tive as showing the possible degree of sound insulation that may be expected from partitions of this type. The particular material employed is clearly unimportant. Furthermore, one notes that equal increments of weight do not yield equal increments in the logarithm of the reduction, as is the case with quilt-like materials. Extrapolating the curve, it appears that for a logarithmic reduction of four a masonry wall weighing 50 lbs. per sq. ft. would be required, a figure which for cost and structural loading would be excessive in ordinary practice.

The investigation is now being extended to distinctly different types of construction.

# Furfural from Corncobs<sup>1</sup> I-Factors Influencing the Furfural Yield in the Steam-Digestion Process

#### By F. B. LaForge

#### BUREAU OF CHEMISTRY, WASHINGTON, D. C.

The reactions involved in the production of furfural from corn-

cobs by the steam-digestion process occur in three stages. The

conversion of the pentosans into furfural does not take place quanti-

tatively; the yield depends upon the temperature, the time, and the

ratio of the amount of cobs to the amount of water employed. The

optimum conditions of operation were determined in order to apply

them to larger-scale investigations. These conditions are a temper-

ature of about 180° C., a reaction period of about 2 hrs., and a

ratio of cobs to water of not greater than 1:4.

Since the publication of the first preliminary article<sup>2</sup> on the production of furfural by the action of superheated water on corncobs, the work done by the Bureau of Chemistry on this subject has been extended until it has now reached the stage where the process is being

put into operation on a semicommercial scale at the Color Laboratory at Arlington, Va. Before this stage was reached, however, it was necessary to determine the optimum conditions of operation by small-scale laboratory experiments.

Because of the lack of exact knowledge of the chemical nature of the corncob, the reactions involved are still imperfectly understood. It is apparent, however, that they proceed in three stages, as follows:

(1) Under the influence of superheated water the pentosans are partially hydrolyzed and changed to a condition in which they pass into solution.

(2) Hydrolysis then follows and the soluble colloidal pentosans are transformed into the sugars, largely pentoses such as xylose.

(3) The pentoses are dehydrated, yielding furfural.

 $C_5H_{10}O_5 = C_5H_4O_2 + 3H_2O$ 

These stages overlap somewhat, so that some furfural is produced before complete solution of the pentosans has taken place. The conversion of pentoses into furfural does not take place quantitatively. In fact, there is a very great loss before or after the last stage of the process is complete, so that only a portion of the furfural, as indicated by the usual analytical method, is actually obtained. The maximum amount seems to be about 10 per cent, or 50 per cent of the theoretically possible yield.

The yield of furfural is dependent upon the conditions of operation in which three factors are involved—the temperature, the duration of the reaction, and the ratio of the amount of cobs employed to the quantity of water present.

For the laboratory experiments a gas-heated autoclave, provided with thermometer and outlet tube and connected with a large glass condenser, was used.<sup>2</sup> The distillate was measured and the furfural was determined by precipitating an aliquot portion in 400 cc. of 12 per cent hydrochloric acid by phloroglucin.<sup>3</sup> The results obtained were about 10 per cent too high, because of the presence in the distillate of aldehydes other than furfural, fatty bodies, and other substances that give precipitates with phloroglucin. How-

<sup>1</sup> Received November 18, 1922.

<sup>2</sup> This Journal, **13** (1921), 1024.

<sup>3</sup> Assoc. Official Agr. Chem. Methods, 1920, p. 96,

ever, since these results are used only for comparison and are those commonly given in reporting determinations of furfural and pentosans, no correction has been made.

The cobs employed were air-dried and contained from 8 to 10 per cent of moisture. Their theo-

retical furfural content (determined by the standard 12 per cent hydrochloric acid digestion method) was about 20 per cent, based on the air-dried weight. All furfural-yield values in this paper are based upon the air-dried weight, because that basis is the only one of importance in commercial work.

### DETERMINATION OF OPTIMUM TEMPERATURE

In the experiments to determine the optimum temperature, conditions were chosen whereby practically all the furfural formed would be obtained as a distillate. In all cases 600 g. of cobs were heated with 5000 cc. of water for 45 min., after which the outlet valve was opened and the vapors were allowed to pass through the condenser at such a rate as to permit about 3000 cc. of distillate to be collected in 2 hrs. There was a variation of from 3 to 4 min. in this time, owing to the difficulty of regulating the rate of blow-off. These relations were chosen arbitrarily.

#### TABLE I-VARIATION IN FURFURAL VIELD WITH TEMPERATURE

|     |                            | Time for<br>Collection    |                        | Furfural<br>Concentra-  | Vield on Air-         |
|-----|----------------------------|---------------------------|------------------------|-------------------------|-----------------------|
|     | Temperature                | of 3000 Cc.<br>Distillate | Total Vol-<br>ume Dis- | tion in Dis-<br>tillate | Dry Weight<br>of Cobs |
| No. | ° C.                       | Min.                      | tilled, Cc.            | % by Volume             | ~ %                   |
| 1   | 155 to 157                 | 119                       | 3325                   | 0.30                    | 1.5                   |
| 2   | 166 to 167                 | 122                       | 3350                   | 1.00                    | 5.6                   |
| 3   | 168 to 170                 | 108                       | 3400                   | 1.10                    | 6.2                   |
| 5   | 170  to  172<br>172 to 175 | 118                       | 3400                   | 1.24                    | . 8.6                 |
| 6   | 175 to 177                 | 117                       | 3400                   | 1.71                    | 9.7                   |
| 7   | 180 to 182                 | 117                       | 3440                   | 1.75                    | 10.0                  |
| 8   | 185 to 187                 | 112                       | 3440                   | 1 68                    | 07                    |

The temperature was held constant to within 2 degrees by regulating the source of heat in each case. After 3000 cc. had been collected the flames were removed and the rate of blow-off was increased. The amount of distillate obtained after the heating had been discontinued was about 300 to 400 cc., in addition to the 3000 cc. collected during the heating period, making a total of from 3300 to 3400 cc. The whole time involved, not including that necessary to reach the temperature in question, was about  $2^{3}/_{4}$  hrs. The distillate was well mixed and the furfural was determined in small, duplicate samples by precipitation with phloroglucin in hydrochloric acid. The results of eight experiments are given in Table I, and are shown graphically in Fig. 1. The yield reached its maximum of 10 per cent at about  $180^{\circ}$  C. Very little furfural was produced at temperatures under  $155^{\circ}$  C., but the amount increased rapidly between  $156^{\circ}$  and  $176^{\circ}$  C. Above this point it remained almost constant up



FIG. 1—TEMPERATURE-YIELD CURVE (TIME=165 MIN. 600 G. COBS TO 5000 Cc. WATER)

to 186° C. It was not convenient to go higher in the temperature scale, as leaks in the apparatus appeared at 190° C. A temperature of approximately 180° C., corresponding to about 135-lbs. gage pressure, seemed preferable.

#### DETERMINATION OF OPTIMUM TIME

In the series of experiments here described, a temperature of  $180^{\circ}$  to  $182^{\circ}$  C. was maintained throughout the reaction period, and 1 part of cobs to 4 parts of water (1000 g. of cobs and 4000 cc. of water) were used. This ratio had been selected as the most suitable in the former work on the preparation of corncob adhesive.<sup>4</sup>

In the course of the process, the cobs absorb about twice their weight of water and an excess of liquid to conduct the heat and assure an even reaction must be present. By employing about 4 parts of water to 1 part of cobs the solid material is just covered with liquid during the reaction period.

In this series of eleven experiments the time was varied from 0 min. in No. 1 to 140 min. in No. 11, exclusive of the time necessary to reach the required temperature, which was from 20 to 25 min. The pressure was not noted as the autoclave used was not provided with a gage. (It must have been higher than the corresponding vapor pressure of water at the same temperatures, because of the formation of gases during the reaction. When an effort was made to work under the same conditions of temperature, using an internally heated steam digester, it was found necessary to maintain a slow blow-off throughout the process in order

• Chem. Age (N. Y.), 28 (1920), 332.

to avoid loss of heating efficiency due to this gas formation. A slightly higher yield is obtained, in small-scale work, by maintaining this slow blow-off. In the time-factor experiments the apparatus was kept closed until the time was up, after which the flames were removed and the pressure was relieved by blowing off the vapors through the condenser.)

The data in these experiments are given in Table II. The most important factor for practical purposes is the total amount of free furfural obtained for a given heating period. This amount, indicated by the figures in the column headed "Total Free Furfural," increases rapidly with the increase in time. The total quantity of free furfural is divided between the distillate and the liquid remaining in the autoclave. Up to a heating period of about 70 min., about twothirds are in the distillate and one-third in the liquid. Beyond this point the proportion which appears in the distillate is higher, reaching about five-sevenths in the distillate in No. 10 and No. 11, with heating periods of 120 and 140 min. Preceding the "Total Furfural" column is one headed "Potential Furfural in Liquid," or the furfural which may be theoretically obtained by the hydrochloric acid method from undecomposed pentosans, pentoses, or other compounds present in solution. Only a part of this potential furfural may be realized as actual furfural by further heating with water. The total furfural (next to last column) is the sum of the total free furfural and the potential furfural in the liquid in the autoclave. The amount of total furfural decreases as the time of reaction increases because of the loss of some of the potential furfural during the conversion of



1000 G. COBS TO 4000 G. WATER

the pentosans to furfural. Some potential furfural remains unconverted, even after the 140-min. heating period. The results are shown graphically in Fig. 2. The optimum heating period is about 120 min.

The quantity of furfural in solution in No. 3 (116.4 g.) is about 57 per cent of the total furfural present in the cobs. At this stage, while some conversion into free furfural has

TABLE II—EFFECT OF TIME OF HEATING ON THE FORMATION OF FURFURAL (1000 g. cobs, 4000 cc. water heated at 180° to 182° C.)

|  |  |   | (1000 g.  | . cobs, 400                 | JU cc. water he   | ated at 180° t  | to 182° C.)   |  |   |   |
|--|--|---|---|-----------------------------|---|---|---|--|---|---|
| No.  | Time<br>Min.                                       | Furfural<br>Concentrationa<br>Per cent  | Free<br>Furfural in<br>Distillate<br>G.   | ° Brix                      | LIQUID<br>Total<br>Furfural<br>in Liquid, A<br>G.   | IN AUTOCLAVI<br>Free<br>Furfural<br>in Liquid, B<br>G.  | Potential<br>Furfural<br>in Liquid, A-B<br>G.                                 | Total<br>Free<br>Furfural<br>G.                  | Total<br>Furfural<br>G.   | Vield of<br>Free<br>Furfural<br>%                           |
| 1<br>2<br>3<br>4<br>5<br>6<br>7<br>8<br>9<br>0 | 0<br>15<br>30<br>40<br>50<br>60<br>70<br>85<br>100 | $\begin{array}{c} 0.13 \\ 0.64 \\ 1.65 \\ 2.32 \\ 2.94 \\ 4.06 \\ 4.34 \\ 5.16 \\ 5.21 \\ 5.26 \end{array}$ | $\begin{array}{c} 0.98 \\ 4.85 \\ 12.16 \\ 16.68 \\ 22.65 \\ 81.50 \\ 34.72 \\ 44.10 \\ 46.90 \\ 49.88 \end{array}$ | .132753845<br>66 <b>655</b> | $\begin{array}{c} 24.48\\ 101.20\\ 104.20\\ 98.00\\ 82.80\\ 64.67\\ 59.92\\ 40.40\\ 40.75\\ 25.55\\ 82.55\\ $ | $\begin{array}{r} 0.214\\ 2.65\\ 7.18\\ 10.68\\ 11.30\\ 15.34\\ 17.94\\ 19.42\\ 19.96\\ 19.96\end{array}$ | 24.27<br>98.55<br>97.08<br>82.32<br>71.50<br>49.50<br>41.98<br>29.98<br>20.79 | 1.197.5019.2827.3633.9546.8452.6668.5266.8669.82 | $\begin{array}{c} 25.46\\ 106.05\\ 116.36\\ 109.68\\ 105.45\\ 96.17\\ 94.64\\ 93.50\\ 87.65\\ 87.65\\ 87.65\end{array}$ | 0.1<br>0.8<br>1.9<br>2.7<br>3.4<br>4.7<br>5.3<br>6.4<br>5.7 |
| iĭ   | <b>1</b> 40  | 5.53  | 51.64   | 4.2                         | 30.63   | 20.02   | 10.61   | 71.66  | 82.09   | 7.1   |

• Calculated from Kroeber's tables.

taken place, most of the dissolved pentosans, etc., have not been very much decomposed.

For approximately 50 min. simultaneous solution of furfural-giving substances and their decomposition to furfural is taking place. After heating for 50 min. there is a gradual decrease in the total furfural, owing to the progressive destruction of pentosans or furfural-yielding substances, or of furfural itself.

A certain amount of furfural-giving substances also remains in the solid residue. A consideration of the furfural content of the residues at various stages (Table III) shows that after about 70 min. practically no more furfural-yielding substances are dissolved and that the portion remaining is very resistant to the action of superheated water.

| TABLE | III– | -POTENTIAL | FURFURAL | IN | RESIDUES | FROM | Time | EXPERIMENTS |
|-------|------|------------|----------|----|----------|------|------|-------------|
|       |      |            |          |    |          |      | -    |             |

|       |                  |                    | Potential Furiura |
|-------|------------------|--------------------|-------------------|
|       | Amount of Washed | Potential Furfural | in Residue from   |
|       | Dry Residue      | in Residue         | 1000 G. Cob       |
| No.   | G.               | %                  | G.                |
| 1     | 587              | 13.38              | 78.49             |
| 2     | 610              | 9,26               | 55.42             |
| 4     | 590              | 4.21               | 24.85             |
| 6     | 586              | 3.25               | 19.05             |
| 9     | 602              | 2.19               | 13.21             |
| $9^a$ | 602              | 1.91               | 11.87             |
|       |                  |                    |                   |

<sup>a</sup> The residue from No. 9 heated for 2 hrs. with 5000 cc. water.

The maximum yield of furfural under the conditions employed seems to be about 7 per cent, and is reached after about 2 hrs., exclusive of the time required to reach 180° C. (20 to 25 min.). Further heating adds very little to the yield; moreover, at this point a new phenomenon begins to manifest itself to a marked degree. Tarry material is deposited in such quantities as would make serious trouble in largescale operations. It is probable that this tar results largely from dissolved substances other than pentosans which undergo deep-seated decomposition with prolonged heating.

The following experiment will illustrate this phenomenon:

A quantity of liquid obtained under the conditions of No. 10, Table II, was concentrated to remove the free furfural. The volume of concentrated liquid was 4750 cc. Five cubic centimeters gave 0.0995 g. of phloroglucin, corresponding to 51.6 g. of furfural in 4750 cc. The liquid was then heated in the auto-clave for 45 min. at 180° to 182° C., after which a slow blow-off was maintained for 45 min. more with the temperature still at 180° to 182° C. After this time the flame was removed and the blow-off was completed. The volume of distillate collected was 1850 cc. Ten cubic centimeters of this distillate gave (a) 0.0625g. and (b) 0.0650 g. of phloroglucin precipitate, corresponding to only 6.58 g. of furfural in the total distillate. Only a trace of furfural was found in the liquid remaining in the autoclave, but about 500 g. of tar had been deposited on the bottom and sides. If it were not for this complication the most economical procedure would be to discontinue the heating process after

from 70 to 80 min. and use the liquid containing the furfural and dissolved pentosans for a subsequent operation. Under the circumstances, however, a cooking period of about 2 hrs. is indicated.

## EFFECT OF VARYING RATIO OF AMOUNT OF COBS TO AMOUNT OF WATER

A slightly increased yield of furfural may be obtained by employing a proportion of water larger than 4:1. In a case where 550 g. of cobs were heated with 4500 cc. of water (1 part of cobs to 8 parts of water), the yield was 7.5 per cent for a 140-min. period and also for a 160-min. period (Table IV).

In one experiment 312 g. of cobs were employed with 5000 cc. of water (1 part of cobs to 16 parts of water), with a yield of 8.28 per cent.

Both of these ratios are disadvantageous, as the increased cost of heating the large volume of water and the distillation of the weak solution of furfural would probably more than offset the slightly increased yields (Fig. 3).



TIME = 160 Min.)

The highest yield of 10 per cent was obtained in No. 7 of the series for the determination of the optimum temperature (Table I). In this experiment the ratio of cobs to water employed was 1:8.3, and a continuous blow-off at the rate of about 25 cc. per min. was maintained for about 2 hrs. after the contents of the autoclave had been heated closed for 45 min.

It was assumed that the large yield in this case was due as much to the fact that a continuous blow-off was maintained throughout the period during which both the formation and the destruction of furfural was taking place at the most

| TABLE IV—EFFECT | OF       | VARIATION OF | RATIO | 0F | COBS TO | WATER | ON THE | VIELD OF FU | RFURAL |
|-----------------|----------|--------------|-------|----|---------|-------|--------|-------------|--------|
|                 | <b>T</b> |              | -     |    |         |       |        |             |        |

| No. | Time<br>Min. | Ratio of<br>Cobs<br>to Water | Furfural<br>Concen-<br>tration<br>% | Free Furfural<br>in<br>Distillate<br>G. | ° Brix | Autoclave<br>Free<br>Furfural<br>in Liquid<br>G. | Potential<br>Furfural<br>in Liquid<br>G. | Total<br>Free<br>Furfural<br>G. | Total<br>Furfural<br>G. | Yield of<br>Free<br>Furfural<br>% |
|-----|--------------|------------------------------|-------------------------------------|---|--------|--|--|---------------------------------|-------------------------|-----------------------------------|
| 1   | 160          | 1:2.5                        | 5.58                                | 31.25                                   | 4.8    | 12.56  | 1,68                                     | 43.81                           | 45.5                    | 4.4                               |
| 2   | 140a         | 1:4                          | 5.53                                | 51.46                                   | 4.2    | 20.02  | 10.61                                    | 71.48                           | 82.09                   | 7.1                               |
| 36  | 160          | 1:8                          | 3.12                                | 29.18<br>(58.00)¢                       | 2.5    | 12.19  | 5.32                                     | 41.37                           | 46.69<br>(84.58)¢       | 7.5                               |
| 4   | 140          | 1:8                          | 3.27                                | 29.80                                   | 2.6    | 11.89  | 9.88                                     | 41.67                           | 51.55                   | 7.5                               |
| 5   | 160          | 1:16                         | 1,81                                | 18,47<br>(59,20)¢                       | 1.5    | 7.37   | 0.10                                     | 25,81                           | 25,90<br>(83.00)¢       | 8.3                               |

a These results were taken from Table II.
b Inasmuch as the figures in Nos. 3 and 4 of this table show no appreciable difference, it may be assumed that there would be none in the case of No.
4 if the heating period had been 20 min. longer.
e Values calculated to 1000 g. basis. Weight of cobs: Nos. 1 and 2, 1000 g.; Nos. 3 and 4, 550 g.; No. 5, 312 g.

| CABLE V-EXPERIMENTS TO | DETERMINE | CAUSE OF | F HIGH | YIELD I | N NO. | 7 OF | TABLE | I |
|------------------------|-----------|----------|--------|---------|-------|------|-------|---|
|------------------------|-----------|----------|--------|---------|-------|------|-------|---|

|              |         | TURLE    | ; V EXPERI | WENTS TO 1 | DETERMINE CAU                   | JSE OF HIGH           | YIELD IN NO. / OF                 | IABLE I          |               |       |
|--------------|---------|----------|------------|------------|---------------------------------|-----------------------|-----------------------------------|------------------|---------------|-------|
|              | Weight  | Weight   | Ratio of   | Rate of    | Concentration<br>of Furfural in | Weight of<br>Furfural | Concentration<br>of Free Furfural | Free<br>Furfural | Total         | •     |
| <b>N</b> 7.0 | of Cobs | of Water | Cobs to    | Blow-off   | Distillate                      | in Distillate         | in Liquid                         | in Liquid        | Free Furfural | Yield |
| NO.          | G.      | G,       | Water      | Cc./Min.   | %                               | G.                    | %                                 | G                | G.            | %     |
| 1            | 800     | 4000     | 1:5        | <b>26</b>  | 2.41                            | 62.10                 | 0,26                              | 3.71             | 65.81         | 8.2   |
| 2            | 800     | 4800     | 1:6        | 19         | 2.61                            | 60.20                 | 0.31                              | 7.96             | 68.16         | 8.5   |
| 3            | 800     | 4800     | 1:6        | 27         | 2.29                            | 65.40                 | 0.27                              | 5.44             | 70.84         | 8.9   |

rapid rate (Table II), as to the large proportion of water employed. This assumption was verified by three experiments (Table V).

In each experiment the heating was done with the outlet valve closed for 30 min., after which a continuous blow-off was maintained for 90 min. In each case the temperature was held within 1 degree of 180° C. for the 2 hrs., after which the flames were removed and the blow-off was completed. The yields obtained are much higher than those in any of the experiments where the autoclave was kept closed throughout the heating period, except No. 5 in Table IV. Moreover, the ratios of cobs to water employed (1:5 and 1:6) are within the range of practical application. A ratio materially higher than 1:4 is unsatisfactory, as it results in a much lower yield, which is evident from the very low yield in the case where the ratio was 1:2.5 (No. 1, Table IV).

# Chemistry of Combustion in Coal-Fired Furnaces

# By W. K. Lewis

MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MASS.

**B**<sup>Y</sup> analyzing the gases at varying points in a coke-fired fuel bed, curves of the type shown in the figure may be obtained. Where petroleum

The combustion reactions in the fuel bed of coal-fired furnaces have been studied by the Bureau of Mines,<sup>2</sup> and the following discussion is a resume of those results, together with an interpretation of their significance in the light of certain other work in this field.

coke or some sort low in ash is used, the curves will start along BC. The individual points will vary considerably from the curves, but this is due to the serious difficulties of sampling the gases. If smooth curves are drawn among the points, the following conclusions may be drawn:

The CO<sub>2</sub>, Curve 1, rises rapidly at the start, and its initial slope varies but little with the air velocity. The oxygen, Curve 2, falls sharply at the start practically independently of air velocity, however great, and is of the logarithmic type—i. e., the rate of disappearance of oxygen is proportional to the amount present. Furthermore, in the initial stages the CO<sub>2</sub> curve is the invert of the oxygen curve. The CO, Curve 3, starts out with practically no slope, rises more and more rapidly, passes through a point of inflection, and fades away to an asymptotic value. Analysis of the data will show that the slope of the CO<sub>2</sub> curve at the same point, and its point of inflection is, therefore, directly below the maximum of Curve 1. Finally, temperature observations prove that the temperature variation through the fuel bed is not great in any given case, and while temperature increases with increased air velocity this increase is relatively small for fuel beds of reasonable thickness. The curves as drawn are diagrammatic and not to scale.

It seems impossible to explain these facts on other than the following assumptions:

The primary reaction of carbon with air is  $C + O_2 = CO_2$ . The rate of this reaction is limited only by the rate of diffusion of oxygen through the stationary gas film around each particle of carbon, the rate of chemical combination of the oxygen with the carbon being indefinitely great in comparison with this diffusion. Were this not the case, the initial slopes of Curves 1 and 2 would be small at high velocities and large at low velocities, since the change in temperature of the bed with velocity is not sufficient to account for the increased reaction rate. CO is formed, not by direct combination of oxygen with carbon, but only by reduction of CO<sub>2</sub>, as shown by the fact that its rate of formation is proportional to the CO<sub>2</sub> present.

Since Curve 3 is much flatter than Curves 1 and 2, it follows that the limiting factor in rate of CO formation is not diffusion but the specific rate of the chemical reaction. It therefore follows that at high air velocity the CO curve will be depressed (3a) and the last part of the CO<sub>2</sub> curve raised

<sup>1</sup> Presented before the Section of Gas and Fuel Chemistry at the 64th Meeting of the American Chemical Society, Pittsburgh, Pa., September 4 to 8, 1922.

\* Kreisinger, Ovitz, and Augustine, Bur. Mines, Tech. Paper 137.

(1*a*). Were the fuel bed indefinitely thick, the  $CO_2$ and CO curves would finally reach equilibrium, as indicated by the asymptotes.

Where the coke is high in ash there exists a zone of ashes, containing but little unburned combustible below the carbon itself, in which the air is largely preheated. In this case the actual curves observed are the dotted ones starting on the line OA. A striking fact, not always appreciated, is that the rate of combustion of carbon on a grate is limited solely by the amount of air forced through the grate bars, and this in turn is limited only by the air velocity that will blow the fuel off the grate. Furthermore, at a point somewhere between 3 and 6 in. practically all the oxygen in the air has been consumed, and this is true whatever the air velocity.

# EXPLANATION OF RESULTS

The explanation of these facts is that the rate of diffusion of oxygen through the gas film around the particles of incandescent carbon is proportional to the gas velocity, since increased velocity thins down the film. Hence, at double the air velocity twice the oxygen diffuses in and reacts, and twice the  $CO_2$  is formed, but since there is twice the air to dilute it, the percentage composition of the gases remains unchanged. Therefore, the fuel burned per square foot of grate area per hour is proportional to the air velocity through the bed.

Since the combustion rate is proportional to air velocity, yet with formation of the same proportion of reaction products within the fuel bed, it follows that the rate of heat evolution in the bed is proportional to combustion rate; thereby, a fraction of this energy leaves the fuel bed as sensible heat in the gases; the rest is emitted by radiation, provided there is a heat-absorbing body "in sight" of the bed to take it up e. g., the steam boiler. Since radiation increases as the fourth power of the absolute temperature, the temperature of the bed will rise only slightly to dissipate the additional heat corresponding to a great increase in combustion rate. This is why the temperature of the bed changes so little with air velocity.

Low-grade fuels may have only enough heat to raise their own products of combustion to a reasonable combustion temperature (one at which the combustion reactions progress at a reasonable rate—i. e., at least 900° C.). In such case the fuel bed must be protected from radiation, since otherwise its cooling effect will put out the fire. This can be done by keeping the bed "out of sight" of any heat-absorbing body, as in Dutch oven construction. Obviously, insulated walls, once they are brought up to furnace temperature, reflect back most of the radiation hitting them and do not cool the bed.