Heat and Moisture-Transfer Studies in Relation to Forced Ventilation of Insulated Columns of Sugar Beets

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The application of forced ventilation with cool night air to piles of sugar beets is comparatively new. The first test conducted by Mr. C. A. Fort and the writer probably introduced more new questions than it answered, although it did introduce a simple means of reducing storage losses. Some of the questions introduced were as follows:

How much air is required for various conditions?

What is the resistance to air flow in a pile of beets?

What kind of temporary or permanent air ducts should be used?

What are the economic limits of height in relation to commercial piling practice?

How much cooling can be expected from evaporative cooling?

Should the air be humidified before being forced into the pile?

At what temperature and for how long can cold air be forced into a pile of beets without producing freezing injury?

Are walls around commercial piles beneficial and if so are they worth the cost?

Some of these questions now have at least tentative answers which have been secured by many different men and organizations who have pooled all information to the common problem.

Some of the questions require special equipment for their solution and the Beet Sugar Development Foundation and the U. S. Department of Agriculture have cooperated in providing equipment and personnel to study them. Some of this equipment at Salt Lake City has been used by the writer in an attempt to secure basic information which is difficult to obtain in commercial installations.

The insulated columns, described in a previous report[2], are three feet inside diameter and 24 feet high. Each column was filled with three tons of beets. Beet temperatures were recorded continuously at the 0, 4, 8, 12, 16, 20 and 24-foot levels. Air temperatures and humidities were measured periodically at the 0, 8, 16 and 24-foot levels by withdrawing samples through a I-inch pipe, a short, flexible gas mask tube, and through a Friez, electrically-ventilated psychrometer.

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[2] Proceedings American Society of Sugar Beet Technologists, pp: 635-640, 1948.

Table 1.—Forced ventilation of columns of beets with humidified vs. normal air from 11:00 p.m. to 7:00 a.m. 10/13/48. Ventilation rate 64 C.F.M. or 21 C.F.M./ton

	Temperature			Moisture		Heat balance			
			Rel.	Per 1,000	Total	Cooling			Beets
Height	Beets	Air	hum.	cu. ft. air	evap.	Air	Evap.	Total	cooled
Ft.	°F.	°F.	%	Lbs.	Lbs.	B.T.U.	B.T.U.	B.T.U.	B.T.U.
SOUTH COLUMN 30,720 cu. ft. humidified air:									
0	46.8	49.0	87.2	0.491	.....	....	...	...	
8	51.5	50.4	95.5	0.564	2.24	834	2,380	3,214	
16	56.2	53.8	97.0	0.649	2.61	2,026	2,773	4,799	
24	61.0	56.0	105.0	0.754	3.23	1,311	3,432	4,743	
Total or difference		7.0		0.263	8.08	4,171	8,585	12,756	12,642
Beets were cooled an average of 2.59 —0.14 = 2.45° F.									
NORTH COLUMN 30,720 cu. ft. normal air:									
0	48.0	51.2	57.8	0.351	......				
8	51.5	50.9	94.8	0.569	6.70	—179	7,119	6,940	
16	58.4	55.1	97.0	0.676	3.29	2,503	3,496	5,999	
24	63.8	58.0	100.8	0.774	3.01	1,728	3,198	4,926	
Total or difference		6.8		0.423	15.OO	4,052	13,814	17,865	15,377
Beets were cooled an average of 2.92 + 0.06 = 2.98° F.									

The flow of air was measured with a 4-inch anemometer placed in the cap of the columns. Air flow adjustment was made by regulating the speed of the blowers and the openings in the caps of the columns.

During some of the earlier studies heat balance data checked quite well because natural cooling through the walls of the closed columns was about equal to the respiratory heat of the beets. During later studies at cooler temperatures, however, it was necessary to determine the temperature change of the beets when the closed columns were exposed to a similar outside temperature for like periods. These temperature-corrections were applied to the average cooling obtained during ventilation tests. Ventilation periods

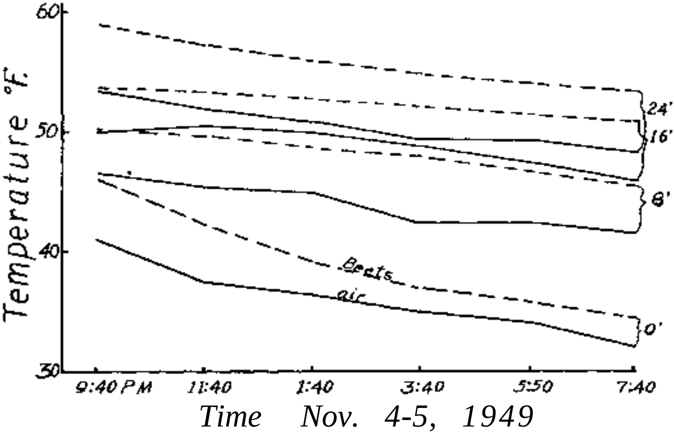

Figure 1. Relation of the temperature of beets to that of the ambient air during a period of forced ventilation at a rate of 60 C. F. M. or 20 C. F. M. per ton of beets.

were usually from seven to twelve hours during nights when air temperatures remained fairly constant. Air-temperature and humidity values at each check-point in the column were measured periodically from four to seven times during the ventilating period.

To simplify tabulation average values for beet and air temperatures, relative humidity and moisture content of the air are given at the 0, 8, 16 and 24-foot levels only. Total pounds of moisture evaporated between the various levels in the columns are obtained by subtracting the pounds of water per 1,000 cubic feet entering a lower position from that at the position *in* question and multiplying by the thousands of cubic feet of air.

Some of the values used in the calculations may be listed as follows: Heat capacity per 1,000 cubic feet of air per ° F. = 19.4 B.T.U. This value

Table 2.—Forced ventilation of columns of beet at different rates of ventilation. 60, 90 **and** 120 C.F.M.

	Temperature			Moisture		Heat balance			
			Rel.	Per 1,000	Total	Cooling			Beets
Height	Beets	Air	hum.	cu. ft. air	evap.	Air	Evap.	Total	cooled
Ft.	°F.	°F.	%	Lbs.	Lbs.	B.T.U.	B.T.U.	B.T.U.	B.T.U.
NORTH COLUMN Nov. 4-5. 10 hrs. 60 c.f.m. = 36,000 cu. ft. of air:									
0	39.1	36.0	91.0	0.316	......	......	......	......	
8	48.2	43.9	106.3	0.501	6.588	5,517	7,000	12,517	
16	52.5	48.8	97.7	0.545	1.584	3,422	1,683	5,105	
24	55.8	50.7	93.3	0.558	0.468	1,327	497	1,824	
Total or difference		14.7			8.640	10,266	9,180	19,446	22,085
Beets were cooled an average of 5.34 — 1.06 = 4.28° F.									
NORTH COLUMN Nov. 14-15. 10 hrs. 90 c.f.m. = 54,000 cu. ft. of air:									
0	38.2	35.2	91.5	0.311	......	......	......	......	
8	45.2	40.8	105.2	0.442	7.074	5,867	7,517	13,384	
16	48.8	44.7	102.7	0.494	2.808	4,086	2,984	7,070	
24	51.2	46.5	98.2	0.507	0.702	1,886	746	2,632	
Total or difference		11.3			10.584	11,839	11,247	23,086	24,562
Beets were cooled an average of 5.64 — 0.88 = 4.76° F.									
NORTH COLUMN Dec. 6-7. 10 hrs. 120 c.f.m. = 72,000 cu. ft. of air:									
0	35.7	35.0	72.5	0.244	......	......	......	......	
8	38.7	36.8	97.2	0.351	7.704	2,514	8,186	10,700	
16	42.6	40.3	96.8	0.399	3.456	4,889	3,672	8,561	
24	45.5	41.9	95.2	0.416	1.244	2,235	1,301	3,536	
Total or difference		6.9			12.384	9,638	13,159	22,797	20,382
Beets were cooled an average of 4.66 — 0.71 = 3.95° F.									

was used without correction for moisture content, temperature or pressure of the air. Heat of evaporation of water = 1,062.6 B.T.U. per pound. Specific heat of beets = 0.86 x 6,000 = 5,160 B.T.U. per ° F. for the beets in one column. The average velocity of the air passing through the columns filled with beets may be calculated by multiplying the total cubic feet of air per minute by 0.35. When ventilating at 65 C.F.M., the average velocity is 21 feet per minute.

It is evident from the data in Table 1 that the heat and moisture transfers to the ambient air are rapid. After passing through an eight-foot layer of beets the air was nearly saturated with water vapor, and the degree of saturation at a given point above eight feet was apparently affected more by the thermal gradient of the layers of beets than by the initial humidity or velocity of the air at the rates studied.

The fine spray used for humidifying the air to the south column delivered only about six gallons of water per hour. This water was relatively warm (59° F.), however, and greatly reduced the amount of evaporative cooling which would have been obtained with cool water. Although the normal air to the north column gave up heat to the first ton of beets, the net cooling of the first ton of beets was more than twice as great as that obtained in the south column which was ventilated with humidified air. The data in Table 1 show that, even after the air had reached nearly 100% relative humidity, more heat was removed by the evaporation of moisture than by the temperature rise of the air as it passed through successively warmer layers of beets. The data in Table 1 and many other similar cooling runs showed that the water used to humidify the air for ventilating beets should be cool. If cool water is not available it should be re-circulated to the humidifying equipment. The consistently greater absorption of heat by evaporation, even after the air reached near saturation, offers an explanation as to why small amounts of air have greatly reduced storage losses in some storage tests. Removal of surplus moisture also reduced effectively rotting due to attack by fungi.

Equipment for humidifying air for ventilation of piles of beets may justify the expense in areas where the temperature is high and the humidity is low but the use of air having a dew point higher than the temperature of the bottom beets involves the risk of increasing attack by fungi by condensing water on the beets. It is very doubtful if humidifying equipment is justified in cold climates because of the difficulty involved in preventing freezing of pipes and plugging of filters, or other equipment for removing spray, with ice.

The data in Table 2 show that, even with much greater volumes of air than are used in commercial installations, the transfer of heat and moisture to the ambient air was nearly as rapid as at lower rates of ventilation. The temperature differential between the beets and air at the top of the column was more greatly affected by the temperature difference between beets in the bottom and top of the column than by the rate of ventilation. The results of many tests showed that the air to beet temperature differential was about 3° F. when the top to bottom differential was about 9° F. This relationship appeared to be roughly linear. The air to beet differential at the top was about 1/3 of the top to bottom beet temperature differential.

The data in Table 2 also show that air cooling accounted for a greater part of the total heat removed from the beets than was shown in Table 1 where air and beet temperatures were warmer. However, the total calculated values checked reasonably well with the heat removed from the beets. By means of the data available it is possible to estimate the cooling which should occur in the internal parts of piles of beets by the use of forced ventilation. The calculated cooling should represent cooling in addition to that due to any draft induced in the pile by the forced movement of air and should apply to any given conditions of temperature and humidity.

Example: To estimate the heat removed from a pile of beets 20 feet high which has an average temperature of 58° F., bottom beets at 54° F. and top beets at 63° F., by ventilating with air at 38° F. and 62% relative humidity at a rate of 20 C. F. M. per ton of beets.

One ton of beets occupies about 50 cubic feet and has about 40% voids. One ton of beets will represent an area of 2.5 square feet of the pile with an average of 1 square foot of air space. The average velocity of the air will be 20 feet per minute. The air will probably come out the top of the pile at 60° F. and 98% relative humidity. The heat absorbed by the air will be: (60 — 38) x 19.4 x 1.2 = 512.16 B. T. U. per ton per hour. The evaporative cooling will be:

Air leaving top 0.821 x 0.98 = 0.8046 lbs. H_2O per 1000 cu. ft.[2]

Air entering bottom 0.378 x 0.62 = 0.2344 lbs. H_2O per 1000 cu. ft.
(0.8046 — 0.2344) x 1.2 x 1062.6 = 727.07 B. T. U. per ton per hour.

The respiratory heat of beets at 58° F. is about 81 B. T. U. per ton per hour[3].

The net cooling will be 512.16 + 727.07 — 81. = 1158.23 B. T. U. per hour.

This should cool the beets an average of $\frac{1158}{(2000 \times 0.86)} = 0.67°$ F. per hour.

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[2] Table 1, p. 638 Proceedings American Society of Sugar Beet Technologists, 1948.
[3] Table 1, p. 12 U and I Cultivator, October, 1946.