INTRODUCTION

The practice of drying hay and grain with unheated or tempered air in Western Canada is limited. The reluctance to use a system that provides low cost drying is due to a number of reasons, not the least of which is the opinion that the climate of Western Canada is not suitable. Difficulties, especially if the season is late, cannot be overlooked. On the other hand Moysey and Wilde (1) concluded for the Saskatoon area that grain with unheated or tempered air in Western Canada is limited. The moisture content could have been nearly two batches of wheat at 18% moisture with as little as 3 cfm of unheated air per bushel where 1959 was considered a poor harvest year. In addition, the opinion ignores the significant effect of tempering the air by adding small amounts of heat.

One of the main difficulties experienced by the author in the promotion of drying with natural and tempered air was the inability to advise on the size of duct and fan system required which in turn is based on the quantity of air required. The common design figure is 3 cfm per bushel which, as noted above, was used by Moysey and Wilde. The figure, however, must vary with the following independent variables:

- the amount of moisture to be removed
- the rate of moisture removal
- the climate during the drying period
- the amount of heat added (if any).

This study was initiated in order to determine the relationship of these variables and provide a guide to air volumes required.

ANALYSIS OF WEATHER DATA

It is important to note that the required air volume is a weather dependent function and, therefore, different values could be expressed for different levels of probability. Instead, an average was determined which by definition, has a probability level of 0.5. The reason for making this simplification is the likelihood of the operator tempering the air under adverse conditions rather than over designing the system. In other words, a large fan and duct should not be considered in order to compensate for the occasional poor drying weather when it is easier to do so by adding some heat.

An examination of the dry bulb temperatures and relative humidities for the period of August through November suggested that the agricultural area of Alberta could be divided into four distinct, but arbitrary, climatic regions. These regions appeared to be represented by the Lethbridge, Calgary, Edmonton and Fairview weather stations. The cost of securing the required weather data from the Climatological Division, Department of Transport, however, precluded obtaining it for more than one station. In view of this, Edmonton was selected because it seemed to be a climatic average of the province in so far as agriculture is concerned.

Brooker and McQuigg (2) defined t–t_x when positive as an index of drying potential and, when negative, as an index of wetting potential where,

\[ t = \text{dry bulb temperature of air entering the grain or hay} \]
\[ t_x = \text{dry bulb temperature of air leaving the grain or hay} \]

and

\[ x = \frac{a + bt_w}{w} \]
\[ x' = \frac{a' + b't_w}{w'} \]

where

\[ a, a', b, b' = \text{constants which vary with the moisture content of the grain or hay} \]
\[ t_w = \text{wet bulb temperature of the air} \]

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\[ t_w = \text{wet bulb temperature of the air} \]

Natural Air

Indices were calculated for the Edmonton station using hourly values of t and t_w summarized for one week intervals from August 1 to November 27 for the period 1950-66. It was necessary to calculate the indices for each 1% moisture content (wet basis) as the constants a and b, and therefore, t_x change with the moisture content of the grain. The relationship of t_x and the moisture content may be noted from the psychrometric chart in figure 1. In the adiabatic process of drying, sensible heat is changed to latent heat with no change in the wet bulb temperature. Also in figure 1 the relationship between t–t_x and ΔX (the amount of water the air can take up) may be noted where:

\[ \Delta X = x' - x, \]
\[ x = \text{the humidity ratio of air entering grain at t and t_x, and} \]
\[ x' = \text{the humidity ratio of air leaving the grain at t_x and t_w}. \]

The amount of water to be removed by the air is:

\[ \Delta w = w - w' \]

where

\[ w = \text{weight of water held by one lb. of grain or hay initially, and} \]
\[ w' = \text{weight of water held by one lb. of grain or hay finally}. \]

It is more useful, however, to substitute M_w, the initial moisture content (wet basis) and M_w', the final, for w and w' or

\[ \Delta w = M_w - M_w' \left(1 - M_w'\right) \]
\[ 1 - M_w' \]

Dividing Δw by ΔX or

\[ \Delta w/\Delta X = \frac{(\text{lbs. water/lb. grain})}{(\text{lbs. water/lb. dry air})}, \]

\[ = \text{lb. dry air/lb. grain}. \]
TABLE I. TAX FOR SMALL GRAINS – EDMONTON.
(MINUTE-LBS. WATER/LB. DRY AIR FOR ONE WEEK INTERVALS)

<table>
<thead>
<tr>
<th>Date</th>
<th>Moisture Ranges (percent - wet basis, drying to 14%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22</td>
</tr>
<tr>
<td>Aug. 1 - 7</td>
<td>8.6</td>
</tr>
<tr>
<td>8 - 14</td>
<td>8.2</td>
</tr>
<tr>
<td>15 - 21</td>
<td>8.1</td>
</tr>
<tr>
<td>22 - 28</td>
<td>6.2</td>
</tr>
<tr>
<td>29 - 4</td>
<td>6.1</td>
</tr>
<tr>
<td>Sept 5 - 11</td>
<td>6.5</td>
</tr>
<tr>
<td>12 - 18</td>
<td>6.9</td>
</tr>
<tr>
<td>19 - 25</td>
<td>6.5</td>
</tr>
<tr>
<td>26 - 2</td>
<td>5.6</td>
</tr>
<tr>
<td>Oct. 3 - 9</td>
<td>5.4</td>
</tr>
<tr>
<td>10 - 16</td>
<td>6.2</td>
</tr>
<tr>
<td>17 - 23</td>
<td>4.8</td>
</tr>
<tr>
<td>24 - 30</td>
<td>3.7</td>
</tr>
<tr>
<td>31 - 6</td>
<td>2.7</td>
</tr>
<tr>
<td>Nov. 7 - 13</td>
<td>1.1</td>
</tr>
<tr>
<td>14 - 20</td>
<td>.94</td>
</tr>
<tr>
<td>21 - 27</td>
<td>.93</td>
</tr>
</tbody>
</table>

The air volume then is
\[ q = 13 W_w \Delta w / \Delta X \]
where
\[ q = \text{cu. ft./min. (cfm) of air} \]
\[ W_w = \text{weight of grain or hay (with moisture) - initial} \]
\[ T = \text{number of minutes of drying per batch period, and} \]
\[ 13 = \text{number of cu. ft. per 1 lb. of dry air} \]

Saturated Air

The difficulty in applying equation 2 is that \( \Delta X \) changes as drying proceeds. In addition, the system should be operating only when \( t - t_x \) is positive for maximum efficiency and, therefore, \( T \) changes as drying proceeds. In view of this, a table of TAX for small grains (see Table 1) is provided for the Edmonton station which is the average for the range of moisture contents noted. The table is based on a seven-day period, though other periods, either shorter or longer, can be easily calculated. In essence this, and the foregoing, assumes that the air leaves the grain at equilibrium with the wettest grain. In order for this to be a valid assumption, the air flow must be moderate and the on-off of the fan must be controlled so that ventilation occurs only when \( t - t_x \) is positive.

An example of the use of the table and equations 1 and 2 is as follows:

A. Drying wheat (60 lb./bus.) from 18% moisture content to 14% during the last week in September (1 week drying period) requires 10. cfm/bus. or,
\[ \Delta w = .18 - .14 = .04 \text{ lb./lb. grain;} \]
\[ q = 13 \times 60 \times .047/3.6 = 10. \text{ cfm/bus.} \]

B. As above, except last week of September and first week of October (2 week period) or,
\[ \Delta w = .18 - .133 = .047/3.6 + 4.7 = 4.4 \text{ cfm/bus.} \]

It can be noted from equation 2 that the air volume is inversely proportional to TAX. From Table 1, therefore, large air volumes are required late in the season when drying to a low moisture content. In fact, drying to a safe moisture content after the third week in October with natural air is virtually impossible. On the other hand, considerable moisture can be removed from very wet grain after this time without adding heat. Such economies of operation are available only if a high level of managerial skill is available.

The "lumpiness" of the data in Table 1 is due to:
- the limited summary period (15 years)
- the step type selection of the constants a and b (and therefore \( \Delta X \))
- the constants a and b change abruptly at 32°F.

Tempered Air

Tempering the inlet air by adding a small amount of heat affects the index \( t - t_x \) significantly. The great-
est wetting potential \( (t - t_x) \) is negative) for the Edmonton station was \( 4^\circ F \) which occurred on the week of Aug. 22-28 at 6:00 a.m. By increasing the dry bulb temperature \( (t) \) 10°, \( t - t_x \) became positive. That is, by increasing the inlet temperature 10°, drying could have taken place anytime day or night from Aug. 1 to November 27 and quite possibly the year around. It is interesting to note that the greatest wetting potential in November was only \( 2.2^\circ F \). The temperature rise to change \( t - t_x \) positive in this instance was only \( 5.5^\circ F \).

Tempering the air is accomplished most conveniently with a propane burner. In fact, there are a number of manufacturers offering fan-burner packages. If the source of power for the fan is an internal combustion engine, this could be the source of heat. The author, by suitable ducting, but excluding the exhaust, found that, when the power of engine was matched to the fan, a 5° temperature rise was typical. If the engine was larger than required, such as using a small tractor, a 10° temperature rise was possible. A British drier manufacturer advertises a temperature rise as much as 25° using no other source of heat but the engine used to drive the fan.

Tables of \( \Delta T \) for tempered air, or even hot air, could be developed and used with equation 2. For a large temperature rise the seasonal and daily variations of \( t \) and \( t_w \) become insignificant. It should be noted that the resulting values would be valid only if the air flow was of such magnitude that equilibrium of moisture occurred before the air left the grain.

**DRYING EXPERIMENTS**

A number of barley samples were dried to check the validity of the assumptions made and their effect on equation 2. The grain used had been harvested late in the Fall of 1968 at approximately 19% moisture content. This was subsequently dried to 13 or 14% in batches of 60-70 bushels. While drying, the air temperature at various levels in the grain (See Figure 2) as well as \( t \) and \( t_w \) of the air (uncontrolled) entering the grain, were recorded using thermocouples and a sequential recorder. The air tempera-

**Results**

Figure 4 illustrates the typical progression of the drying zone through the grain. It is interesting to note that the depth of the drying zone increased with time. It also can be seen that the drying front barely reached the surface when drying was terminated. The location of the front at termination is supported by Figure 3. This illustrates the typical linear regression in the grain bin were useful in locating the drying zone. The air flow in cu. ft. per min. and the loss (or gain) of water were recorded periodically. The latter was determined by weighing the bin and grain on a strain gauge type scale and was the basis for termination of the drying. In addition, the moisture content was determined by twenty random samples at the beginning and ending of drying as a check on the water loss determined above.
TABLE II. RESULTS OF DRYING BARLEY

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>$\Delta m$ (lbs/lb grain)</th>
<th>$t - t_w$ (°F)</th>
<th>$\Delta t$ (hours)</th>
<th>$Q'$ (est.) $(10^4)$</th>
<th>$Q$ (actual) $(10^4)$</th>
<th>$Q'/Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.072</td>
<td>9.5</td>
<td>65.1</td>
<td>3.1</td>
<td>1.3</td>
<td>.9</td>
</tr>
<tr>
<td>2</td>
<td>.075</td>
<td>9.0</td>
<td>95</td>
<td>3.4</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>.080</td>
<td>11.4</td>
<td>65.1</td>
<td>3.4</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>.083</td>
<td>11.6</td>
<td>51</td>
<td>2.9</td>
<td>1.0</td>
<td>.9</td>
</tr>
<tr>
<td>5</td>
<td>.071</td>
<td>10.2</td>
<td>83</td>
<td>3.3</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>6</td>
<td>.056</td>
<td>10.7</td>
<td>51</td>
<td>3.2</td>
<td>.98</td>
<td>.75</td>
</tr>
<tr>
<td>7</td>
<td>.067</td>
<td>9.0</td>
<td>66</td>
<td>3.3</td>
<td>1.4</td>
<td>.9</td>
</tr>
<tr>
<td>8</td>
<td>.069</td>
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<td>73.1</td>
<td>3.3</td>
<td>1.6</td>
<td>1.0</td>
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<tr>
<td>9</td>
<td>.063</td>
<td>7.5</td>
<td>72.1</td>
<td>3.2</td>
<td>1.5</td>
<td>.9</td>
</tr>
</tbody>
</table>

Tempering the air by as little as 5° to 19°F provides for drying under adverse climatic conditions and/or on a 24-hour basis.

EVAPOTRANSPIRATION . . .

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