THERMAL CONDUCTIVITY OF STORED OATS WITH DIFFERENT MOISTURE CONTENT

A. L. BAKKE AND H. STILES

(WITH ONE FIGURE)

Much has been written about the heating that takes place in damp or moist grain, but apparently no measurements have been made of thermal conductivity. In a previous publication by BAKKE and NOECKER (1), it was shown that in oats in storage there is considerable variation in oxygen consumption even with oats of low moisture content. There is a general tendency for respiration to increase with the moisture content, although there is considerable variation. In certain localized areas where the grain is not sufficiently dry for storage, spoilage takes place owing to rapid oxidation of the grain. In these areas or "heat pockets" the heat generated has been largely retained owing to the fact that the grain is a poor conductor of heat. The work reported in this paper is an attempt to measure the thermal conductivity of oats stored at different moisture contents.

Stiles's method of measuring thermal conductivity

The thermal conductivity of oats was measured by the apparatus developed by STILES (2, 3) in obtaining the thermal conductivity of heat-insulating materials. Briefly the method is to place the material to be tested between the ice vessel and the hot water tank, being sure that the upper temperature is constant at 32° F. Heat passage through the material to be tested is then determined by timing the water-level drop in the measuring tube which depends on the rate of melting of the ice in the cylinders.

The tank is a copper cylinder 14 1/2 inches high and 16 inches in diameter, holding approximately 100 pounds of water. The water is heated by a Bunsen burner. On account of the large heat capacity of the water, it has been found possible after a little practice to keep the temperature of the water constant to within one-half degree for hours. The water is kept in circulation by a stirrer which consists of two sets of vanes mounted on a short shaft placed in a brass cylinder 3 inches in diameter. The pulley at the top of the shaft is belted to a one-eighth horsepower motor and the water circulated through holes near the top and near the bottom of the cylinder. The cylindrical sides of the boiler and ice container are of gal-

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2 Gratitude is expressed for the assistance given by Dr. I. E. MELHUS in the preparation of this manuscript.

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vanized iron lagged with asbestos. The bottom of each container and the
top of the boiler are brass plates \( \frac{3}{8} \) of an inch in thickness; a hole near the
top provides for the insertion of the thermometer.

By means of a cylinder of bakelite co-axially placed, the ice container
is divided into two compartments, the outer one, which is about 3 inches
wide, serving as a guard ring. Bakelite is used on account of its low
thermal conductivity, lessening the possibility of transfer of heat into the
cylinder. The cylinder is mounted on a short thin brass ring which is
soldered to the bottom of the container. The top of the cylinder is
machined out for a short distance down on the inside so as to contain a
brass sleeve, which is threaded to mesh with the threads of the edge of the
brass disk serving as a lid for the cylinder. The lid is slightly concave
on the lower surface and has a hole in its center into which may be fitted
a one-holed rubber stopper. Into this stopper is passed a glass tube the
upper part of which has two bulbs. Two fine index marks are etched on
the tube, one above and the other below the lower bulb. Further details
concerning the apparatus may be secured by referring to the original
articles.

In series 2 and 3 the oats were not weighed. Whatever oats were
needed to fill the space between the two layers were used. In series 1 and 2
the thickness of the layer was 0.94 cm. In part of series 3 the layer was
1.48 cm. in thickness.

The general procedure has been adequately given by the junior writer
and need not be repeated here. In order to make the calculations clear,
however, it may be well to define some of the terms employed.

In making measurements in c.g.s. units, the specific gravity of ice is
taken as 0.9164. For every 0.9164 gm. ice melted in the cylinder there is a
volume shrinkage of approximately 0.0836 cc., and the water in the tube
would decrease by that amount.

The volume of ice water contained by the lower bulb between the two
marks of one of the tubes used was determined and for one of the tubes
was found to be 3.87 cc. Therefore \((3.87 \div 0.0836) \times 0.9164\) equals the
number of grams of ice melted in the cylinder during the test. With the
heat of fusion of ice taken as 79.8 calories per gram, the total quantity of
heat, \(Q\), passing into the cylinder during the test was \((3.87 \div 0.0836)\)
\times 0.9164 \times 79.8 = 3385 \) calories. This figure is taken as a constant for all
tests made with a particular tube. The thermal conductivity, \(k\), of the
grain was then readily calculated from the equation

\[
k = \frac{Qd}{AT(t_1 - t_2)}
\]

where:
d = thickness of the specimen
A = area under the cylinder
T = time in seconds

t₁ and t₂ = temperatures of the lower and upper surfaces of the specimen

In these studies the temperature of the boiler was maintained at or near 40° C. The moisture content was determined in the usual manner by taking a sample of the oats at the time they were tested. They were subsequently dried in an electric oven held at 100° C. until there was no further loss in weight. In order to bring the oats up to the approximate moisture content desired, a measured amount of water was added to a weighed amount of oats and flasks were shaken at intervals for three days. At the end of this time the moisture was evenly distributed. All determinations were run in duplicate and the average taken.

The oats were of Iowar variety and were grown on the Agronomy Farm the previous year.

A specific example of the calculations used is as follows:

Time—March 4, 1932

200 gm. oats + 20 gm. water
Percentage moisture = 16.48

Oats placed in between the boiler and ice compartment 11:00 A.M.
Q = quantity of heat passing through; A = area; T = time; d = thickness; k = specific thermal conductivity.

\[ Q = \frac{kA \cdot (time) \cdot (t_1 - t_2)}{d} \]

\[ k = \frac{Qd}{A \cdot time \cdot (t_1 - t_2)} \]

\[ Q = \frac{3.87}{0.0836} \times 0.9164 \times 79.8 = 3385 \text{ calories} \]

d = 0.94 cm.

\[ A = 122.71 \text{ sq. cm.} \]

Time = 3639 seconds

Temp. diff. = 40° C.

\[ \therefore k = \frac{3385 \times 0.94}{122.71 \times 3639 \times 40} = 0.0001781 \]

Volume of tube no. 2 = 3.87 cc.

\[ Q = \frac{3.87}{0.0836} \times 0.9164 \times 79.8 = 3385 \text{ calories} \]
I. Time

<table>
<thead>
<tr>
<th>Time</th>
<th>Tube</th>
<th>Inserted</th>
<th>Temperature of boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:30</td>
<td>3.87</td>
<td>cc.</td>
<td>40°C</td>
</tr>
<tr>
<td>1:45</td>
<td></td>
<td></td>
<td>40°C</td>
</tr>
<tr>
<td>2:17</td>
<td>37</td>
<td>(water at top mark of tube)</td>
<td>40°C</td>
</tr>
<tr>
<td>2:40</td>
<td></td>
<td></td>
<td>40°C</td>
</tr>
<tr>
<td>3:00</td>
<td></td>
<td></td>
<td>40°C</td>
</tr>
<tr>
<td>3:18</td>
<td>42</td>
<td>(water column at lower mark of tube)</td>
<td>40°C</td>
</tr>
</tbody>
</table>

Time, 1 − 1 − 05 = 3665 seconds

Temperature of boiler

II. Time

<table>
<thead>
<tr>
<th>Time</th>
<th>Tube</th>
<th>Inserted</th>
<th>Temperature of boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:29</td>
<td>25</td>
<td>(water column at top mark of tube at start)</td>
<td>40°C</td>
</tr>
<tr>
<td>3:45</td>
<td></td>
<td></td>
<td>40°C</td>
</tr>
<tr>
<td>4:00</td>
<td></td>
<td></td>
<td>40°C</td>
</tr>
<tr>
<td>4:15</td>
<td></td>
<td></td>
<td>40°C</td>
</tr>
<tr>
<td>4:29</td>
<td>38</td>
<td>(water column at lower mark)</td>
<td>40°C</td>
</tr>
</tbody>
</table>

Time, 1 − 0 − 13 = 3613 seconds. Average temp. 40°C

Average time 3639 seconds

Experimental data

Three series of experiments are reported in this paper: (1) run January 29 to April 15, 1932; (2) run October 8 to December 16, 1932; and (3) run January 6 to March 10, 1933. The first trial is reported in table I.

**TABLE I**

**THERMAL CONDUCTIVITY OF OATS OF DIFFERENT MOISTURE CONTENTS. SERIES 1, JANUARY 29 TO APRIL 15, 1932**

<table>
<thead>
<tr>
<th>Date</th>
<th>Moisture content</th>
<th>Thermal conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 29</td>
<td>9.88</td>
<td>0.0001527</td>
</tr>
<tr>
<td>February 12</td>
<td>10.51</td>
<td>0.0001650</td>
</tr>
<tr>
<td>February 19</td>
<td>11.87</td>
<td>0.0001668</td>
</tr>
<tr>
<td>February 26</td>
<td>12.34</td>
<td>0.0001747</td>
</tr>
<tr>
<td>March 4</td>
<td>16.48</td>
<td>0.0001830</td>
</tr>
<tr>
<td>March 11</td>
<td>25.23</td>
<td>0.0001895</td>
</tr>
<tr>
<td>March 18</td>
<td>27.66</td>
<td>0.0001910</td>
</tr>
<tr>
<td>March 25</td>
<td>30.32</td>
<td>0.0002014</td>
</tr>
<tr>
<td>April 1</td>
<td>34.35</td>
<td>0.0002149</td>
</tr>
<tr>
<td>April 8</td>
<td>36.82</td>
<td>0.0002168</td>
</tr>
<tr>
<td>April 15</td>
<td>38.38</td>
<td>0.0002220</td>
</tr>
</tbody>
</table>

The oats used in series 1 ranged from 9.88 to 38.38 per cent. moisture content. The thermal conductivity ranged from 0.0001527 to 0.000222. The graph (fig. 1) shows that in general the thermal conductivity increases with the moisture content.
In Table II and figure 1 it is found that in series 2 there is a general increased value in the thermal conductivity when the moisture content is raised. The range in moisture contents is between 9.54 and 32.49 percent and the thermal conductivities are found to be between 0.000153 and 0.0002455. The thermal conductivities of the air dried oats are practically...
the same in both cases, but the thermal conductivity of the oats with high moisture content is considerably higher than given in table I. In the first series there were 200 gm. of the oats in a layer 0.94 cm. thick; in series 2, the 0.94 cm. layer was filled with oats and leveled off regardless of the exact weight. This apparently produced a more uniformly packed layer. The correlation between moisture content and thermal conductivity became closer.

**TABLE III**

**THERMAL CONDUCTIVITY OF OATS OF DIFFERENT MOISTURE CONTENTS. SERIES 3, JANUARY 6 TO MARCH 10, 1933**

<table>
<thead>
<tr>
<th>Date</th>
<th>Moisture content</th>
<th>Thermal conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 17</td>
<td>9.877</td>
<td>0.0001671</td>
</tr>
<tr>
<td>March 3</td>
<td>12.365</td>
<td>0.0001767</td>
</tr>
<tr>
<td>January 6</td>
<td>13.202</td>
<td>0.0001776</td>
</tr>
<tr>
<td>February 24</td>
<td>13.50</td>
<td>0.0001701</td>
</tr>
<tr>
<td>February 3</td>
<td>14.37</td>
<td>0.0001811</td>
</tr>
<tr>
<td>January 20</td>
<td>15.451</td>
<td>0.0001840</td>
</tr>
<tr>
<td>January 20</td>
<td>16.324</td>
<td>0.0001893</td>
</tr>
<tr>
<td>February 10</td>
<td>17.094</td>
<td>0.0001935</td>
</tr>
<tr>
<td>March 10</td>
<td>18.073</td>
<td>0.0001948</td>
</tr>
<tr>
<td>February 10</td>
<td>19.873</td>
<td>0.0002000</td>
</tr>
<tr>
<td>February 17</td>
<td>20.254</td>
<td>0.0002060</td>
</tr>
<tr>
<td>February 24</td>
<td>25.862</td>
<td>0.0002134</td>
</tr>
<tr>
<td>March 3</td>
<td>29.640</td>
<td>0.0002388</td>
</tr>
<tr>
<td>March 10</td>
<td>31.786</td>
<td>0.0002393</td>
</tr>
</tbody>
</table>

In this series, table III and figure 1, the thermal conductivity of the air-dried oats (9.877 per cent.) was 0.0001671, a little higher than in the previous two series. With a moisture content of 31.786 per cent. the thermal conductivity had arisen to 0.0002393. The graph drawn from the lowest moisture content to the highest becomes a straight line.

**Discussion**

In the data submitted and represented graphically in figure 1, series 2 and 3, the thermal conductivity values increase with the moisture content. In table I, weighed amounts of oats (200 gm.) were used. The tempered grain, that is, that which had had water added, had to be tamped considerably in order to get the weighed amount between the boiler and the ice compartment. This no doubt accounts for the deviation in the moisture contents from 10.51 to 12.34 per cent. In the case of the higher moisture contents the oats did not experience as much increased compression as the oats with lower moisture contents.
In series 2 and 3 the graphs are practically straight, the points are not far removed. In this case the layer of oats was tamped as uniformly as possible but no effort was made to place in this space a known weight of oats.

In table III, series 3, and figure 1, the data bearing dates on and after February 10, 1933, were secured from those where the thickness of the layer of oats used was increased to 1.48 cm. instead of 0.94 cm. as before. Instead of using a tube as large as the one in the other cases the contents were cut to 2.479 cm. It took 350 gm. of air dried oats to fill the space. The thermal conductivity results secured here are in harmony with those secured where the layer of oats was thinner and where the contents of the tube were greater.

It is evident that the moisture increases the thermal conductivity considerably, but even so the rate of heat movement through either dry or damp oats is extremely slow. STILES determined the thermal conductivity of wallboard and found it to be approximately 0.0001150. This value is somewhat lower than that given for dry oats (0.000153). Even with this difference, dry oats makes a rather effective insulating material.

In BAKKE and NOECKER'S (1) previous publication on the relation of moisture to respiration and heating, it has been pointed out that "heat pockets" are often formed. These areas are often restricted and well defined and are formed through the rapid oxidation of the grain and associated micro-organisms and the low thermal conductivity of grain even when the moisture content is high. Any method which will dissipate the heat will naturally operate against the low thermal conductivity and produce conditions which will secure a more rapid dissipation of heat. This will make for better storage conditions.

Summary

The thermal conductivity of dry oats has a value of about 0.000153, and increases directly with the moisture content. At a moisture content of 9.88 per cent., the thermal conductivity is 0.000153 and at 38.32 per cent. moisture, 0.000222 in c.g.s. units.

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