

DEVELOPMENT AND FIELD PERFORMANCES OF A FLOOR HEATING SYSTEM with DX GSHP IN A PIGGERY

V. MINEA, Ph. D.

**Laboratoire des technologies électrochimiques et des électrotechnologies
d'Hydro-Québec (LTEE), Shawinigan, Canada**

ABSTRACT

This paper presents the conception of an original floor-heating system using a direct expansion, non-reversible ground-source heat pump in a pig nursery facility, along with a six-month winter-time field demonstration. The heating system was installed in a new, non-conventional building using a combined heat reclaim system with thermal rotary wheels and geothermal heat pumps, and an improved ventilation and air quality control. After a brief description of the system and of the experimental approach, the seasonal heating performance of the main components (building, heat pump, ground DX heat exchanger, soil, radiant floor and indoor air) are discussed. Measuring instantaneous, daily or seasonal variations of several operating parameters (temperature, pressure, energy consumption, etc.) allowed to understand how the system operated in a cold climate and to establish guidelines for improving the thermal and mechanical design of such concepts in the future. It also allowed to estimate the impact of a combined radiant floor and direct air heating system on pig-rearing.

1. INTRODUCTION

In the Canadian agricultural sector, the swine industry accounts for about 10% of the energy bill (electricity, propane, oil). For example, in a pig nursery where energy represents 6,3% of the operating costs, heating accounts for 65%, followed by ventilation (18%) and lighting (7%) (Godbout et al. 2000). Conventional pig nurseries are kept at a high indoor temperature (29°C) with electric heating lamps that entail high energy costs. However, some studies have shown that lower indoor temperatures should increase the animals' daily average gain. When a radiant heating floor is used, the objective is to create a comfortable environment for the piglets' bedding stalls at a lower ambient temperature. Floor heating systems also have the advantage of a higher winter ventilation rate, an excellent piglet performance, and a better working climate for the operators (McDonald 1994). Aside from electric heating floors, electrical energy is practically non-existent on the piggery heating market. The main objectives of this study were to demonstrate that it is possible to reduce pig nursery heating costs without diminishing production efficiency, and also to develop a new electrical heating technology based on geothermal heat pumps and heat recovery. In fact, soil generally constitutes an inexhaustible heat source and its temperature varies relatively little from one season to another. The technology uses electricity very efficiently as a primary source of energy, so that the use of fossil fuels for heating (natural gas, propane or oil) may be limited or even eliminated with many positive environmental consequences. Among the ground-source heat pump (GSHP) heating systems available, are the direct expansion (DX) systems, involving heat pumps that circulate refrigerant directly through underground heat exchangers. This generally serves to heat a radiant floor or, directly, the indoor air or hot water.

2. BUILDING AND PROCESS DESCRIPTION

The building (705 m^2) houses a nursery holding a maximum of 1800 piglets, divided into eight rooms ($0,25 \text{ m}^2/\text{piglet}$), and an office section with annexes (40 m^2) (Figure 2.1). Each room consists of a central concrete aisle, 1,2 m in width (heated) separating two sets of 8 rearing pens. The floor of these pens consists of plastic-covered metal trellises and a heated concrete bedding stall ($1,35 \text{ m}^2$). The outer walls (R-20) are covered in galvanised sheet metal and the inner walls and ceiling are made of polyethylene (R-30). During the winter, the air is expelled by a low-level extraction ventilation system including a rotary wheel, and is supplied through a perforated ceiling. During the summer, the upper-level extraction ventilation is assumed by a dedicated fan, and since the rotary wheel is turned off, another fan is used for lower-level extraction ventilation. However, when the temperature rises, the high-level extraction fan can also be used. Piglets of 4 to 6,5 kg are first transported here and accommodated in highly sanitary rooms. In order to ensure optimum growth, the winter ventilation rate must be 0,4 to 0,7 L/(s)(piglet), and the summer rate between 12 and 16 L/(s)(piglet). The average rearing period is about five weeks.



Figure 2.1 – View of the Pig Nursery Building

3. TECHNOLOGY AND APPROACH

As mentioned, the use of electrical energy for heating can often be optimised by applying the ground-source heat pump principle. In fact, the soil temperature, due to its high thermal inertia, varies relatively little from one season to another. It absorbs energy from the sun and, indirectly, from the ambient air and rain. The nursery heating system comprises four identical units, of which only one was instrumented. Each of these units heats two adjoining rearing stalls (Figure 3.1), and involves a 2,5-ton, direct expansion ground-source heat pump and an air-to-air heat reclaim rotary wheel (Figure 3.2). A supplementary heat recovery heat exchanger reheats the fresh drinking water.

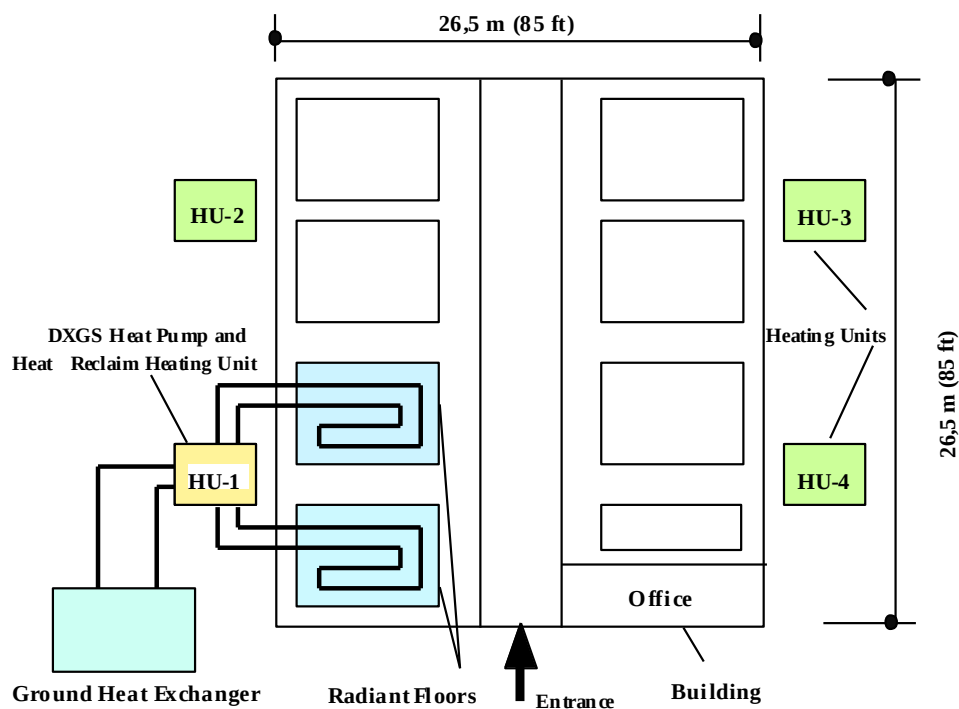


Figure 3.1 – General Placement of the Four Heating Units

The DX GSHP system recovers a part of the ground-source energy with a network of ½-inch copper polypropylene-covered tubes buried 90 cm under ground, having a total length of 360 m, with four loops going back and forth, spaced 60 cm apart. Another network of tubes, totalling approximately 140 m and spaced every 12 cm, is integrated into the concrete floor, allowing the central aisles of each room and the bedding stall of each pen to be heated. The advantages of this type of heating system include the possibility of operating at a lower ambient temperature, higher winter ventilation rate, lower heating costs, excellent piglet performance and a better indoor climate for the operators. Each refrigerant circuit is provided with solenoid valves controlled by a thermostat with its sensor installed directly on the concrete surface. Part of the superheating energy is used to heat the animals' drinking water. What is special about this refrigeration circuit is that the refrigerant also serves as the intermediate fluid between the heat pump and both floor and ground heat exchanger, the last being buried at only 90 cm deep. The rotary heat exchanger contains two air ventilators (supply and extraction), a re-heating/defrosting electrical coil, conventional air filters and various control devices. Used to preheat the air entering the building with the air being expelled, this well-known system consists of a revolving cylinder filled with an air-permeable medium with a large internal surface designed for contact with the air passing through it. The porous medium that is heated from the warm duct air-stream, rotates into the cold duct air-stream where sensible heat is released. As well, the dessicant material permits it to transfer moisture from one air-stream to another.

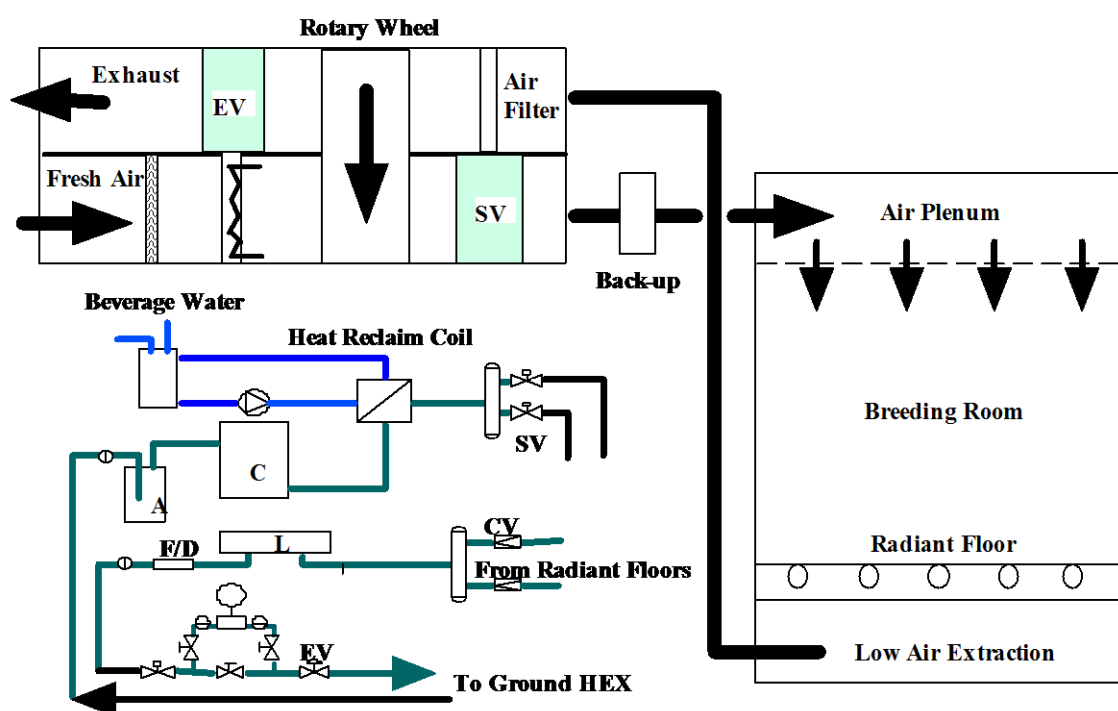


Figure 3.2 – Schematic Diagram of the Heating and Ventilation System

Measuring instruments were installed on the refrigerant circuit of the DXGS heat pump (temperature, flow rate, pressure, electrical power, operating state, etc.), on the rotary wheel, in the building's electrical panels, inside the rearing room (indoor temperature and vertical stratification, relative humidity and CO₂ concentration) and underground. The measuring equipment made it possible to reproduce and confirm the heat pump's instantaneous thermodynamic cycles and to calculate the power and thermal energy transferred, as well as the relevant coefficients of performance. The ground temperature was taken up to a depth of 90 cm. The temperature was measured with type T thermocouples, CO₂ concentration with YES-203 waves and electric power using OSI watts transducers, which were all directly connected to an HP 75 000 data acquisition device. The parameters measured within the thermodynamic cycles were scanned every 8 seconds and saved every 2 minutes. The room and soil temperatures were measured and saved at intervals of 10 minutes, while the all data recorded every 24 hours were transferred by modem to a central computer and integrated into the overall energy analysis.

4. DISCUSSION OF RESULTS

Field testing of the new heating system developed for pig farms was carried out under typical cold climate conditions, with a minimum monthly average temperature of up to -15°C and a total monthly precipitation ranging from 20 mm (April) to more than 150 mm (January). The rearing rooms were filled with 2 or 3 shipments of animals weighing on average 5 kg. During the experiment, three sets of animals (between 230 and 350) were placed inside the experimental room for rearing periods of about five weeks each. The gain rate reached 0,4 kg/day, so that the animals finished weighing approximately 20 kg each. The total monthly profile of the electrical energy consumed by the building generally corresponded to the

change in outdoor temperatures (Figure 4.1). The extremely high consumption rate in January can be explained by a momentary faulty setting control of the back-up electrical coil. During the winter, electric energy consumption just for heating represented about 42% of the total building consumption (82 kWh/m^2 or $\text{CAN}\$4,80/\text{m}^2$).

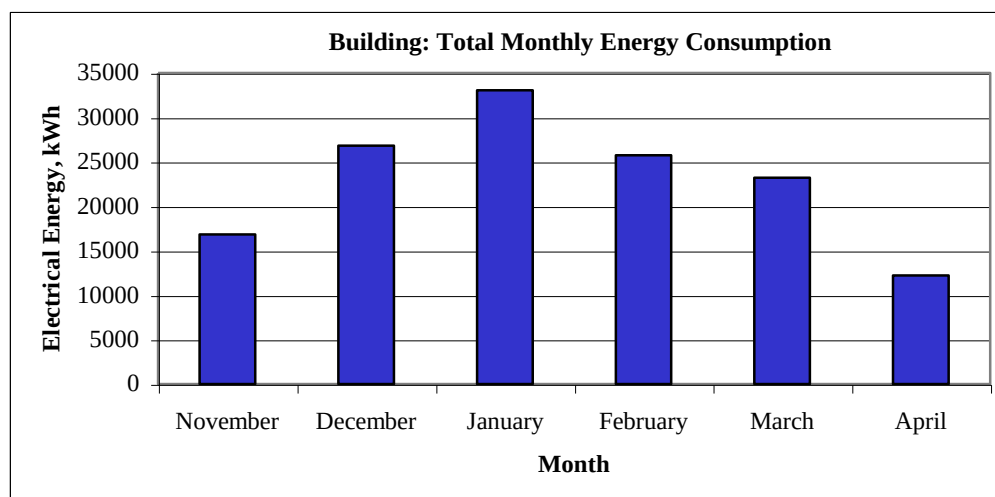


Figure 4.1 – Building Monthly Electrical Energy Consumption Profile

All tests have demonstrated that the best location for the thermostat's temperature sensors is on the radiant floor surface instead of inside the concrete. This simple arrangement extended the length of the heat pump's operating cycle (increase of 25% since the start of the experiment) and allowed better control of the animals' comfort level. The average monthly evaporation temperatures, calculated as a function of the measured suction pressure, varied between -5°C (November) and -24°C (February) (Figure 4.2), with a seasonal average of $-14,8^{\circ}\text{C}$. The suction temperature hovered around 5°C , indicating a significant amount of superheating due to the length of the pipe carrying refrigerant from the ground heat exchanger to the compressor (about 10 m), in majority located at 90 cm under ground, resulting in an efficient heat exchange.

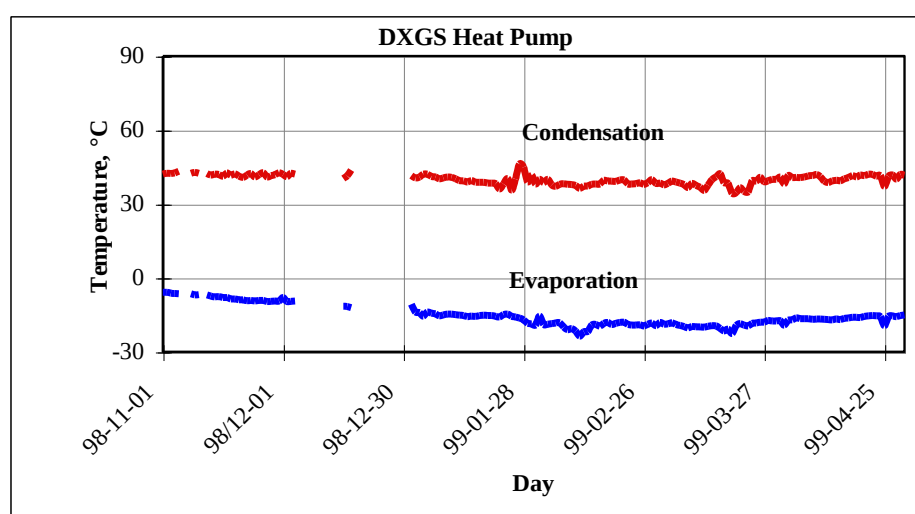


Figure 4.2 – Evaporating and Condensing Saturation Temperatures

The discharge temperature generally varied around 120°C, with the higher temperatures corresponding to the colder periods (Figure 4.3). Following each pause in the normal working cycle, the maximum refrigerant temperature was very quickly reached, as opposed to conventional hot water systems where the floor reheating period is typically longer. This positive effect was diminished in part due to the lower thermal capacity of liquid HCFC-22 as compared to that of water. As well, the heat pump developed for this project allowed the liquid refrigerant to remain in the condenser located inside the concrete slab for certain periods of time, at temperatures nearing 40°C, while the compressor was not in use. As mentioned above, part of the mass enthalpy of the compressed superheated vapour was used to reheat the animals' drinking water.

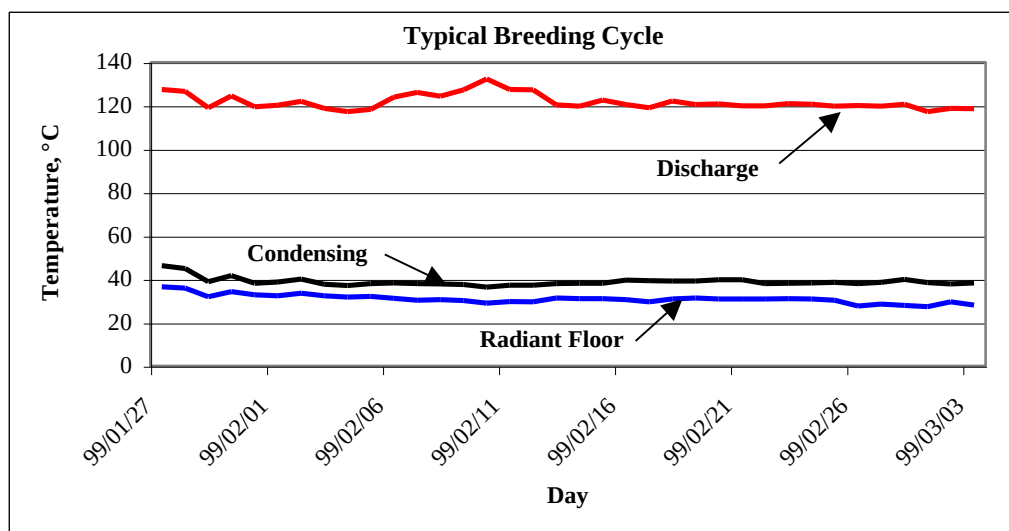


Figure 4.3 – Heat Pump's Discharge and Condensing Temperature, and Radiant Floor Temperatures during a Typical 5-week Breeding Cycle

The average seasonal condensation temperature hovered around 40°C, with a monthly average sub-cooling of 2 to 4°C, which resulted in an average seasonal radiant floor surface temperature of over 29°C (Figure 4.3). Measured compressor's inlet and outlet pressures allowed us to determine the pressure drop and the average seasonal compression ratio (5,2). So, the pressure drop through the ground heat exchanger varied between 1,1 and 2,4 kPa/m, while the average pressure drop inside the condenser hovered around 0,2 kPa/m, according to the actual refrigerant flow rate. Total energy extracted from the ground, calculated using the thermodynamic parameters and refrigerant flow rate measured during the six month period (winter), totalled 14 238 kWh, with a 6-month seasonal coefficient of performance (COP) of 3,7 (Figure 4.4).

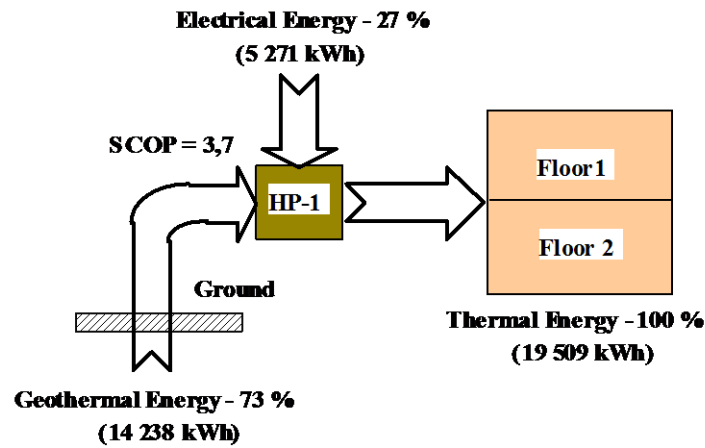


Figure 4.4 – DXGS Heat Pump 6-Month Energy Balance

In spite of the fairly low evaporation temperatures in February, the average ground temperature in the immediate proximity of the ground heat exchanger, and at the same depth, never fell below -5°C (Figure 4.5). This resulted in a significantly high temperature difference (16°C) between the heat source (ground) and the refrigerant. The sharp drop in ambient air temperature therefore did not immediately affect the temperature difference between the heat source and the refrigerant. The undisturbed soil temperatures were measured at a point situated approximately 3 m from the ground heat exchanger. The temperature in the disturbed zone was also measured at a depth of 90 cm, at a distance of about 150 mm from one of the sections of the ground heat exchanger. At that depth, i.e., at the level that the geothermal heat pump was buried, the average monthly temperature of the *undisturbed soil* varied between $7,5^{\circ}\text{C}$ (November) to $1,4^{\circ}\text{C}$ (March). However, the average monthly temperature of the *disturbed soil* varied from 6°C (November) to close to -4°C (March).

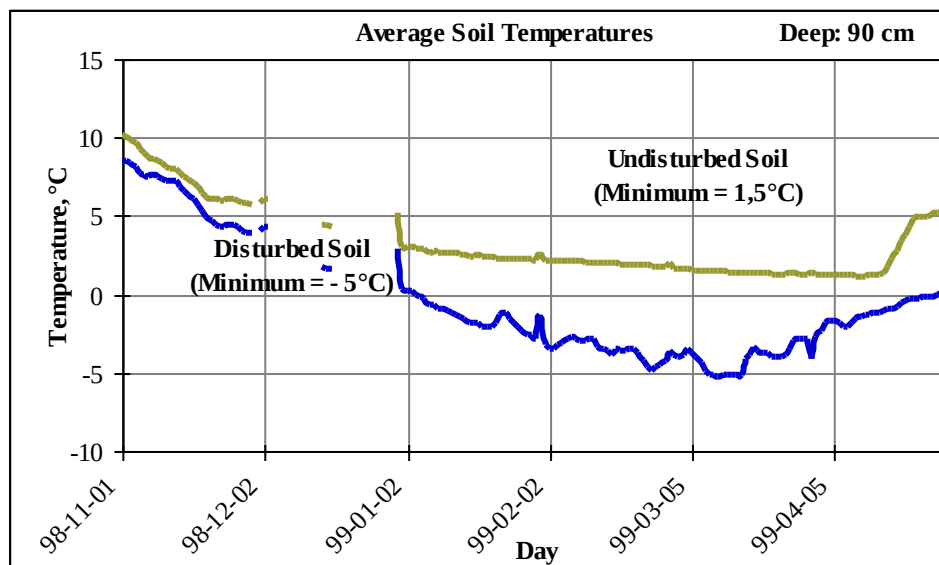


Figure 4.5 – Average Daily Temperature of *Undisturbed* (red curve) Versus *Disturbed* (blue curve) Soil

Compared to the minimal average external air temperature, the difference was quite significant, ranging from 5°C (November) to around 13°C (January), which generally favours

the use of geothermal heat pumps. In fact, the average seasonal difference between the *undisturbed* and *disturbed* soil reached 7°C (March). The instrumented rotary wheel was used to reclaim heat from the polluted air and transfer it to the fresh air. This type of device is generally very reliable and has a very high performance level. Daily profile analyses led to the conclusion that, during the entire winter season, the average air temperature at the thermal wheel outlet was approximately 9°C, which was considered insufficient for this type of heat reclaim system. The low fresh-air temperature at the outlet can be explained by the drop in thermal efficiency of the equipment, mostly due to *air filter clogging* and the lack of regular maintenance. The indoor air temperature was measured at six points on a vertical axis situated at the centre of the production area. For every new rearing cycle, the ambient temperature began at 26°C and went down to 21°C by the end, as required by the industry (Figure 4.6). At the same time, the radiant slab temperature was 36°C at the start of the experiment, and dropped to 30°C after 3 or 4 days. Afterwards, the temperature corresponded to the decrease in air temperature, which fell by 1°C every week, before reaching 26°C by the end of the cycle. The difference between the slab temperature and the set temperature varied between 7 and 10°C.

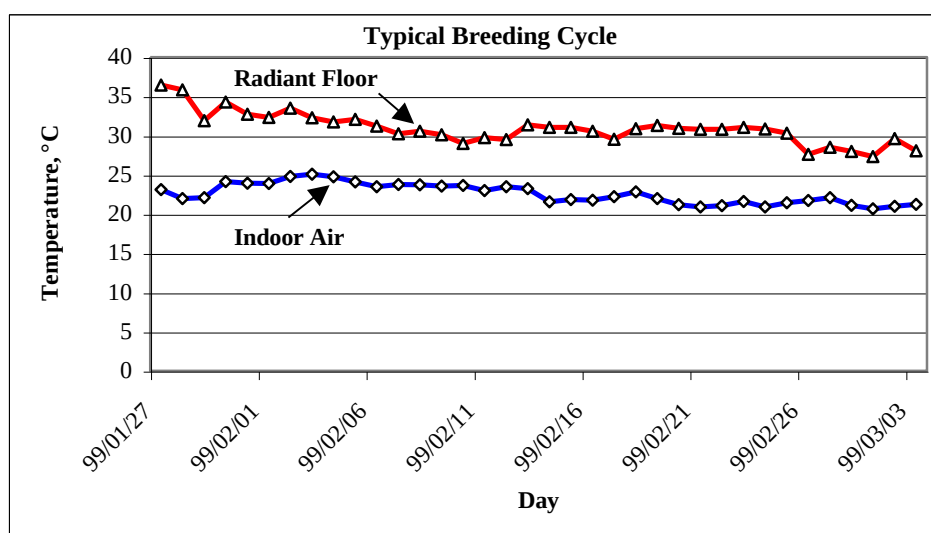


Figure 4.6 – Radiant Floor and Indoor Air Daily Average Temperatures During a Typical Breeding Cycle

It should be noted that the indoor temperature was only partly guaranteed by the heating floor and the thermal rotary wheel. The electrical back-up elements also helped compensate for the drop in efficiency resulting from clogged filters. It is also possible to observe that the original ventilation concept and its controls may be improved in order to increase the advantages of radiant floor heating by heat pump. In fact, the thermal wheel alone was insufficient to ensure full back-up heating during the cold periods of the year. Indoor air relative humidity varied as well, although they were occasionally too low at the beginning of each rearing cycle (40%). This low relative humidity was explained by the absence of fuel combustion and the low level of latent heat produced by small piglets. The concentration of CO₂ (Figure 4.7) consistently fluctuated between 2000 and 3000 ppm, even if during this period, the piglets were small and generated very little CO₂. As opposed to conventional buildings, the absence of fuel combustion should result in very low CO₂ concentrations (between 500 and 1000 ppm). This situation was mainly attributed to poor ventilation and an insufficient air-flow rate through the thermal wheel.

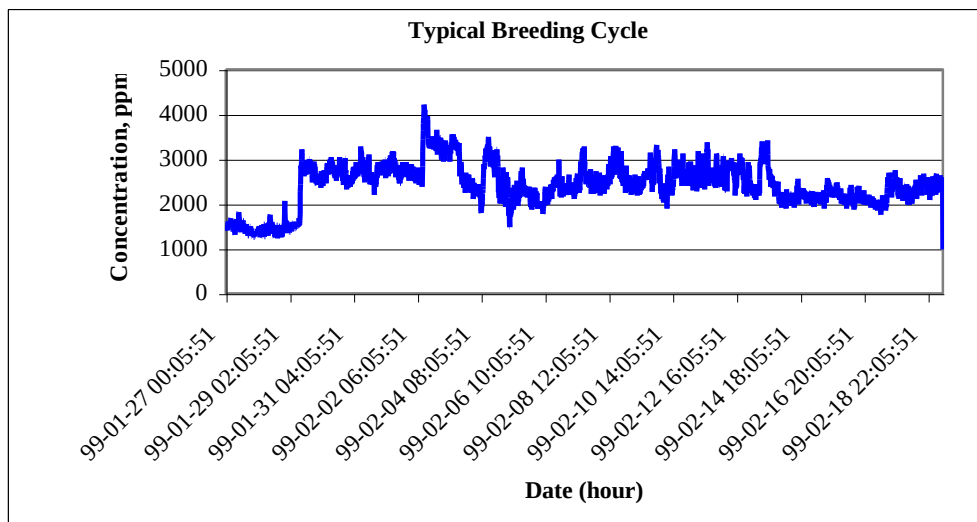


Figure 4.7 – Indoor CO₂ Concentration During a Typical Breeding Cycle

In fact, the thermal wheel's air-flow rate was adjusted to 1400 cfm under ideal conditions, without taking into account the clogged filters, other losses in pressure and possible air leaks. The efficiency of the thermal wheel was, on average, 45%, although this figure should have been 65% with peaks reaching 75% or more. The annual production cost of the nursery under study was CAN\$0,83/piglet/year, while the value in the province is about CAN\$0,925/piglet/year (Godbout et al. 2000). On the other hand, the cost of the new heating technology, during this early prototype phase of development, was almost twice as much as conventional technology, so that the simple pay-back period remains for instance too high for producers. However, the initial cost may substantially decrease in the future with an increasing number of field implementations, and by reducing the specific cost of the refrigerant-to-ground/slab, special gained pipes.

5. CONCLUSIONS

A nursery-type building was targeted in order to develop a new heating system, because this stage of piglet-rearing requires a high ambient temperature. This system used four air-to-air heat-reclaim rotary wheels and four non-reversible, direct expansion heat pumps with horizontal ground heat exchangers buried at a depth of 90 cm. The instrumented unit operated about 61% of the time during a six-month winter field test, with a seasonal coefficient of performance of 3,7, signifying that 73% of the energy consumed for heating floors and drinking water was supplied by the soil. The average seasonal thermal power of the ground heat exchanger was 5,4 kW, equivalent to a specific capacity of about 15 W/m. The average seasonal temperature of the concrete floor was over 29°C, which generally met the animals' average comfort requirements. However, the energy efficiency of the rotary wheel was depleted due to the filters having been clogged by polluted air and lack of maintenance. Its thermal efficiency in fact went from more than 75% immediately following a filter change, to less than 30% at the end of each rearing cycle. It was therefore suggested to use water-washable filters and more frequent maintenance. Generating heat by a geothermal heat pump, thermal wheel and electrical back-up coils produced a very homogeneous vertical thermal stratification of indoor air, with average daily temperatures going from 25°C at the beginning up to 21°C at the end of each rearing cycle. This shows that the system adopted in this experiment lowers the indoor air temperature by 5°C at the beginning of each cycle and by a

further 0,5°C each subsequent week. Finally, the seasonal (winter) average power demand for the building was about 44 W/m², while the specific energy consumption was approximately 195 kWh/m². About 42% of this energy was used to heat the building. The average obtained gain rate of the animals finally was of 0,4 kg/day. The heat pump only consumed 15% of the total heat energy, due to its relatively short period of use. The space and water heating with a DX GSHP was a true success also because the system reached and maintained the optimal surface temperatures targeted for the heating slabs (28°C to 31°C) for each production cycle. However, integrating the thermal wheel into the ventilation system in order to reclaim heat would require a more profound analysis to determine the productivity and/or relevance of this type of application. Future developments aim to increase the capacity of the thermal wheel ventilators to compensate for progressive filter clogging, identify a more efficient and effective procedure to clean the filters and/or develop new self-cleaning filters, automate the lower-level extraction ventilators, refine the control mechanisms, separate the exchangers under the central aisle and bedding stall slabs and increase the period of use of heat pumps in order to improve seasonal efficiency, i.e., by using geothermal energy even to preheat the outdoor fresh air.

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