Temperature observations in a bottom-unloading concrete silo

S. JIANG[1], J. C. JOFRIET[1], and J. BUCHANAN-SMITH[2]

[1]*School of Engineering, and* [2]*Department of Animal and Poultry Science, University of Guelph, Guelph, Ontario N1G 2W1.*

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Jiang, S., Jofriet, J.C. and Buchanan-Smith, J. 1988. **Temperature observations in a bottom-unloading concrete silo.** Can. Agric. Eng. 30: 249–255. Temperatures were measured hourly in a 6.1 × 22-m concrete bottom-unloading oxygen-limiting silo over a 52-d period, 26 July–16 Sept. 1985. Twelve thermocouples were used to observe alfalfa silage temperatures about 2 m below the surface and 13 thermocouples were located throughout the head space. Gas temperatures in the head space were found to follow the ambient temperature variation with a delay and a reduced amplitude of fluctuation. Silage temperatures reached 47°C at the center of the silo and remained above 40°C for the entire 52-d test period. Cooling of silage was very slow except within the 0.3-m region nearest the wall, where fluctuations with the ambient temperature were observed and solar radiation seemed to have a significant effect on temperature changes.

INTRODUCTION

Temperature is one of the major factors influencing silage quality. In general, high temperatures tend to favor clostridia fermentation since these organisms tolerate and thrive at higher temperatures than the lactic acid bacteria (McDonald 1981; Ohyama et al. 1973; Wieringa 1958). Reduced water contents, which may be realized by field wilting, can suppress the growth of the *Clostridia*. However, if a sufficient amount of lactic acid is not built up when the condition becomes anaerobic, the pH will not be lowered to a stabilization level and the growth of the *Clostridia* cannot be inhibited.

Temperature is an important factor affecting silage stability and protein damage during the entire storage period. A survey of alfalfa silage in Michigan showed that an extensive amount of silage was heat damaged, and this occurred in both sealed and unsealed structures (Thomas et al. 1972). Ohyama et al. (1975) observed that aerobic deterioration occurred in grass silage when the ambient temperature was above 10°C. In most of the deteriorated silages, a marked reduction in lactic acid content and water soluble carbohydrates was found.

The temperature fluctuation and consequent pressure variation of gases in the head space of a silo cause an intensive gas exchange with the surrounding atmosphere (Meiering 1971, 1986). Though the breather bags in some oxygen-limiting silos reduce the amount of oxygen intake, the capacity of these bags may be exhausted when temperature fluctuation is great, or the silo is large and the silage level is low. This may result in serious surface losses, especially in bottom-unloading silos where the upper surface of the silage remains exposed to the head space gases for a long period of time.

Measurements of silage temperatures have been conducted in experimental pilot-scale silos (Henderson et al. 1972; McDonald 1981) and in full-scale top-unloading silos (Rotz 1986; Csermely 1975). In well-sealed, 1-t-capacity silos the temperature increase in 48 h was less than 4°C and it then gradually decreased to the ambient temperature at a rate of 0.5–0.7°C/d (Henderson et al. 1972). In poorly consolidated materials an increase of 14°C from the initial of 18°C was reported (McDonald 1981).

Rotz's (1986) measurements at three levels (2.5, 5.5 and 8.5 m below the silage surface) in a 3.0 × 12.0-m-high concrete-stave silo showed that the highest temperature occurred at the upper level. In this layer the temperature increased from 9°C initially to 43–48°C in 5 d. At some locations the temperatures near the silo wall were higher than that near the center. His results also showed that the temperature below 5.5-m depth was much lower and was uniformly distributed.

Csermely (1975) also reported that the highest temperature occurred in a layer of 2 m below the silage surface in a 9.0 × 7.0-m-high polyester and a 9.0 × 23.5-m-high concrete silo. At day 10 of ensiling the temperature near the center reached 55–60°C. The temperatures near the silo wall were about 30–35°C lower than that near the centre.

O'Leary et al. (1981) measured weekly the temperatures of corn silage as it was removed from the silo. Three silos were involved, one 5.2-m-diameter oxygen-limiting silo and two 4.3-m-diameter stave silos. The method of measurement was not reported. Silage temperatures from the oxygen-limiting silo were found to be higher than that from the stave silos. As well, the silage from the former was found to be less stable.

Wilcke (1966) recorded both silage and gas temperatures in a 4.0 × 7.0-m-high steel silo that was 45% full. However, the measurements reported were during the daylight hours of 15 Aug. 1965, with a solar zenith angle of 37°C. The gas temperature varied from 31°C near the silage surface to 51°C near the silo dome, while the silage temperature and the steel dome temperature averaged about 26 and 70°C, respectively.

Measurements by Meiering (1987) in Waterloo Township, Ontario showed much different results. Four evenly spaced thermocouples along the center line in the head space of a 33–50% full 6.1 × 18-m-high steel silo registered a temperature difference of less than 6°C at any time during a 51-d test period in summer 1983. It is difficult to compare these results with those of Wilcke since no measurements of silage temperatures were taken in this work.

A more complete measurement of both silage and gas temperatures is necessary to further monitor silage quality, and to examine silage storage structures and the functions of the breather bags in oxygen-limiting silos. Oxygen-limiting silos are believed to provide better anaerobic conditions for silage fermentation. Therefore a lower silage temperature may be expected. However, to the authors' knowledge no temperature measurements of silages in full-scale oxygen-limiting bottom-unloading silos are available, possibly due to the difficulties associated with installation of thermocouples in this type of structure.

To remedy the lack of information, an experiment was conducted in a 6.1 × 22-m-high bottom-unloading oxygen-limiting concrete silo in Baden, Ontario. The temperature data of silage and silo gases were collected during summer 1985 because the major interest was the observation of maximum silage temperatures, as well as the duration of these maxima. An additional objective of this work was to provide experimental data to verify numerical results from a finite element study of temperatures in tower silos now in progress at the University of Guelph.

METHOD OF TESTING

The construction of the silo is that of a typical sealed reinforced concrete silo. The wall thickness is 140 mm; the roof is cone-shaped and constructed of reinforced concrete. The silo has a center-fill arrangement without a distributor. The structure has dual breather bags with a total expansion volume of 24.1 m^3 located in two chambers below the silo floor. The bags are connected to the head space above the silage with an external plastic pipe. A pressure relief valve is located on the roof. The pipe and the valve were checked regularly to ensure proper functioning.

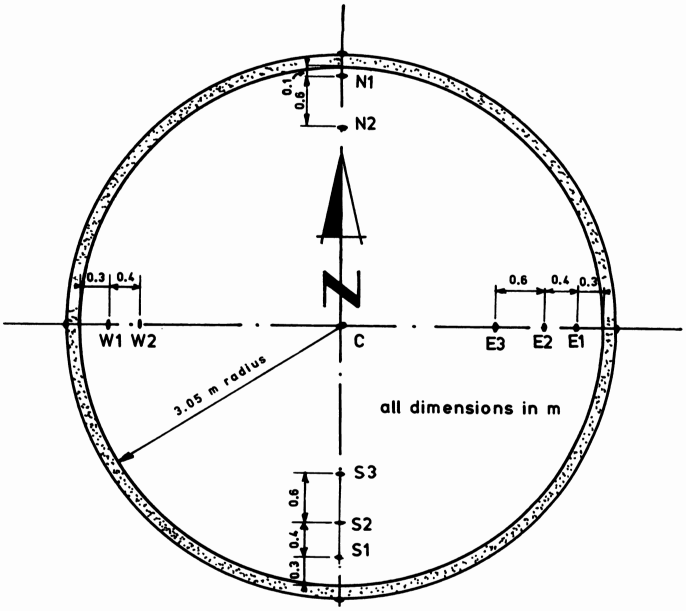
In a bottom-unloading silo, thermocouples have to be installed from the top. Therefore, the measurements can be taken only in the top layer of the silage. Fortunately, the highest silage temperature occurs usually in the top 2.5-m layer (Csermely 1975; Rotz 1986). The present tests were carried out at 1.8-m depth.

Thermocouples cannot be put in until the silo is filled and have to be removed before the next filling. In addition, thermocouples have to be arranged in such a way that they can move with the silage during the consolidation or unloading period. The length of the experiment is therefore limited.

The period between the second-cut and third-cut alfalfa in Southern Ontario takes place around August, lasting 50–60 d. This time period was considered to be adequate for the experiment since the highest ambient temperatures usually occur during this time of the year.

The silo was filled in June 1985 with first-cut alfalfa with an average moisture content of 51% (WB). The filling of the second-cut material started on 18 July and ended on 25 July. The silo was about 70% full at the beginning and 90% full at the end. The material was field wilted to an average moisture of 43% (WB). The chopping length of the material was 10-12 mm for both cuts.

At the center of the silo, temperatures were measured at five levels, 1.8 and 0.7 m below the silage level, 0.4 and 1.0 m above the silage level, and at a fixed location 1.0 m below the roof. Temperatures were measured along the north-south and east-west axes of the silo. Along the east and south radii the measurement locations were 1.3, 0.7 and 0.3 m from the inside face of the wall. Along the west and north radii only two locations were monitored 0.7 and 0.3 m from the wall for the west, and 0.7 and 0.1 m from the wall for the north radius. More thermocouples were placed along the south and east radii because there the solar radiation effect is more significant and the silage temperature was expected to be higher in these two directions. The intention was to insert one thermocouple in each direction as close to the wall as possible. However, at the time of installation it was found to be difficult to place thermocouples into the silage close to the wall. Several broken thermocouples resulted during a preliminary trial. Therefore three thermocouples were installed 0.3 m away from the wall and only one (N1) was successfully placed at 0.1 m.



Thermocouples at 1.0 above and 1.8 m below silage level at all stations N, E, S and W. At station C 1.8 m and 0.7 m below, and 0.4 m and 1.0 m above level of silage, and 1.0 m below roof.

Figure 1. Location of the 11 thermocouple stations.

At each of these 10 locations silage temperatures were measured at 1.8-m depth and the gas temperatures 1.0 m above the silage level. Finally, the outside face of wall temperature was monitored along the four radii at a fixed level 1.4 m above the floor of the silo. The ambient air temperature at a shaded spot was also recorded. Figure 1 shows a layout of the thermocouples.

All temperatures were measured hourly with type-T thermocouples. At each station inside the silo the thermocouples were mounted inside a 19-mm-diameter copper tube of sufficient length to contain both the thermocouples above and below the silage level. The exception was the upper thermocouple in the center of the silo which was simply suspended from the roof. Figure 2 shows the mounting of the thermocouples in the copper tubes. The four thermocouples for measuring the outside face of wall temperatures were embedded into a small hole drilled into the concrete of the wall and thence secured with epoxy. All thermocouples were calibrated before the start of the experiment.

The copper tubes were installed into the silo by a person equipped with a self-contained respiration apparatus on 26 July, the second day after filling. The copper tubes were driven into the silage as closely as possible to the desired location and to the required depth. A 50-m-long, 36-pair conductor thermocouple extension cable connected the inside thermocouples to the datalogger located in a shed next to the silo (see Figure 3). The cable passed through a sealed hole in the access hatch in the silo roof. Enough slack was left to allow the free motion of the thermocouples during consolidation and unloading of the silage. The top of the silage was approximately 2.5 m below the top of the wall at the start of the test (26 July). At the end

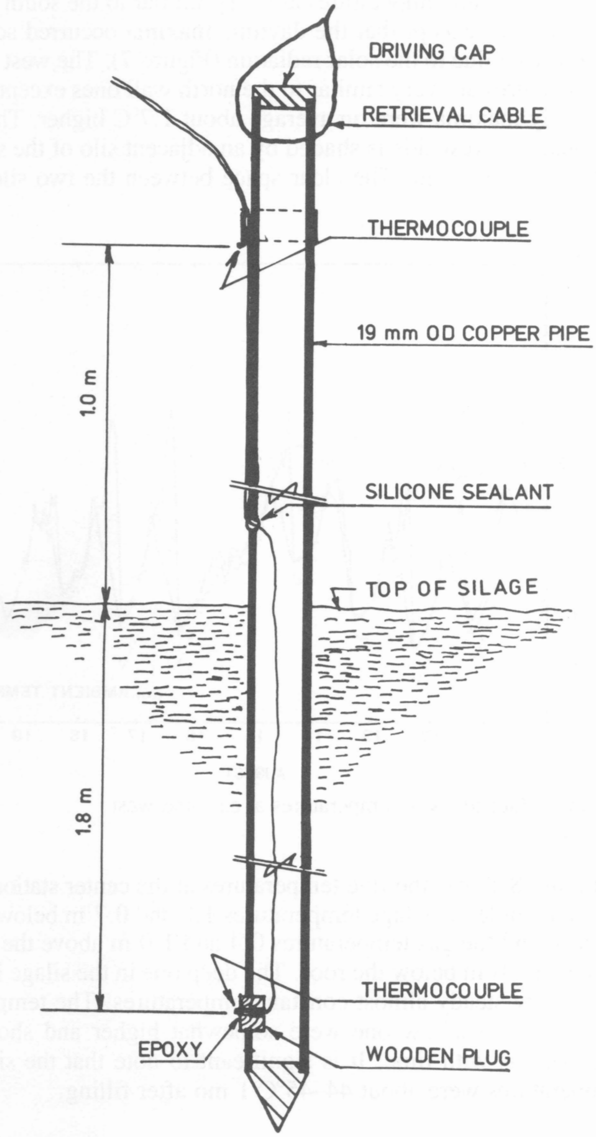


Figure 2. Mounting of the thermocouples in the copper pipe probes.

(16 Sept.) the silage level was about 5.5 m below the top of the wall. The dry matter density, ρ_d, was estimated from $\rho_d = 150 + 250\ (1 - e^{-0.11z})$ (Jofriet et al. 1982). At depth $z = 1.8$ m this provided an estimated bulk density of 342 kg m^3 for the 43% moisture content silage.

The thermocouples were connected to a HP3497 datalogger, which was controlled by a HP85F microcomputer. All readings were stored on the magnetic tape of the HP85F and printed out on a printer. Readings were taken hourly from 26 July 1985 to 16 Sept. 1985.

The meteorological data for this time period were obtained from the University of Guelph Weather Station at Elora, Ontario (longitude 80.25 W, latitude 43.39 N). The station is about 50 km north-east of the experiment site (longitude 80.65 W, latitude 43.40 N). Figure 4 shows the total daily radiation on a horizontal surface and mean wind velocity for the 52-d test period. Figure 5 illustrates the frequencies of wind occurrance in different directions.

TEST RESULTS

The test results are presented in two parts. In order to show the

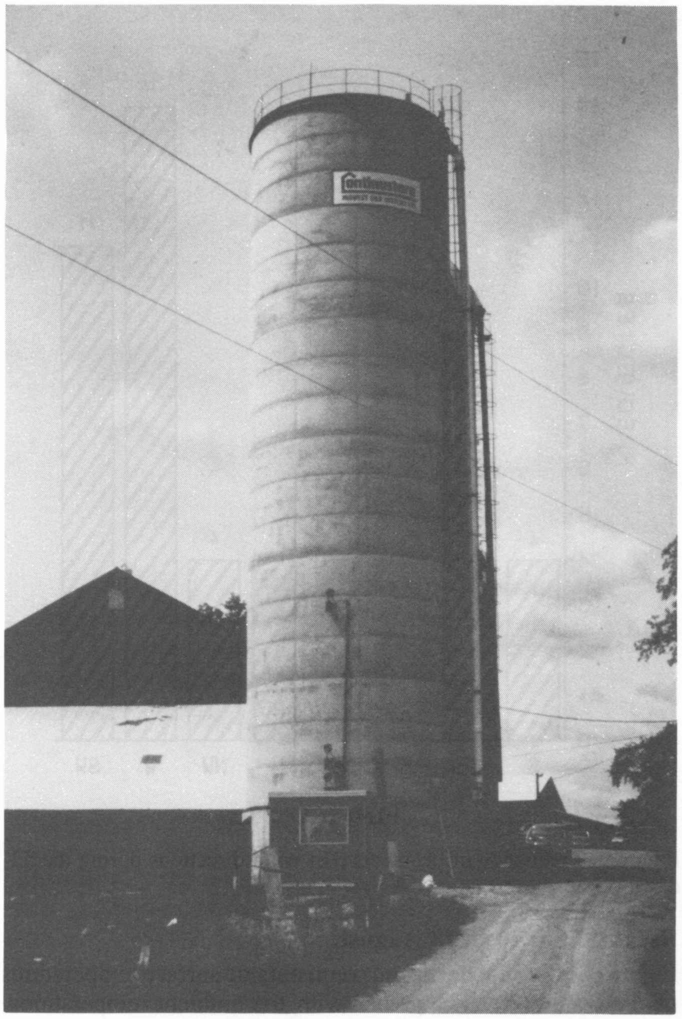


Figure 3. General view of test silo.

detailed temperature variation, results of wall temperatures as well as gas temperatures and silage temperatures at the center stations are presented for the period 10–18 Aug. Daily fluctuations in this 9-d period are typical for the test period. Silage temperatures for the entire test period are presented and compared in the second part.

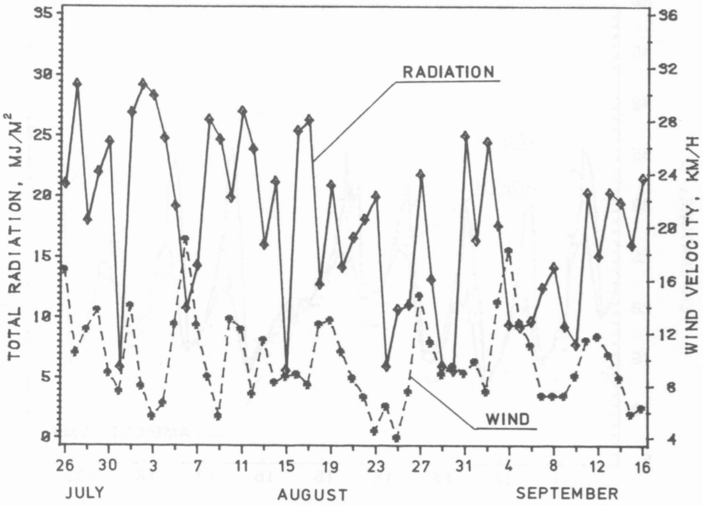


Figure 4. Daily total solar radiation on a horizontal surface and mean wind velocity for the test period.

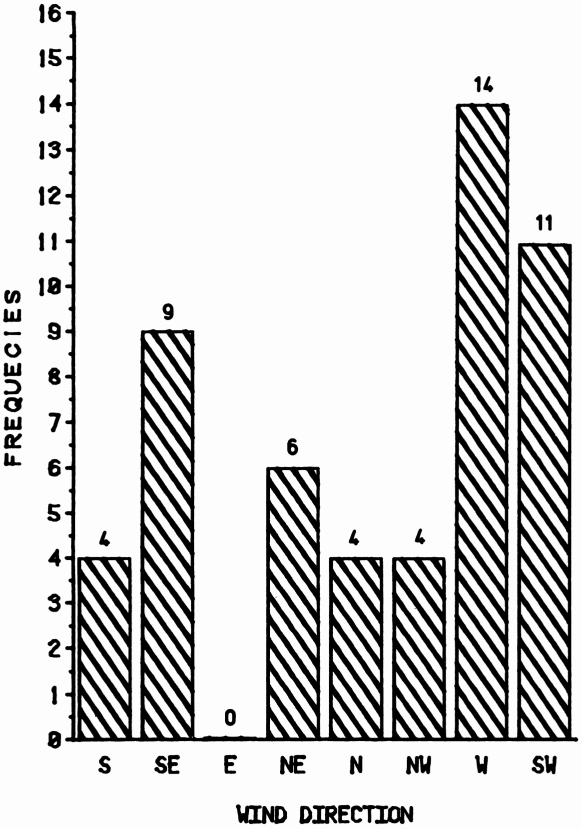


Figure 5. Frequency of occurrence of wind directions during the 52-d test period.

Results from 10 to 18 August

Figure 6 shows the north and south outside surface temperatures of the concrete wall together with the ambient temperatures. The division lines on the horizontal axis indicate 12 midnight, the date indicates the start of that day.

August 10, 11, 12, 14, 16 and 17 were bright sunny days (Fig. 4). This resulted in significantly higher outside surface temperatures of the south wall compared with the north one. The temperature difference between south and north reached 14°C at around 13:00 h on 16 Aug., while at midnight or a rainy day (e.g., 15 Aug.) the difference was usually less than 1°C.

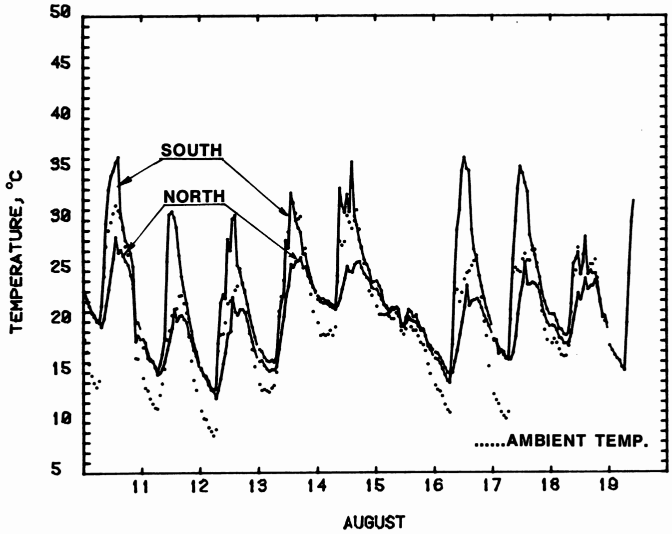


Figure 6. Outside wall temperatures at south and north.

The east wall temperatures are very similar to the south wall temperatures except that the daytime maxima occurred somewhat earlier due to the solar radiation (Figure 7). The west wall temperatures are very similar to the north wall ones except that the daily maxima were on average about 1.7°C higher. This is because the west side is shaded by an adjacent silo of the same size as the test silo. The clear space between the two silos is about 1 m.

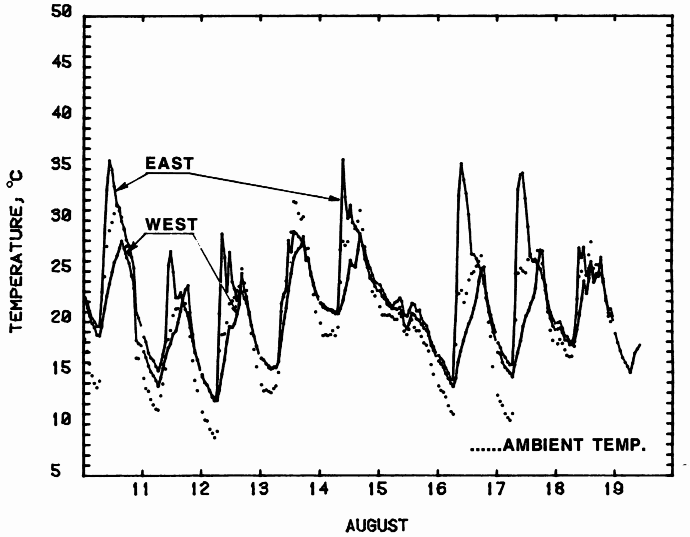


Figure 7. Outside wall temperatures at east and west.

Figure 8 shows the five temperatures at the center station C. These include the silage temperatures 1.8 and 0.7 m below the surface and the gas temperatures 0.4 and 1.0 m above the surface and 1.0 m below the roof. The deep one in the silage indicated very steady almost constant temperatures. The temperatures of the shallow one were somewhat higher and showed fluctuations with time. It is significant to note that the silage temperatures were about 44–45°C 1 mo after filling.

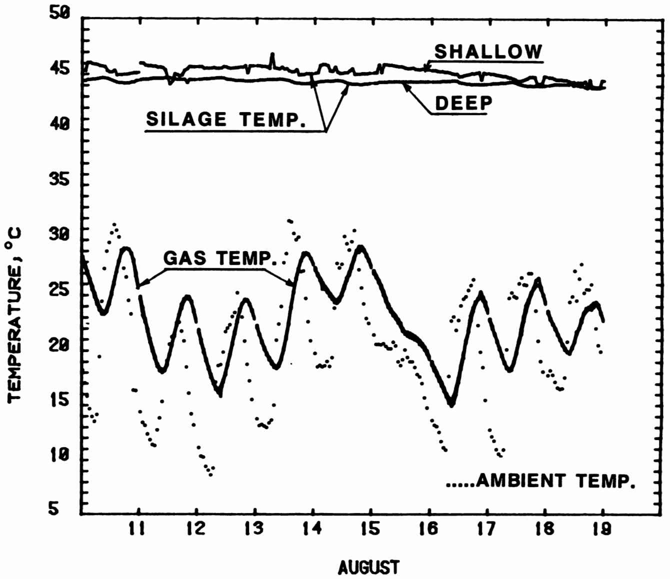


Figure 8. Temperatures at silo center, 0.7 and 1.8 m below silage surface, 0.4 and 1.0 m above silage surface, and 1.0 m below silo roof.

The gas temperatures at all stations are virtually identical despite the fact that the sensors were located at different levels in the head space. Gas temperatures fluctuated drastically following the changes in ambient temperature with a delay that averaged about 7 h. The amplitude of the fluctuation averaged about 8.5°C for this 9-d period with a maximum of 14°C occurring between 14 and 16 Aug.

Results from 26 July to 16 September

Figure 9 presents the silage temperatures for the entire testing period along the south and north radii. These include stations S1, S2, S3, N1, N2 and C at 1.8-m depth. The ambient temperatures are also included for easy reference. In a similar fashion, Figure 10 illustrates the temperatures across east and west radii.

The silage temperature at the center of the silo reached 44°C on the second day of filling. It slowly increased to 45°C on day 16 (10 Aug.) and then gradually decreased to about 40°C at the end of test (Figs. 9 and 10). The drop in temperature over these 37 d was 5°C, a reduction of less than 1.4°C per 10 d.

It can be seen clearly from Fig. 9 that the temperature at station N1 followed the overall profile but not the individual fluctuations of the ambient temperatures. The reason is that the thermocouples at this station were located very close to the wall (see Fig. 1).

Inside the circular area 0.3 m or more away from the wall, temperatures at all stations decreased steadily over the testing period. Though small fluctuations were observed, the silage temperatures at S1, E1 and W1 were surprisingly steady despite the fact that the locations of measurements were only 0.3 m from the inside face of the wall. It is noted that at stations S3 and E3, 1.3 m from the inside face, the silage temperatures were higher than 40°C for at least 3 wk after filling. The reduction of temperatures over the entire test period was 9°C for S3 and 12°C for E3.

Figures 11 and 12 illustrate the comparison of silage temperatures in the three directions at 0.3 m from the wall and four directions at 0.7 m from the wall, respectively. The total drop in temperature at stations S1, E1 and W1 (Fig. 11) ranged from 12 to 19°C and averaged 15°C. The smallest drop of 12°C

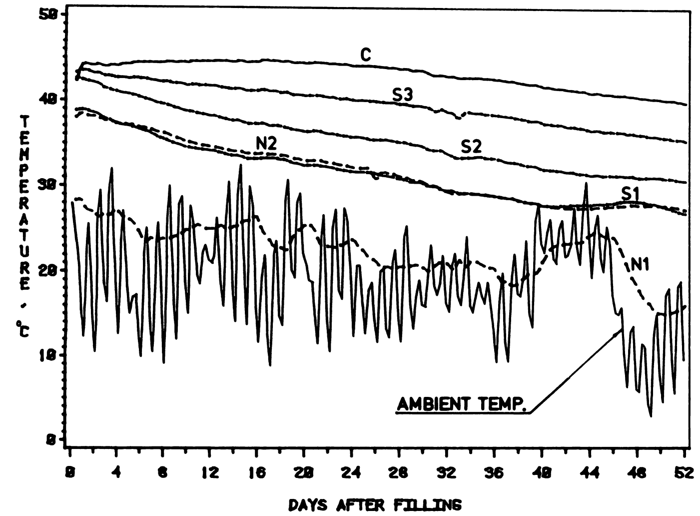


Figure 9. Silage temperature variation across north-south radii for 52-d test period

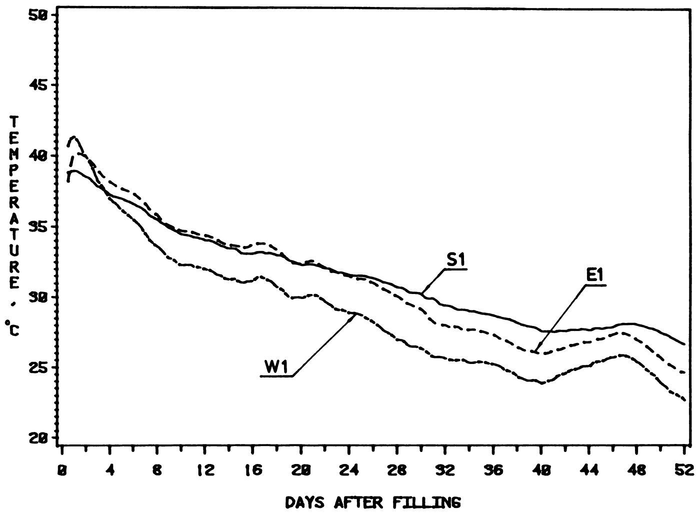


Figure 11. Comparison of silage temperatures at south, east and west, 0.3 m from wall.

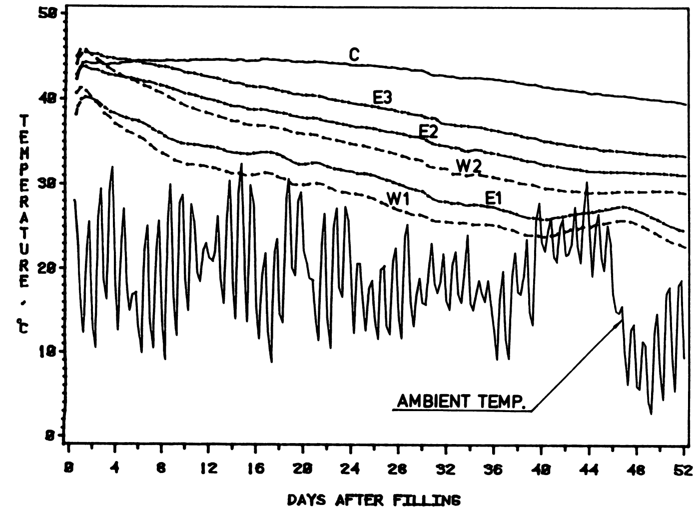


Figure 10. Silage temperature variation across east-west radii for 52-d test period.

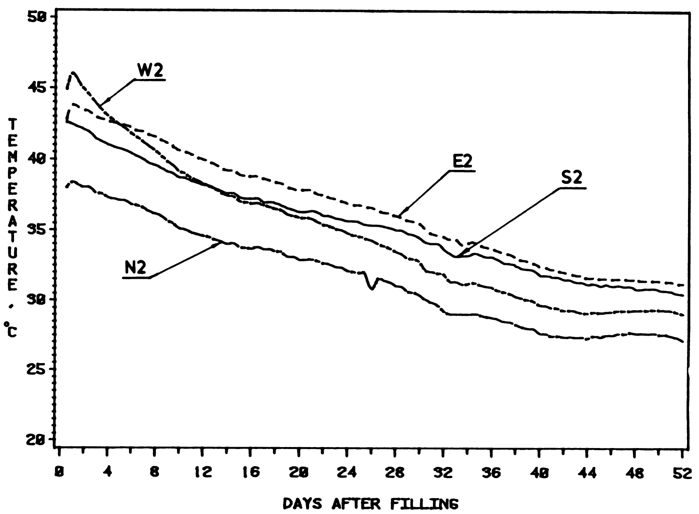


Figure 12. Comparison of silage temperatures at south, north, east and west, 0.7 m from wall.

occurred at the south, and the highest at the shaded west side (Fig. 11). At the station 0.7 m from the wall (Fig. 12) the drop in temperature over the 52 d ranged from 11 to 16°C and averaged 13°C. The highest drop again occurred at the west, the lowest at the north and south.

DISCUSSION

It can be seen from Figs. 6 and 7 that the outside wall temperatures at the south and east were much higher than the ambient air temperatures because of the solar radiation. This influences the gas temperatures in the silo head space. However, this effect in concrete silos is not as significant as in steel silos. The results obtained in the steel silo (Meiering 1987) showed that the ratio of the amplitude of gas temperature fluctuation over that of the ambient one averaged 1.75. In some extreme cases, this ratio reached as high as 2.93 (Meiering 1971). The results of the present study showed that in the concrete test silo solar radiation did not cause larger fluctuations of the head space gas temperatures than those of the ambient temperatures. The amplitudes of the fluctuation in gas temperatures averaged 6.5°C, about 70% of that in ambient temperatures. This is due to the fact that concrete has much lower thermal conductivity and higher heat capacity than steel. The thermal conductivity of normal weight concrete ranges from 1.3 to 1.7 W/(m.K), which is much lower than the conductivity of steel which lies between 36 and 43 W/(m.K). The specific heat ranges from 840 to 920 J/(kg.K) for concrete and 470 to 490 J/(kg.K) for steel (ASHRAE, 1981; Kreith and Black 1980). Another reason is the white-painted roof and the light-colored concrete wall which absorbs less radiative heat than the dark-colored steel silos.

The maximum drop in gas temperatures during the 52-d testing period occurred between 14–16 Aug. (Fig. 6). The total solar radiation for 14 and 15 Aug. was 21.2 and 5.6 MJ/m^2, respectively. The wind velocities for the 3 d were about the same (8.2, 8.6 and 8.8 km/h) (Fig. 4). The gas temperature reduction was 14°C when the ambient temperature dropped continuously from 31.0°C to 11.2°C over these 3 d. This value would have resulted in a corresponding pressure reduction of less than 5% at constant volume.

Figure 8 shows that the gas temperatures were uniformly distributed across the height of the head space. The observations at other locations were almost identical with these three locations shown in Fig. 8. The temperature difference between the 13 thermocouples located over the entire head space was less than 1°C during the 52-d test period. Convective heat transfer within the gases seems to exist. This is in conflict with the findings by Wilcke (1966), who reported a 20°C gradient in a silo head space of 3.85 m high. Wilcke's measurements were taken only at one particular time and the changes of gas temperature with time were not reported. One explanation is that Wilcke's silage temperature was about 25°C at the surface, which was much lower than the 70°C temperature of the steel roof, thus inhibiting natural convection flow. A theoretical study seems necessasry to relate the gas temperatures with the outside weather conditions as well as the silage temperatures.

The data collected by Meiering (1987) agree much better with results of this study. He recorded gradients of less than 6°C in a head space 9.0–12.0 m high during a 51-d test period and a time interval of 6 min. Considering the height of the head space of the present silo varied only from 2.5 to 5.5 m during the test period and the higher resistance to heat flow of concrete compared to steel, a gradient of 1°C seems to be reasonable.

Silage temperature at the center of 0.7 m depth was about 1.5°C higher than that at 1.8 m depth. It remained about 1.0–1.5°C higher for the first 3 wk of the test. In addition, the temperature at 0.7 m depth fluctuated irregularly with time (Fig. 8). After 24 d (18 Aug.) temperatures at the two levels became closer, and then the shallow one started to drop faster than the deep one. At the end of test the shallow one was about 3°C lower and the curve became almost as smooth as the deep one. This may imply that the aerobic activities near the silage-gas interface carried on for the first 3–4 wk of ensiling. After that no evidence of serious air re-entry was indicated.

Silage temperatures in a full-scale silo are quite different from those in small-scale experimental silos. Due to the larger silage mass per unit area of boundary surface and the resulting larger amount of heat retention, temperature increase is much greater in large silos. The maximum ambient temperature on the last day of filling (26 July) was 28.1°C. The silage temperature at the center of the silo reached 42°C at the time the measurements started (noon on 26 July). Figures 9 and 10 show that the increase of temperature virtually stopped on 27 July, the second day after filling. The maximum temperature of 47°C occurred at the west 0.7 m from the wall and at the center at 0.7 m depth. The average reduction was about 0.24°C/d. At the center the reduction was only 0.14°C/d.

Csermely (1975) recorded a much higher silage temperature. In both test silos temperatures of 55–60°C were reached near the center, 10 d after ensiling. It remained over 50°C over a 50-d period while the ambient temperature decreased from 18–23°C to 10–13°C. Yet, the rate of decrease in silage temperature near the center is similar to that found in this study. Considering the moisture contents used in his work were about the same as (46% for the small silo) or higher (70% for the large one) than the present work and the ambient temperature variation was similar (mean temperature varied from 23 to 8°C in the present work, see Fig. 9), one suspects that the higher temperatures were caused by some other factors, such as the size of silos and especially the availability of air.

Rotz (1986) recorded a much higher temperature near the wall than at the center of a concrete stave silo. At the location near the south wall a maximum temperature reached 65°C after 9 d and it remained over 50°C for 15 d, while the temperature at the center was only 44°C or less. However, this was not observed in the present study. It can be seen from Figs. 9 and 10 that the highest temperature occurred in the center area. It gradually decreased along the radius of the silo. The difference between the center and 0.3 m from the wall averaged about 4.0°C at the beginning and 14.7°C at the end of the test period, indicating that heat transfer to the environment occurred at the boundary. The fluctuation with the ambient temperature was observed only within a region about 0.3 m from the inside face of the wall.

Figures 9 and 10 also show that at the center area the temperature decreased steadily after the first 3 wk of ensiling despite the fact that the average ambient temperature increased from 14.5 to 25°C during the period of 36 and 44 d after filling (Figs. 9 and 10). However, Rotz (1986) measured a temperature increase at the center of 37.0–40.2°C at the end of the 47-d test at a rate of 0.23 °C/d. The average ambient temperature varied from 21 to 26°C during this time period. This is further evidence that the oxygen-limiting silo has a more stable temperature pattern than the open ones.

In general, heat transfer from the silage to the environment is very slow due to the low conductivity and high specific heat of silage. Jiang et al. (1986) reported that the conductivity and diffusivity of silage were dependent on the moisture content and bulk density of the material. By extrapolating the regression equations derived in their work, the conductivity and specific heat for a silage with 43% moisture content (WB) and 342 kg/m^3 bulk density were estimated to be 0.190 W/(m.K) and 3.54 kJ/(kg.K), respectively. Therefore, silage temperatures greatly depend on the initial temperatures resulting from the aerobic respiration. Ambient weather conditions have a significant effect on the temperature reduction, especially in the region near the wall. Figures 11 and 12 show that the greatest temperature reduction occurred in the west and the smallest was in the south. At the stations 0.3 m from the wall (Fig. 11) the initial temperature at the west was about 2.5°C higher than that at the south, whereas it was about 4.0°C lower after 52 d. This can be explained by the fact that the sun was blocked in the west and that the wind direction was most frequently from the west and south-west during the test period (Fig. 5). The environmental effect became smaller further away from the wall. At the stations 0.7 m from the wall (Fig. 12) the west was about 3.5°C higher and 1.5°C lower than the south at the beginning and end of the test period, respectively. At the minimum radiation exposed north, the temperature was the lowest throughout the whole test.

CONCLUSIONS

The following conclusions may be drawn from this study:

(1) The concrete wall of the test silo had a damping effect on the fluctuations of the head space gas temperature. The amplitude of gas temperature fluctuations was less than 70% of that of ambient temperature fluctuations.

(2) The gas temperatures in the silo head space were very uniform under the test conditions. At no time during the 52-d test period was a temperature difference greater than 1°C observed between any of the 13 head space sensors. Natural convection appears to mix the gas well.

(3) The bottom-unloading silo has more stable silage temperatures than the open silo. No evidence of serious air re-entry was observed during the 52-d test period. The silage temperature increased drasticaly in the first 2 d of ensiling and the cooling was very slow. Silage temperature near the silo center remained above 40°C during the entire testing period.

(4) The effects of diurnal temperature fluctuation were observed only within the 0.3-m region nearest to the wall. Solar radiation seems to have some effect on the rate of decrease in temperature of the silage. This effect is most significant in the layer near the wall.

ACKNOWLEDGEMENT

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