THERMAL CHARACTERISTICS OF A HOOP STRUCTURE FOR SWINE PRODUCTION

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ABSTRACT. *The thermal performance of a low-cost, hoop-type swine building (3.55 × 5.7 × 10.3 m) was evaluated under the winter weather conditions of Central Japan. The hoop building had two curved roofs made from 2.5 cm diameter tubular steel pipes each covered with a reflective film. There was a 20 cm air space between the inner and outer covers through which the exhaust air flowed. A positive-pressure ventilation fan and an air distribution duct were used to supply the fresh air. The evaluation was conducted for three opening configurations of the air distribution duct (one, two, or four holes on a cross-section of the duct) and presence or absence of an internal curtain. Furthermore, the effect of replacing the reflective film with a PVC film for the east side cover on solar transmission and thus the internal temperature rise was quantified. The building was simulated to house 30 pigs at a body weight of 70 kg. Resistive heating wire was used to simulate the sensible heat generation of the pigs at 131.5 W/pig at 10°C temperature.*

The inside temperature averaged 6.9°C higher than the outside temperature during the minimum ventilation period. As the exhaust air passed through the double-layer air space, 25.4% of exhaust heat transferred back into the building and 74.6% lost to the outside. When replacing the reflective covers with the PVC film covers on the east side, the internal temperature rise increased to an average of 7.6°C with a maximum of 12.7°C. The magnitude of temperature rise was proportional to the transmitted solar radiation, as evidenced by the higher temperature rise during the day and significantly reduced temperature rise at night. To eliminate the effects of cold, nocturnal radiation, the PVC film cover should be covered by the regular reflective cover at night. One-holed air duct had a tendency to produce drafts in the pig occupied zone (POZ, 1.2 × 0.7 m), whereas four-holed air duct tended to have less mixing effects on the air. In comparison, the combination of two-holed air duct and use of the internal curtain was found to be the best in achieving warmer air temperature and minimizing drafts in POZ. **Keywords.** *Low-cost swine building, Thermal environment, Air distribution.*

Modern, environmentally controlled livestock buildings generally require high capital investment. One challenge facing the producers is to reduce the cost of a building without sacrificing its environmental quality, particularly the thermal environment. Such an alternative housing system would be particularly attractive to producers who are uncertain of their long-term production situation or plans. This article describes the thermal performance of a low-cost, hoop-type building for swine production under Japanese climatic conditions.

Air temperature and air velocity have been known to be two major factors that affect pig performance. Bond et al. (1965) reported the effects of 0.18, 0.76 and 1.52 $m \cdot s^{-1}$ air velocity on 36 to 127 kg pigs in the 10.0 to 37.8°C temperature range, and found that the high air velocity significantly reduced daily gain, especially at low temperatures. The effects of 0.05 to 0.15 $m \cdot s^{-1}$ air velocity on 44 to 98 kg pigs in temperature range of 10°C to 21°C were reported by Gunnarson et al. (1967) who stated that the higher air velocity significantly reduced daily gain. Mount et al. (1980) studied the effects of 0.1, 0.45, and 0.8 $m \cdot s^{-1}$ air velocity and air temperatures of 8, 12, 16, and 20°C on pigs having a mean initial weight of 23.2 kg, and found that the variation in temperature had no significant effect on daily gain, although an increase in air velocity from 0.4 to 0.8 $m \cdot s^{-1}$ at 12°C reduced the daily gain. Riskowski and Bundy (1990) investigated the effects of 0.11 to 0.4 $m \cdot s^{-1}$ air velocity and 23.9 to 35.0°C air temperature on three-week-old piglets for a two-week period and reported that daily gain and daily feed intake were significantly affected by air velocity. The effects of air temperature on pig performance, behavior, and energetics have also been reported by numerous other researchers (Morrison et al., 1975; Hahn et al., 1987; Brumm and Shelton, 1988; Nienaber et al., 1987; Nienaber and Hahn, 1989; Xin and DeShazer, 1991).

The objective of this study was to quantify the thermal characteristics, particularly internal temperature and air flow distribution, of a low-cost, hoop-type swine building located in Central Japan. The building featured a double-layer reflective cover with exhaust air flowing between the layers and a positive pressure fresh air distribution duct. The presence or absence of an internal curtain on the environment was also examined.

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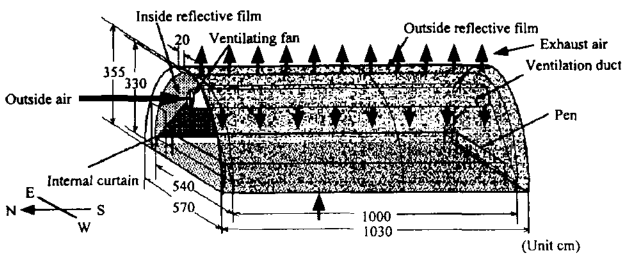


Figure 1–A schematic representation of an experimental low-cost, hoop swine building.

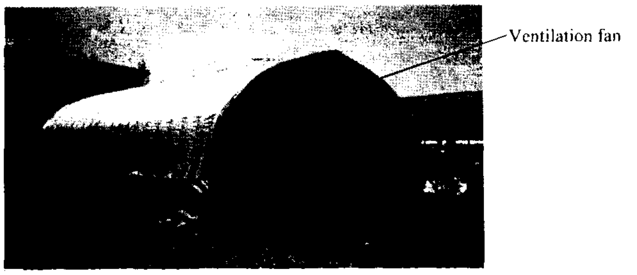


Figure 2–An exterior view of the experimental low-cost, hoop swine building.

MATERIALS AND METHODS

A schematic representation of the experimental hoop swine building is shown in figure 1. A picture of the building exterior is shown in figure 2. The building was oriented south-north with an outside dimension of 3.55 × 5.7 × 10.3 m and an inside dimension of 3.3 × 5.4 × 10.0 m. Both the outside and the inside frames of the hoop were formed by 2.5 cm diameter tubular steel pipes erected at a 0.5 m spacing. The outer cover of the hoop was an aluminized polyester fiber film (Tech-Mirror No. 38, Nihon WaveRock), and the inner cover of the hoop was an aluminized reflective film (Sunny-wide, Keiwashoukou). There was a 20 cm air space between the covers. The thermal properties of the covers are summarized in table 1.

Table 1. Thermal conductivity, emissivity, and reflectivity of the hoop structure covers

Cover	Thermal Conductivity ($W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$)	Surface	Emissivity (-)	Reflectivity (%)
Outer	6.25	Outside	0.83	37.2
		Inside	0.87	73.0
Inner	50.0	Outside	0.55	24.5
		Inside	0.24	69.5

The thermal conductivity, emissivity, and reflectivity were measured, respectively, with a thermal conductivity meter (QTM- MD, Syouwa. ±5% accuracy), an emissivity meter (AERD, Syouwa. ±0.03 accuracy), and a spectral reflectivity meter (Type-323, Hitachi. ±3% accuracy). Ventilation of the building was provided by a positive pressure system that consisted of a 38 cm diameter fan (MH-15S, Kamakura) and a 25.5 cm diameter air distribution duct near the peak of the inner cover (2.9 m above the floor). The fresh air forced the internal air into the double-layer space via the openings near the bottom of the inner cover (all sides), through the air space, and then to the outside from a peak opening of 0.2 × 10.3 m of the outer cover (figs. 1 and 3).

The measurement points and the opening configurations of the air distribution duct are shown in figure 3.

The building was assumed to house 30 pigs weighing 70 kg each with a pen measuring 1.0 × 4.0 × 10.0 m at a stocking density of 1.3 $m^2 \cdot pig^{-1}$. The pigs were assumed to stay near the center of the pen along the longitudinal line. Model pigs (measured 0.7 × 0.33 × 1.1 m), instead of real pigs were used to simulate the sensible heat production of 131.5 $W \cdot pig^{-1}$ at 10°C temperature (Okada, 1986; ASAE, 1994). Thus, a total of 3945 W of heat was generated using a resistive electric heating wire. The number of air changes (ACH) was set to be 4.4 h^{-1} which was the minimum ventilation during winter. Three different opening configurations of the air distribution duct (25.5 cm diameter) were tested, i.e., one, two, or four holes on the cross-sections of the duct. There were 110 sets of holes in the longitudinal direction of the duct, and the total opening area was equal to the cross-sectional area of the duct.

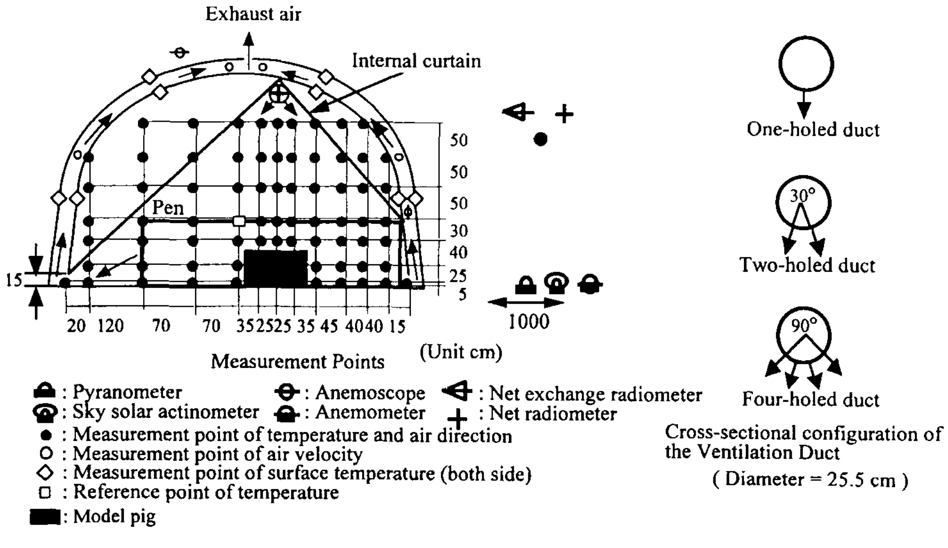


Figure 3–Sensor location and cross-sectional configurations of the ventilation duct.

In addition, air distribution as influenced by an internal curtain (fig. 3) and the building temperature rise influenced by transmitted solar radiation on the east side of the building (fig. 4) were evaluated. The internal curtain could be rolled up when the operator needed to walk along the pen. A polyvinyl chloride (PVC) film was used on the east side of both the outer and the inner covers to increase the solar transmission and thus the temperature rise in the building. The PVC film had a reflectivity of 10% and an emissivity of 0.58.

Air distribution was first measured at three cross-sections of the building, and the results were essentially identical among the three locations. Thus, subsequent measurements were conducted at the middle cross-section of the building. Air temperatures and surface temperatures were measured with 0.3 and 0.1 mm diameter T-type thermocouples, respectively. The short- and long-wave radiation were measured with a solarimeter and radiometer (CN-40, Eikouseiki). Wind velocity and direction were monitored with an anemometer (AF750, Makino) and an anemoscope (VF016, Makino), and air current direction in the building was measured with a smoke tester. The data were logged by a digital recorder (HR2500, Yokogawa) every five minutes for four months.

The heat balance of the covers was analyzed under the assumption of steady state. The heat transfer by convection was calculated using the following equation:

$$Q_{conv} = Ah_{conv}\Delta\theta$$

where

Q_{conv} = rate of convective heat transfer (W)
A = surface area (m^2)
h_{conv} = convective heat transfer coefficient ($W{\cdot}m^{-2}{\cdot}{}^{\circ}C^{-1}$)
$\Delta\theta$ = temperature difference between the cover surface and air (°C)

The convective heat transfer coefficient was calculated using the experimental equation of Jurges (Watanabe, 1965):

$$h_{conv} = 5.2 + 3.6V$$

where V is air velocity ($m{\cdot}s^{-1}$).

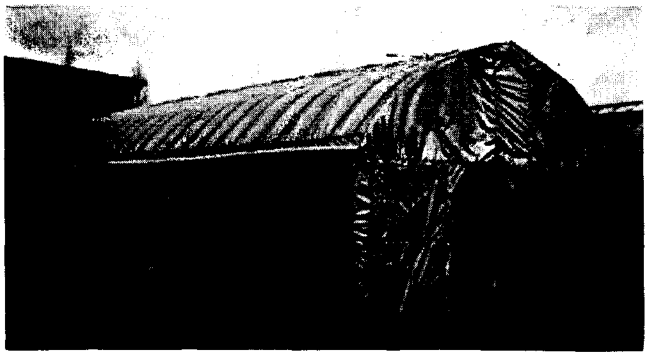


Figure 4–An exterior view of the hoop building showing the PVC film on the east side of the covers to enhance solar transmissions. The outside reflective cover was rolled up to a height of 1.8 m from the floor.

RESULTS AND DISCUSSION

EFFECTS OF TRANSMITTED RADIATION

The diurnal profiles of air temperature and all-wave radiation from the sky are plotted in figure 5. The outside air temperature varied from –3.6 to 9.4°C (mean of 2.5°C), and the average temperature inside the building ranged from 3.8 to 17.0°C (mean of 9.4°C). The average temperature inside the building was approximately 6.9°C higher than the outside temperature throughout this period. This relatively low temperature rise presumably attributed to the moderate heat generation in the building and reflection of most of the all-wave radiation from the sky by the reflective covers.

When replacing the reflective covers with the PVC film covers on the east side (1.8 m height), the temperature, all-wave radiation from the sky, and transmitted solar radiation in the building are plotted in figure 6. The corresponding temperature difference between the inside and outside of the building is shown in figure 7. The temperature difference between the inside and outside of the building varied from 4.8 to 12.7°C, with a mean of 7.6°C. The magnitude of temperature rise was proportional to the transmitted solar radiation into the building, as evidenced by the higher temperature rise during the day and significantly reduced temperature rise at night.

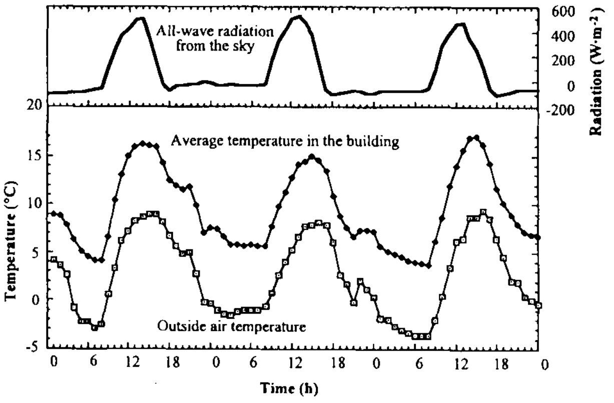


Figure 5–Temperature and all-wave radiation from the sky vs time (1/23/92-1/25/92).

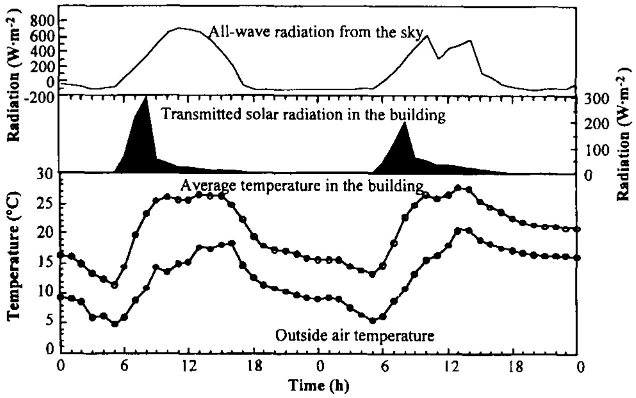


Figure 6–Diurnal variations of building temperature and transmitted solar as influenced by use of PVC film on the east side cover (4/17/92-4/18/92).

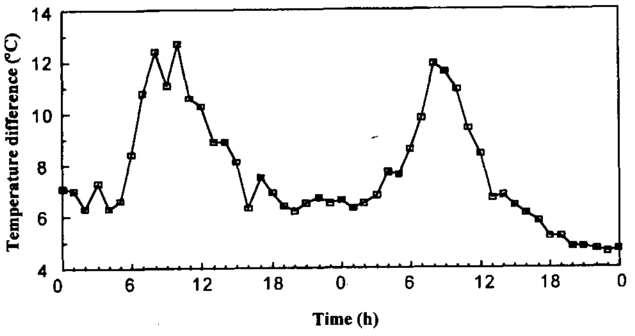


Figure 7–Diurnal variation of temperature difference between the inside and the outside of the building that used PVC film on the east side cover (4/17/92-4/18/92).

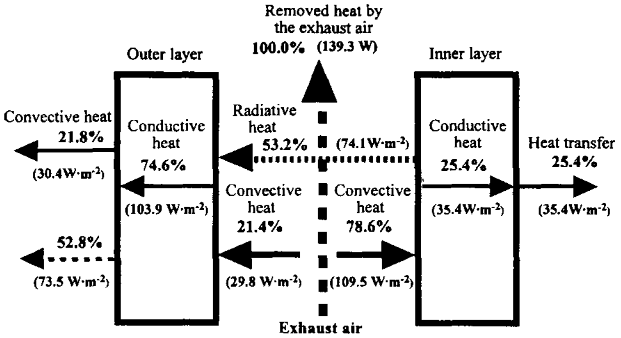
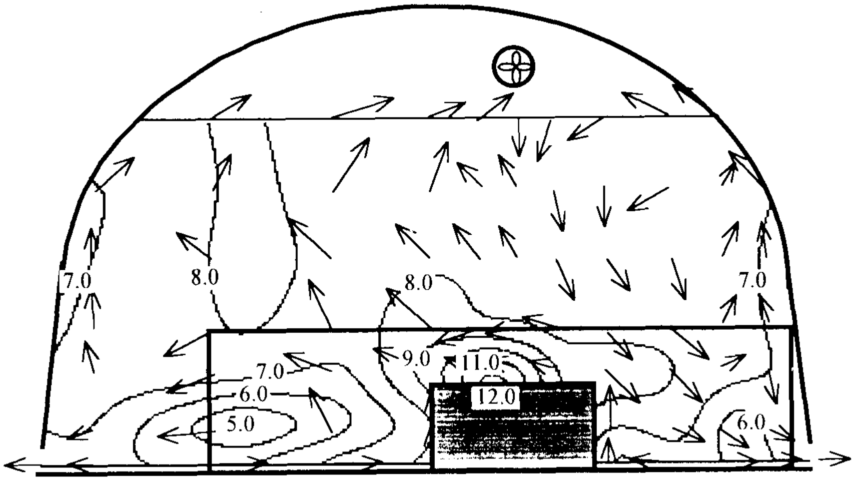


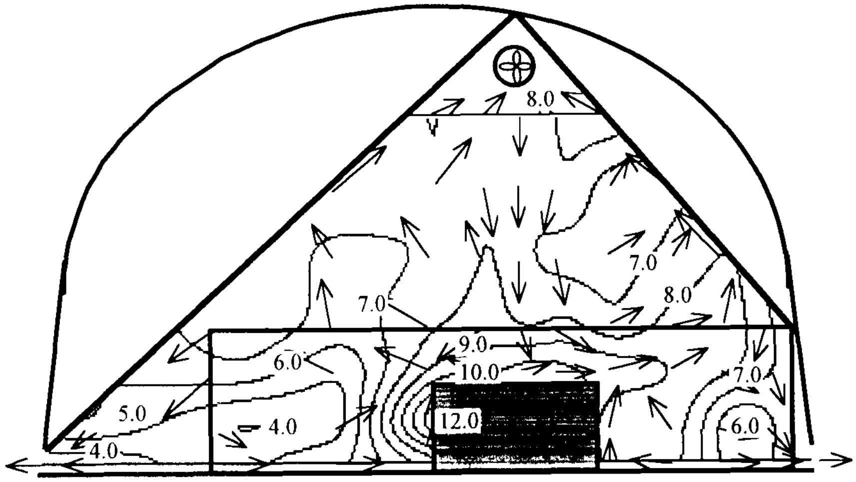
Figure 8–Partition of heat transfer when the heat removal by the exhaust air was taken as 100%.

HEAT BALANCE OF COVERS

Figure 8 illustrates the partition of heat exchange when the heat carried by the exhaust air was taken as 100%. The air velocity in the air space of the double-layer covers was less than 0.25 m·s^{-1}. For the 139W heat contained by the exhaust air, 74.6% (104W) was transferred to the outside and 25.4% (35W) was transferred back to the building. The 74.6% was further partitioned into 53.2% radiative heat



Without curtain



With curtain

(Unit C°)

Figure 9–Effects of internal curtain on temperature distribution and air flow while using single-holed air distribution duct.

from the inner layer and 21.4% convective heat from the exhaust air. The 74.6% heat loss to the outside surroundings were in the form of long-wave radiation (52.8%) and convection (21.8%). The 25.4% of net heat transfer back into the building arose from 78.6% convective heat gain from the exhaust air and 53.2% radiative heat loss from the inner layer to the outer layer. These results suggest that the cover system with the air flowing through the layers improved the heat recovery.

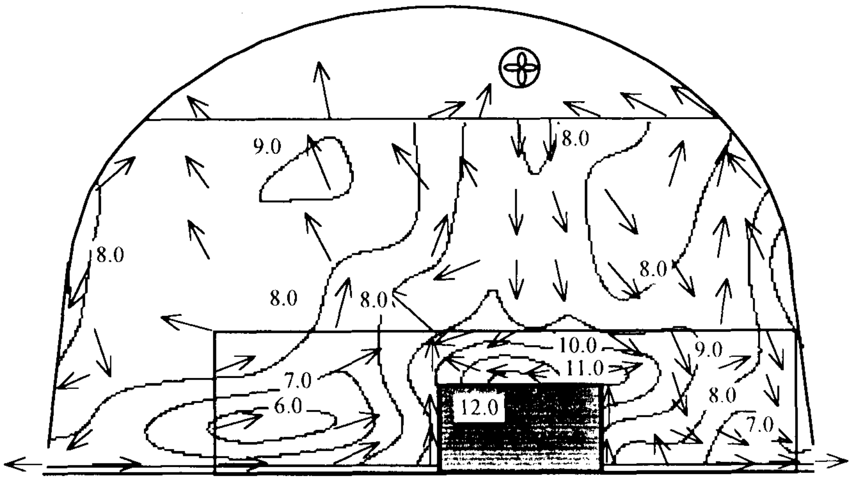
AIR DISTRIBUTION

Six air distribution patterns from combinations of three duct configurations (one, two, or four holes) and two internal curtain conditions (with or without curtain) were evaluated under the conditions of 4.4 ACH and 0.3°C outside air temperature. Air temperature distributions and air current directions for one-holed duct conditions are shown in figure 9.

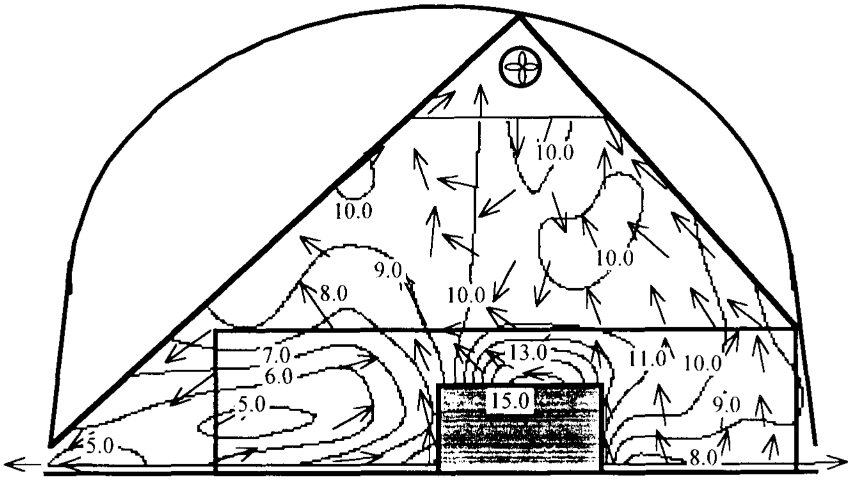
Without the internal curtain, the air jet from the one-holed duct flowed obliquely to the right side of the building which resulted in relatively stagnant air on the left side of the building. The air temperature on the right side was more isothermal than that on the left side. The highest temperature area occurred near the surface of the "pigs". With the curtain in place, the air jet flow from the duct was more vertical, and separated into two directions above the "pigs". The high temperature area occurred on the left side of the "pigs".

The air temperature distribution and air current directions for the two-holed duct configuration, with or without the internal curtain, are shown in figure 10.

The air jet from the duct passed vertically over the pigs without contacting the animal. The air current may be best divided into four zones separated by a vertical line from the duct to the pig and a horizontal line immediately above the pig. The temperature on the right side of the pen was higher than that on the left side of the pen. The high temperature area occurred near the top of the pigs both with and without curtain conditions.



Without curtain



With curtain (Unit C°)

Figure 10–Effects of the internal curtain on temperature distribution and airflow while using two-holed air distribution duct.

Air temperature distributions and air current directions under the four-holed duct, with or without the internal curtain, are shown in figure 11.

The air jet from the four-holed duct flowed downward to a height of about 2.5 m above the floor, then flowed down along the inner cover or the internal curtain. The high temperature zone was near the top of the pigs in both cases.

From the results, it could be noted that the air jet from the one-holed duct had an excessive momentum compared to that for the two- or four-holed duct, which would cause cold drafts at the pig level. In comparison, the air jet from the four-holed duct might have insufficient momentum which would lead to uneven air distribution in the building. The air jet from the two-holed duct seemed to have a suitable momentum which produced an air distribution that surrounded the pig with the higher temperatures. The average temperature in the building, pen, and pig occupied zone (POZ, 1.2 × 0.7 m), and the results of Duncan's multiple range test are indicated in table 2.

Table 2. The average temperature in the building, pen, and pig occupied zone

		With Internal Curtain			Without Internal Curtain		
Location		One*	Two*	Four*	One	Two	Four
Building	Mean	7.4_b	9.3_a	7.8_b	7.5_b	8.2_b	7.4_b
	SD	2.0	2.3	2.5	1.3	1.4	2.1
	CV†	0.3	0.2	0.3	0.2	0.2	0.3
Pen	Mean	7.6_{bc}	9.3_a	7.6_{bc}	7.5_{bc}	8.5_{ab}	7.3_c
	SD	2.3	2.6	2.9	1.8	1.8	2.7
	CV	0.3	0.3	0.4	0.2	0.2	0.4
POZ‡	Mean	9.8_a	11.4_a	9.6_a	8.9_a	10.3_a	9.5_a
	SD	2.3	3.3	3.4	2.3	1.9	3.1
	CV	0.2	0.3	0.4	0.3	0.2	0.3

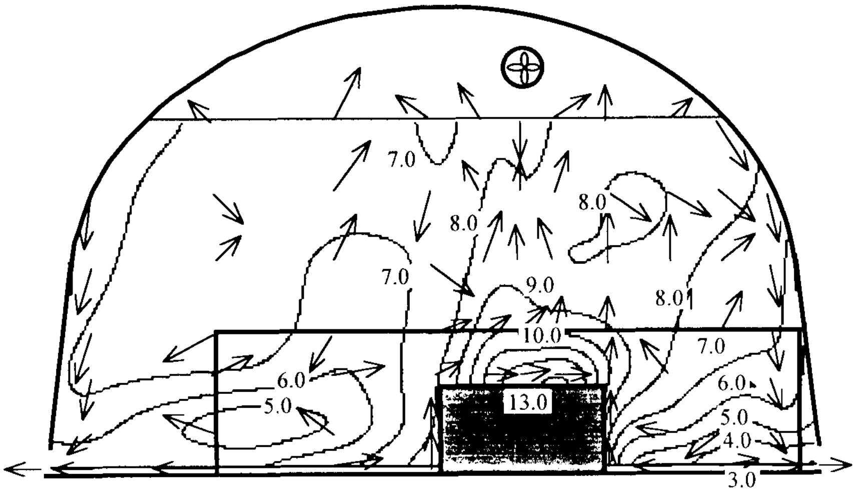
* Number of duct openings.

† Coefficient of variation.

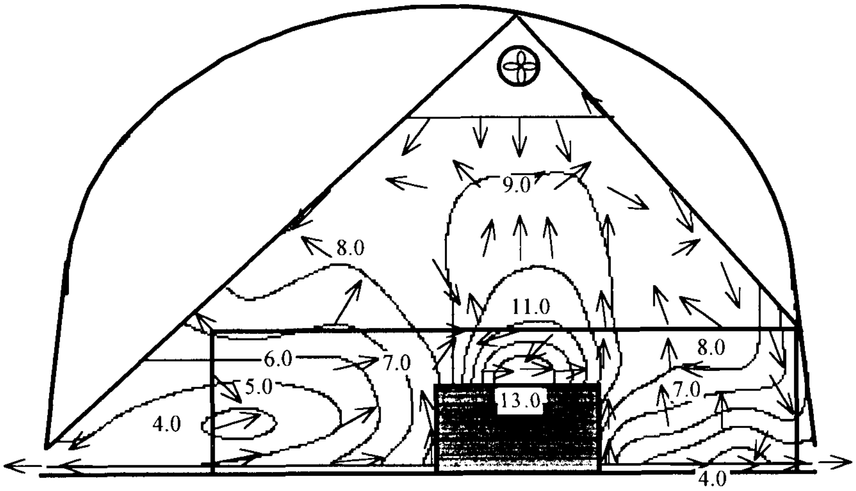
‡ POZ — Pig occupied zone (1.2 × 0.7 m).

Row means with the same superscript letters within each location and curtain condition are not significantly different ($P > 0.05$).

The average temperatures for the two-holed duct with presence of the internal curtain (9.3°C for the building, and the pen area) were significantly higher ($P < 0.05$) than the temperatures for the other conditions in the building and pen area, as shown in table 2. Although no significant difference in air temperature was detected among the



Without curtain



With curtain (Unit C°)

Figure 11–Effects of the internal curtain on temperature distribution and airflow while using four-holed air distribution duct.

conditions in POZ, the two-holed air duct with internal curtain had the highest numerical value in POZ temperature. The temperature uniformity can be reflected by the coefficient of variation (CV), which was similar for all the conditions. Thus, the combination of two-holed duct and internal curtain was considered to be best in this study in achieving warmer air temperature, and minimizing drafts in the POZ.

CONCLUSIONS

The following conclusions were drawn from this study:

1. During minimum winter ventilation (4.4 ACH), air temperature inside the hoop building averaged 6.9°C higher than the outside air temperature as a result of heat generation inside the building and partial heat recovery (25.4%) from the exhaust air.
2. A PVC film cover on the east side of the building significantly enhanced solar transmission and the temperature rise during the day (maximum 12.7°C). To reduce the effect of nocturnal radiation on internal temperature, the PVC cover should be covered with the regular reflective cover at night.
3. A two-holed air distribution duct with an internal curtain seemed to produce the best air temperature and minimal air drafts in the pig occupied zone.

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