal at uniform speed gives it time for complete combustion, which is the secret of smokelessness. The fires of the stoker fired boilers were in general thinner and of more uniform thickness than was the case with the hand fired boilers. This of course follows from the stoker feeding the coal into the furnace at a definite rate. This was not the case with the hand fired boilers because these were fired at almost any time and with varying amounts of coal. Fired in this way the coal already fired may have been half burned when another firing took place. This method of firing did not allow for complete combustion hence the high density of the smoke. The stoker fired boilers were regulated so as to keep up a certain steam pressure, while the hand fired boilers were fired when the steam pressure commenced to drop. The stoker fired boilers kept the steam pressure uniform whereas with the hand fired boilers it was rising or lowering depending on the fire. The fires of the hand fired boilers were too thick to allow for complete combustion hence the escaping of a great amount of unburned matter from the stack in the form of smoke. The water tube
boiler may be hand fired so as to reduce the density of the smoke to a great extent but whether the water tube boiler will entirely eliminate the smoke is a very doubtful matter. If the smoke is to be entirely eliminated from a hand fired water tube boiler a special designed setting will be necessary coupled with greater skill in firing than is commonly used.

3. RELATION OF THE FIRINGS, SETTINGS, AND SMOKE RECORDS OF HORIZONTAL RETURN TUBULAR BOILERS.

The smoke records as taken from tests of the actual operation of the fire tube boilers made plain the fact that this type of boiler is a much greater smoke producer than the water tube boiler. All of the fire tube boilers tested were hand fired.

The chief advantage of the fire tube boilers are their cheapness and their economical operation with all grades of coal, especially those containing a high fixed carbon content. This type of boiler is only used in small units very rarely exceeding 150 H.P. in capacity, whereas the water tube boiler is used in much larger units. The same is true of the batteries of these two types of boilers, that is the water tube boiler far exceeds the fire tube boiler in battery capacity.

The coal as used in the boilers when the tests were run could possibly be burned with less smoke, if a special setting suitable for better combustion were installed, and more skill exercised in firing. A boiler equipped with a special setting is shown on page 44 and this arrangement is supposed to operate without smoke. In the test run upon this boiler, however, it was plain that if this boiler was operated with anywhere near full load and fired at reg-
ular times it would smoke. The boiler at the time when the test was run did not carry its normal load. The smoke chart of this boiler on page 44 shows that practically no smoke was made when the boiler was left to itself but as soon as fired the density of the smoke rapidly increased to one-hundred per cent.

In hand firing the common method is to introduce coal directly into the hot furnace by the spreading method, in fine dust and large lumps, thus preventing slow or uniform distillation of coal gases. The air meanwhile coming into the furnace through the doors, through holes in the fire, or through a fuel bed of far too great thickness was neither correct in quantity nor properly heated. The products of combustion from such firing come in contact with the cool surface of the plates of the boiler, practically reducing the existing temperature of the unburned gases below their ignition point before complete combustion had taken place, thus causing dense smoke to issue from nearly every hand fired stack.

4. RELATION OF THE WATER TUBE BOILER TO THE HORIZONTAL RETURN TUBULAR BOILER.

A noticeable fact concerning these two types of boilers was the absence of mechanical stokers under the fire tube boilers. Of all of the fire tube boilers tested by the writers not one was found to be equipped with a stoker. The reason for this is not generally known, but from circumstances regarding the matter will say that the cost of a stoker in comparison to the boiler is very high. The general plan of the fire tube boiler would not as a rule admit the installation of a stoker without involving much trouble and expense in rearranging walls and arches. The fire tube boiler is installed not that it is the best boiler, but because it is cheaper
than the water tube boiler, and that its operation is more simple.

The fire tube boiler is never used in large capacities or units. The settings of the water tube boilers and the fire tube boilers differ chiefly in the manner of conducting the hot gases among or through the tubes. Baffles are used in connection with the water tube boiler to guide the hot gases in a certain definite path so as they will do the most possible good. The fire tube boiler makes use of walls and arches in conducting the hot gases from the combustion chamber into the tubes. The combustion chamber of the water tube boiler is generally arranged so as to keep the hot gases away from the cool tubes until complete, or comparatively complete, combustion has taken place.

V. METHODS OF CONDUCTING TESTS AND COLLECTING RESULTS.

1. EQUIPMENT.

The boilers tested were all operating under every-day conditions. Some of these tests may not have been run at the time suitable to get the smoke observations at a maximum, but it is believed that the records obtained are average values of the density of the smoke as produced by these boilers.

No special apparatus was necessary in conducting these tests. The articles used were a thermometer to obtain readings of the external air, and Professor Ringelmann's smoke charts.

The boilers, upon which the tests were run, were all in the vicinity of Champaign and Urbana. The following boilers were tested: in the University of Illinois Power Plant two 220 H.P. and one 150 H.P. Babcock and Wilcox boilers, and three 260 H.P. Stirling boilers; in the New York Central Power Plant six 100 H.P Chandler and Taylor boilers; in the Champaign Electric Power Plant two 350 H.P.
Heine boilers, two 260 and one 220 H.P. Babcock and Wilcox boilers, and two 300 H.P. Stirling boilers; in the Urbana Light, Heat, and Power Plant one 350 H.P. Heine boiler; in the Twin City Ice and Cold Storage Power Plant one 100 H.P. Murray boiler; in the Mechanical Engineering Laboratory one 210 H.P. Heine boiler; in the Horticultural Power Plant one 60 H.P. specially designed boiler; and in the Champaign and Urbana Water Works Power Plant two 100 H.P. Chandler and Taylor boilers.

2. SMOKE CHARTS.

The smoke charts were plotted from the records taken from the observations of the smoke as made during the time of test. The curves being drawn by using the time in hours as the abscissae and the density of the smoke in per cent as ordinates. Points were also plotted along the time line indicating the period at which the boiler was fired, and from this arrangement can be seen the effect firing will have upon the density of the smoke by noticing the direction of the curve from the time of firing. All of the smoke charts with the accompanying data relating to the boilers are shown on pages 24, 27, 30, 32, 34, 37, 40, 41, 42, 45, and 48. The average smoke chart is shown on page 50.

3. OBSERVATIONS.

In making observations of the smoke from the various stacks, four charts ruled like those on page 20, together with a chart printed in solid black and another left entirely white, were placed in a horizontal row and hung at a point about 50 feet from the observer and in such a line so that he can look at the smoke issuing from the stack then directly at the charts within the least possible
The above are the Ringelmann smoke charts. With the above are included No.0, which is entirely white, and No.5, which is entirely black.
interval of time. At this distance the lines become invisible, and the charts appear to be of different shades of gray, ranging from very light gray to almost black. The observer glanced from the smoke issuing from the stack to the charts, which are numbered 0 to 5, determined which chart most nearly corresponded to the color of the smoke, and made a record accordingly, noting the time. Observations were made continuously for one minute, and the estimated average density during the minute recorded, and so on, records being made every minute for a period of three hours. The average of all the records made during the duration of three hours was taken as the average value of the smoke density during the test.

The charts shown on page 20 are made according to the following and represent the corresponding density of smoke: chart No. 0 is all white, representing no smoke; chart No. 1 had black lines 1 mm. thick crossing so as to leave squares 9 mm. square representing 20 per cent smoke; chart No. 2 had lines 2.3 mm. thick and spaces 7.7 mm. square representing 40 per cent smoke; chart No. 3 had lines 3.7 mm. thick and spaces 6.3 mm. square representing 60 per cent smoke; chart No. 4 had lines 5.5 mm. thick and spaces 4.5 mm. square representing 80 per cent smoke; and chart No. 5 was all black representing 100 per cent smoke.
APPENDIX.

Containing smoke charts, drawings of boiler settings, and photographs of stacks.
SIDES ELEVATION.

Setting for Heine water-tube boiler. The capacity of this boiler is rated at 210 H.P.

One of these boilers was tested at the Mechanical Engineering Laboratory of the University of Illinois.
Smoke Chart No. 1.

Time in Hours

Mechanical Engineering Laboratory Testing Plant, in Urbana, Ill.


Duration of test: Three hours.

Boiler: One Heine water tube, 210 H.P.

Grate: Chain grate.

Firing: Automatic.

Draft: 1/4 inch.

Steam pressure: Average of 125 lb. per sq. in.

External air: Average temperature 40°F.

Stack: 3 1/2 feet in diameter and 45.5 feet high.

Coal: Electric Mine screenings.

Average smoke: 0.30 per cent.
SIDE ELEVATION.

Setting for a Stirling water tube boiler. The capacity of this boiler was rated at 260 H.P.

Three of these boilers were tested at the University of Illinois Power Plant placed in battery with the boilers on next page.
Settings for Babcock and Wilcox water tube boilers. The capacities of above boilers are 220 H.P.

These boilers were tested in the University of Illinois Power Plant, being in a battery with the Stirling's on the previous page. Another Babcock and Wilcox boiler was in the battery at the time of test. It being rated at 150 H.P.
SMOKE CHART No. 2

DENSITY OF SMOKE

No. 5
No. 4
No. 3
No. 2
No. 1
No SMOKE

9 10 11

TIME IN HOURS

UNIVERSITY of ILLINOIS POWER PLANT in URBANA, Ill.
December 20 1909, Weather: Moderate, bright, and windy.

Duration of test: Three hours.
Boilers: 5 Stirlinga, and 5 Babcock and Wilcox, total H.P. 1440.
Grate: Chain grates and Rooney stoker grates.
Firing: Automatic.
Draft: Natural, about 3/8 inch.
Steam pressure: 125 lb. per sq. in.
External air: Average temperature 41°F.
Coal: Electric Mine screenings.
Stack: 6 feet in diameter and 150 feet high.
Average smoke: 50 per cent.
Photograph of the stack of the battery of boilers at the University of Illinois Power Plant.
SIDE ELEVATION.

Setting for a Heine Safety boiler. This boiler was rated at 350 H.P.

Two of the above type were tested at the Champaign Electric Power Plant.
CHICAGO and URBANA ELECTRIC POWER PLANT, in CHICAGO, ILL.

December 29, 1903.

Weather: Moderate; bright; and windy.

Duration of test: Three hours.

Boilers: Two steel water tubes, 550 H.P. each.

Drum: Chain grate, each 8 feet by 9 feet.

Firing: Automatic.

Steam pressure: Average of 150 lbs. per sq. in.

Exterior size: Average temperature 40° F.

Stack: 7 feet in diameter and 150 feet high.

Average smoke: 20 per cent.

DENSITY OF SMOKE

SMOKE CHART No. 3
SIDE ELEVATION.

Setting for Stirling water tube boiler. The capacity of this boiler was rated at 300 H.P.

Two of these boilers were tested at the Champaign and Urbana Electric Power Plant.
SMOKE CHART No. 4

DENSITY OF SMOKE

- No. 5
- No. 4
- No. 3
- No. 2
- No. 1
- No SMOKE

TIME IN HOURS

CHAMPAIGN and URBANA ELECTRIC POWER PLANT, in CHAMPAIGN, I11.

December 29, 1908
Weather: Moderate, bright, and windy.

Duration of test: Three hours.
Boilers: Two Stirling water tubes, 300 H.P. each.
Grate: Rocker type, each 7 feet by 7 1/2 feet.
Firing: By hand.
Steam pressure: Average of 120 lb. per sq. in.
External air: Average temperature 40° F.
Stack: 6 feet in diameter and 125 feet high.
Coal: Electric Mine screenings.
Average smoke: 25.2 per cent.
Setting for a Babcock and Wilcox boiler. The above boiler was rated at 220 H.P.

Two of the 220 H.P. Babcock and Wilcox boilers and one 260 H.P. boiler were tested in battery at the Champaign Electric Power Plant.
SMOKE CHART No. 5

TIME IN HOURS

CHAMPAIGN and URBANA ELECTRIC POWER PLANT, in CHAMPAIGN, I1L.

December 29, 1908. Weather: Moderate, bright and windy.

Duration of test: Three hours.

Boilers: Three Babcock and Wilcox water tubes, 2 of 220 H.P. each and one 260 H.P.

Firing: By hand.

Grate: Straight flat type, 2 being 7 ft. by 7 ft., and one 6 ft. by 11 ft.


Steam pressure: Average of 120 lb. per sq. in.

External air: Average temperature 40° F.

Stack: 10 feet in diameter and 125 feet high.

Coal: Electric Mine screenings.

Average smoke: 59.2 per cent.
The above view shows the three stacks at the Champaign and Urbana Electric Power Plant. The stack to the right is connected to the two Heine boilers, the middle stack to the three Babcock and Wilcox boilers, and the left stack to the two Stirling boilers.
Settings of two Heine Safety boilers. Double drum type rated at 375 H.P. each.

One of the above boilers was tested at the Urbana Light, Heat, and Power Plant.
SMOKE CHART No. 6

URBANA LIGHT HEAT AND POWER PLANT, in URBANA, ILL.
March 9, 1909. Weather: Cool, windy, and clear.

Duration of test: Three hours.
Boilers: One Heine water tube, 175 H.P.
Grate: 7 ft. 10 in., by 9 ft. 8 in.
Firing: By hand.
Draft: About 1/8 inch.
Steam pressure: Average 54 lb. per sq. in.
External air: Average temperature 65° F.
Coal: Electric Mine mine run.
Stack: 120 feet high and 6 feet in diameter.
Average smoke: 1.32 per cent.
The above stack is the one at the Urbana Light, Heat, and Power Plant connected to the Heine boiler.
Setting for a Chandler and Taylor horizontal return tubular boiler. The capacity of this boiler is rated at 100 H.P.

Six of these boilers were tested at the New York Central Railroad's Power Plant, and two at the Champaign and Urbana Water Work's Power Plant.
Smoke Chart No. 7

Density of Smoke

No. 5
No. 4
No. 3
No. 2
No. 1
No Smoke

Time in Hours

2  3  4

CHAMPAIGN and URBANA WATER WORKS, in URBANA, ILL.
December 31, 1908
Weather: Cool, bright, and windy.

Duration of test: Three hours.

Boilers: Two Chandler and Taylor fire tubes, 100 H.P. each.
Grate: 5 feet by 4 1/2 feet, Herring-bone bars.
Firing: By hand.
Draft: About 3/16 inch.
Steam pressure: Average 80 lb. per sq. in.
External air: 23° F.
Coal: Harrisburg screenings.
Stack: 4 feet in diameter and 85 feet high.
Average smoke: 36 per cent.
SMOKE CHART No. 8

NEW YORK CENTRAL POWER PLANT, in Urbana, Ill.
March 6, 1909
Weather: Cold, cloudy, and windy.

Duration of test: Three hours.
Boilers: Five Chandler and Taylor fire tubes, 100 H.P. each.
Grate: 5 feet by 4 1/2 feet, Herringbone bars.
Firing: By hand.
Draft: About 1/4 inch.
Steam pressure: Average 60 lb. per sq. in.
External air: Average temperature 44° F.
Coal: Electric Mine screenings.
Stack: 6 feet in diameter and 100 feet high.
Average smoke: 51 per cent.
SMOKE CHART No. 9

NEW YORK CENTRAL POWER PLANT, in URBANA, ILL.


Duration of test: Three hours.

Boilers: Six Chandler and Taylor fire tubes, each 100 H.P.

Grate: 5 feet by 4 1/2 feet, Meering-tone bars.

Firing: By hand.

Draft: About 1/4 inch.

Steam pressure: Average 70 lb. per sq. in.

External air: Average temperature 54°F.

Coal: Electric Mine screenings.

Stack: 6 feet in diameter and 100 feet high.

Average smoke: 54 per cent.
The above stack is the one at the New York Central Power Plant, being connected to six Chandler and Taylor boilers.
Setting for a specially designed horizontal return tubular boiler. The capacity of this boiler is rated at 60 H.P.

One of the above boilers was tested at the University of Illinois Horticultural Heating Plant.
HORICULTURAL HEATING PLANT OF THE UNIV. OF ILL., in URBANA, I11.


Duration of test: Three hours.

Boilers: One specially designed fire tube, 60 H.P.
Grate: 4 feet by 4 1/2 feet, ordinary bars.
Firing: By hand.
Draft: About 1/4 inch.
Steam pressure: Average 57 lb. per sq. in.
External air: Average temperature 39° F.
Coal: Electric Mine screenings.
Stack: 4 feet square and 85 feet high.
Average smoke: 15 per cent.
The above stack is the one at the University of Illinois Hori-
cultural Power Plant, being connected to the specially designed 60
H.P. fire tube boiler.
Setting for a Murray boiler. This boiler was rated at 150 H.P. One of the above type was tested at the Twin City Ice and Cold Storage Power Plant.
TWIN CITY ICE AND COLD STORAGE POWER PLANT, in CHAMPAIGN, ILL.

Duration of test: Three hours.
Boilers: One Murray fire-tube, 150 H.P.
Grate: 5 feet by 7 feet, straight bars.
Firing: By hand.
Draft: About 1/8 inch.
Steam pressure: Average 85 lb. per sq. in.
External air: Average temperature, 45° F.
Coal: Pana Mine screenings.
Stack: 6 feet in diameter and 85 feet high.
Average smoke: 22.2 per cent.
The above stack is the one at the Twin City Ice and Cold Storage Power Plant, being connected to one Murray boiler.