Air-type solar collectors and liquid thermal storage for a livestock building

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Sokhansanj, S., Gartner, D. M. and Stumborg, M. A. 1990. Air-type solar collectors and liquid thermal storage for a livestock building. Can. Agric. Eng. 32: 105–109. The solar collector/storage system tested on a swine building in Saskatoon consisted of two collectors and two storage media. The collectors were a prefabricated commercial collector and an on-site built collector. The thermal storage consisted of plastic containers filled with either Glauber's salt or water. The overall collector efficiency was 61% and the annual contribution of the collector/storage system to heating the building was 48%. Water containers underwent freeze and thaw cycles during winter, storing heat in the form of sensible and latent heat. The salt containers did not show any sign of freeze and thaw cycle.

BACKGROUND

Ventilation heat losses account for almost 75% of the total heat loss in well-insulated hog barns in cold climates (Sokhansanj et al. 1980). Confined livestock buildings are often ventilated continuously with fresh air at a minimum rate of 1–4 air changes per hour to keep moisture and toxic gases within the building at a safe level (Midwest Plan Service 1980). Tempering fresh outside air by 10–15°C provides 60–70% of total annual heating requirement for these buildings in cold climates.

Air-type solar collector and storage systems are technically feasible for use on livestock buildings (Sokhansanj and Jordan 1981; Sokhansanj and Townsend 1985; Williams et al. 1985). In northern latitudes, a livestock building oriented east-west provides ample sun-exposed area on the vertical south-facing wall. For Saskatoon, at 52°17’ northern latitude, the amount of solar radiation during the heating season (mid-October to mid-April) is almost 50% of the total annual solar radiation on a vertical south-facing surface (Sokhansanj and Townsend 1985; Sokhansanj, 1984).

The collection of the incident solar heat on the south wall can be achieved by modifying the wall to accommodate a solar collector. The collected solar heat at a given time may exceed the required supplemental heat. Storing the excess collected heat for use when solar radiation is not available extends the usefulness of a solar heating system. Water, an excellent thermal storage medium, is inexpensive, nontoxic and nondegradable. In liquid form, its thermal storage capacity in the form of sensible heat is 4200 kJ·m⁻³·K⁻¹. Its solid/liquid phase change is at 0°C with a latent heat of fusion of 317 kJ·kg⁻¹. Therefore, when water freezes or thaws, 317 kJ·kg⁻¹ of energy are released or stored, respectively.

Table I lists thermal storage properties of ice and water, and of the dehydrated salt commonly known as Glauber’s salt. The salt is a colorless natural chemical (Na₂SO₄, 10 H₂O) and is abundant in nature in salty lakes. Glauber’s salt, in its natural state, contains 44% Na₂SO₄ and 56% water on a mass basis. The nontoxic salt solution changes phase at 32°C with a corresponding latent heat of fusion of approximately 238 kJ·kg⁻¹. The phase change temperature can be reduced by about 10°C with the addition of a mixture of clay and borax (Marks 1980).

The phase change temperature of water at 0°C makes it a suitable medium for storing excess heat when the air temperature exceeds 0°C. This condition prevails when solar heat is used to preheat fresh air in livestock ventilation. The freezing temperature of Glauber’s salt at 32°C makes it suitable for storing heat within a building where inside air is recirculated through a solar collector without mixing it with outside air. Glauber’s salt has been used in solar-assisted home heating systems.

The objective of this research was to investigate thermal performance of the solar collectors and water or Glauber’s salt containers under Saskatchewan’s winter conditions. The system was tested to supplement space heating of a swine building in Saskatoon, Canada.

DESCRIPTION OF THE BUILDING AND SOLAR HEAT SYSTEM

The livestock building on which the solar heat collectors were installed is located at the University of Saskatchewan’s Prairie Swine Research Center. The Center is located 16 km south of Saskatoon (52°17’ north latitude).

Description of building and ventilation system

The wood-frame building is oriented east-west. It contains facilities for continuous swine gestation, farrowing, and nursery operations. In 1981, a concrete Trombe-wall was added to the south wall of the farrowing section (Sokhansanj and Townsend 1985). The solar unit discussed in this paper was installed on the gestation room which houses 40–50 sows. The south wall of the gestation room is 2.4 m high and about 16 m long. The building space is ventilated under a negative pressure created by four exhaust fans. One fan runs continuously, the remaining fans are thermostatically controlled.

The fresh air for winter ventilation passes through the solar collector prior to entering the building. Additional summer ventilation is provided through a duct located in the attic. Summer ventilation is controlled manually by varying the gap size in the duct outlet.

Solar heat collectors

Two types of collectors were installed on the south wall of the barn. A prefabricated collector was purchased from a manufacturer in Saskatchewan. The collector was made of louvered fins which were painted black. The louvers were sloped at angle of about 20° from horizontal and were slotted to provide air passages (see Fig. 1). The collector, 6.1 m long and 2.34 m
Table I. Thermal storage properties of water and Glauber’s salt

<table>
<thead>
<tr>
<th></th>
<th>Density (kg·m⁻³)</th>
<th>Spec. heat (kJ·kg⁻¹·K⁻¹)</th>
<th>Density × spec. heat (kJ·m⁻³·K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice</td>
<td>918</td>
<td>2.0</td>
<td>1836</td>
</tr>
<tr>
<td>Liquid</td>
<td>998</td>
<td>4.2</td>
<td>4200</td>
</tr>
<tr>
<td>Heat of fusion</td>
<td>317 kJ·kg⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Glauber’s salt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frozen</td>
<td>1600</td>
<td>2.1</td>
<td>3360</td>
</tr>
<tr>
<td>Liquid</td>
<td>1120</td>
<td>3.4</td>
<td>3808</td>
</tr>
<tr>
<td>Heat of fusion</td>
<td>238 kJ·kg⁻¹</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: (Telkes 1974).

Figure 1. Cross section of solar collectors and storage containers. The left is louver type and the right is the plate type.

The second plate-type collector was constructed at the site and installed on the building (see Fig. 1). The plates were made of dark brown prefinished metal siding with the same configuration and dimensions as the original siding of the wall. The new siding was installed on the old siding such that a 32-mm space was created between the ribs to provide air passages. The brown siding was precut such that its length was shorter than the wall siding leaving a 50-mm air space at the bottom. Black prepainted corrugated wood strips were attached and sealed to the sides of the collector. Clear corrugated fiberglass sheets were installed over the new siding with the corrugations running horizontally. About 50 mm was left open under the eave for the air entrance.

Solar heat storage

Water and Glauber’s salt provided the media for solar heat storage. A plastic container 404 × 200 × 30 mm similar in shape to a re-usable ice-pack contained the fluid. The two faces of the container were molded such that they could be interlocked while leaving and airspace in between when stacked. About 200 containers were filled with a mixture of Glauber’s salt and peat-moss provided by the Saskatchewan Mining and Development Corporation. A long plenum in which the storage containers were housed was fabricated at the site. The plenum, 460 mm wide and 610 mm high, was made of 13-mm-thick plywood and was installed inside the building along the wall such that the ceiling and the south wall formed the other two sides. The plenum was insulated to prevent condensation on the outside surfaces. A series of holes were drilled in the wall and lined with PVC pipes. These holes connected the air space behind the collectors to the plenum space.

Ten storage containers stacked lengthwise were placed along the plenum against the wall; 200 water containers in the east half and 200 salt containers on the west half of the plenum. An open space, 150 mm wide was formed between the stack and the front side of the plenum. This space facilitated air movement in the plenum. Air passages were also formed between the stacks.

The storage plenum was connected to a central collection plenum which extended to the center of the barn and connected to a distribution chamber. Two tubular fans were installed at the ends of the distribution chamber. The fourth side of the distribution chamber was open to the room. The fans recirculated the barn air through two circular perforated tubings along the barn as shown in Fig. 2.

INSTRUMENTATION

Type ‘‘T’’ (copper-constantan) 22-gauge shielded thermocouple wire was used to sense temperatures throughout the system. Three thermocouples were connected in parallel to measure the outside ambient temperature. Two vane anemometers were installed in the collector plenum duct connecting the storage plenum to recirculation plenum. Prior to installation, the anemometers were calibrated in a straight circular duct against pitot tube. Two star pyranometers were installed on the eave of the building, one horizontally and the other vertically. Two wattmeters were connected in series with the three 5-kW space heaters, allowing for continuous monitoring of the electricity consumption. Wattmeter readings were taken daily. The remaining data were collected every minute, averaged over an hour, and the hourly data were stored on magnetic tape at the site. The data were later transferred to a VAX computer and calculations were performed.

SYSTEM PERFORMANCE

In the following sections, the thermal performance of each component of the solar heat collector/storage system during the experimental period is discussed.

Thermal efficiency of solar collectors

The equation used to calculate the energy collected by the collectors for any particular hour was as follows:

\[
Q_i = S \cdot V \cdot C_p \cdot \rho \cdot (T_e - T_s) \cdot 3600
\]

where:

- \(S\) is cross sectional area of the duct in which the air velocity was measured (m²),
- \(V\) is air velocity in the duct (m·s⁻¹),
- \(C_p\) is specific heat of air (kJ·kg⁻¹·K⁻¹),
- \(\rho\) is air density (kg·m⁻³).

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$T_e$ is air temperature entering building ($^\circ$C),
$T_a$ is outside temperature ($^\circ$C), and
$Q_i$ is hourly energy (kWh)

$T_e$, $T_a$ and $V$ were the hourly averaged values. Air density, $\rho$, was calculated from a psychrometric routine using $T_e$. The specific heat of air assumed constant 1.008 kJ·kg$^{-1}$·K$^{-1}$.

The collector performance was defined in terms of its overall thermal efficiency defined by:

\[
\text{Efficiency} = \frac{Q_u}{Q_a} \times 100
\]

(2)

where:

\[
Q_a = \sum_{i=1}^{n} Q_i
\]

(3)

$n$ is the number of hours, and $Q_a$ is the available solar energy on the wall (kWh) during those hours.

Table II lists the available solar heat as measured by the pyranometer, $Q_a$, the amount of heat collected by the collectors, $Q_u$, the amount of supplemental heat provided by the electric heaters. "The total heat load" is the sum of $Q_a$ and supplemental heat. The overall annual efficiency of the two solar collectors was 61%. The contribution of the solar collectors was calculated as a ratio of the total collected heat to the total heat supplied to the building (including solar heat). These calculations were based upon the assumption that in the absence of the solar collectors, the heat provided by them would have to be provided by the electric heaters. Almost half of the heat required by the barn (48%) was provided by the solar collectors.

### Table II. Long-term thermal performance of solar collections

<table>
<thead>
<tr>
<th>Month</th>
<th>Incident solar rad (kWh)</th>
<th>Total collected (kWh)</th>
<th>Supplemental heat (kWh)</th>
<th>Total heat load (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 84</td>
<td>3309</td>
<td>1934</td>
<td>2788</td>
<td>4722</td>
</tr>
<tr>
<td>Nov. 84</td>
<td>3503</td>
<td>2058</td>
<td>2395</td>
<td>4453</td>
</tr>
<tr>
<td>Dec. 84</td>
<td>4069</td>
<td>3025</td>
<td>4074</td>
<td>7099</td>
</tr>
<tr>
<td>Jan. 85</td>
<td>3771</td>
<td>2473</td>
<td>2915</td>
<td>5388</td>
</tr>
<tr>
<td>Feb. 85</td>
<td>3597</td>
<td>2465</td>
<td>2377</td>
<td>4842</td>
</tr>
<tr>
<td>Mar. 85</td>
<td>5591</td>
<td>3065</td>
<td>1890</td>
<td>4955</td>
</tr>
<tr>
<td>Apr. 85</td>
<td>3541</td>
<td>1717</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>27381</td>
<td>16737</td>
<td>16439</td>
<td>31459</td>
</tr>
</tbody>
</table>

Collection efficiency 61%
Contribution to heat the building 48%

In order to evaluate the thermal performance of water and salt, we chose three periods of moderate, cold, and warm ambient air conditions. Temperature responses of each storage medium during these typical periods are presented in the following.

### Moderate ambient air conditions

Sample air temperatures past the collectors (curve 1), past storage containers (curve 2), and the ambient air (curve 3) during 5 d in March of 1985 are plotted in Fig. 3. The effect of water had on air temperature as water underwent a phase change is evident from comparing curves 1 and 2. While curve 1 which represents temperature rise due to solar radiation shows a sharp increase followed by a sharp decrease, the temperature of the air past storage shows a much more dampened fluctuation. The time lag between the maximums of air temperature before the storage (curve 1) and after storage (curve 2) was 1–2 h. The collector temperature exhibits fluctuations ranging from a high of 56°C to a low of –19°C, but the temperature past storage remains near 0°C most of the time except during the peaks in solar radiation.

The temperature of air past the salt containers followed the fluctuations in collector temperature with 1–2 h of lag time. Unlike the water storage, curve 2 did not show any horizontal
Figure 3. Air temperatures during a moderate period.

Figure 4. Air temperatures during a cold period.

followed the collector temperature. Apparently during these warmer periods, the storage media remained in the liquid state and as a result the heat storage was in the form of sensible heat in the mass of liquid material.

In livestock ventilation, fresh air flows continuously from outside to the inside passing through solar collectors and storage. Most of the time the temperature of the solar-heated air fluctuates about 0°C. This provides a condition for water to undergo freezing and thawing and thus providing a means of solar heat storage.

**CONCLUSIONS**

Solar collector and storage system supplemented about 48% of the heat demand of a swine facility in Saskatoon, Saskatchewan in 1984–1985 heating season. Water storage containers had superior thermal storage characteristics to those of Glauber’s salt containers when outside ambient air temperatures fluctuated between 0 and −20°C. During warmer or colder periods, little phase change in either water or salt was observed. We concluded that a retrofitted solar collector combined with water as a thermal storage medium can be effective in collecting and storing solar heat.

Further work is required to test materials that change phase at temperatures less than zero. These materials may prove to be effective in storing solar heat during periods when ambient temperatures remain below zero for extended time periods.
ACKNOWLEDGMENT

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REFERENCES


Figure 5. Air temperatures during a warm period.