Thermal modeling of an annualized geo-solar building
By: David Elfstrom

Abstract

Annualized geo-solar (AGS) is an innovative and affordable "net zero energy" approach to solar heating system design. After installation, space heating of a well-insulated, one-storey passive solar building with slab-on-grade foundation can be met without additional energy inputs or costs.

In the summer season, a fan-driven AGS system removes hot air from a roof plenum and circulates it through a duct one or two meters deep running along the centerline of the building from one end to the other. Heat is released to the soil, and the cooled air returned to the roof. Once the roof temperature is lower than the storage medium, air circulation is stopped. Thermal properties of soil effectively store the heat by delaying heat transfer to the floor by up to six months, with early summer heat arriving in early winter at the floor. An insulation cape and water barrier extending beyond the building below grade diverts water runoff, prevents heat loss, and protects the foundation from frost.

Performance data of annualized geo-solar buildings is hard to find in the literature. In 2006, students of Fleming College constructed an AGS building near Minden, Ontario with temperature sensors in appropriate locations. This paper describes a simulation of the building's annualized geo-solar heating system with HEAT2 software and suggests AGS design concepts applicable to future buildings requiring an inexpensive "net zero energy" heating system.

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1. The Kinark Sustainable Living Centre

The Sustainable Living Centre at Kinark Outdoor Education Centre is a single-storey building with external wall footprint area of 135 m2 (1450 ft2) located near Minden, Ontario, Canada. Constructed in 2006 by students of Fleming College's Sustainable Building Design and Construction program under direction of instructor and program coordinator Chris Magwood, the building features extensive use of natural materials including straw bale walls, a round log structural frame, and a clay-sand slab floor. The foundation is a shallow frost-protected double-wall insulated grade beam made from flexible-formed rammed earth (Magwood 2006). Frost protection consists of below-grade insulation panels extending up to 4 m out from the building. The panels are a mix of expanded polystyrene sheets and waste insulated steel door cutouts.

The building was designed for winter passive solar gain, including minimal north glazing, and optimal south exposure, with appropriate roof overhang for summer shading. It is predominantly a rectangular shape with the long dimension situated east-west.

The main heating system is a hot water radiant mass wall located in the centre of the building, fired by a propane boiler. Like the foundation, the radiant wall is made from flexible-form rammed earth with the water pipes placed between courses of the earth-filled bags. The wall is finished in with an earthen plaster surface.

Annualized geo-solar is a secondary heating system for the building. This implementation, with material cost of approximately $500, features a closed-loop air duct system powered by two 11 cm diameter axial fans. The fans circulate air heated in the roof plenum, down an insulated duct to approximately 2.8 m (9 ft) underground, then horizontally along the east-west length of the building where heat is released to the ground (Figure1). Cooled air returns in the loop to the roof, where the cycle continues.

The site soil is predominantly a well-drained natural sand deposit. The spring season water table is at least three meters below the surface, which is important because groundwater in contact with the thermal mass store will conduct heat away from the building (Hanks 1992). The shallow insulation skirt with a vapour barrier directs rainwater away from the building, protecting the ground below from being robbed of its heat by the migration of rainwater into the soil (Stephens 2005).

In this implementation, each fan is powered by a 15 W photovoltaic panel, costing an additional $170 each, allowing for a simple control of air speed in proportion to incident sunlight. For the winter season, the fans are switched off. Dampers located in each vertical duct section are used to close off the duct and further restrict airflow during the winter.

The south roof surface is dark grey metal, chosen to increase solar heat capture. Aluminum foil on the roof deck below the collection ducts reflects radiant heat back on to the heat capture pipes, improving heat collection and reducing summer heat gain through the roof.

Ductwork is a combination of salvaged PVC water pipe in the roof plenum, and 11 cm diameter high-density polyethylene flexible pipe, also known as “Big O”, in the underground duct and vertical ducts. Expanded polystyrene and waste carpet below the buried duct section prevents some heat from moving further down and away from the building.

Digital temperature sensors were installed in the duct to measure heated air temperature exiting the roof, and cooled air exiting the ground. Temperature sensors were also placed in the ground under the centre of the building footprint at depths of 0.9 m (3 ft) and 1.8 m (6 ft).

The building was completed mid-August 2006, and the solar hot air collection system ran for approximately one month. During this time, duct air exiting the roof reached temperatures between 50 to 60°C on sunny days, and the return air re-entering the roof was cooled by the ground to 9°C (Elfstrom 2006).

Design of the AGS system was created under tight time constraints during construction using published simple guidelines (Stephens 2005) but without calculations or modeling of the system.

2. Thermal modeling

To model the annualized geo-solar system of the Sustainable Living Centre, a representational cross section was created using HEAT2 software. HEAT2 is a PC-program for modeling heat transfer in two dimensions, produced by the Lund Group for Computational Building Physics (Blomberg 2000).

Because of symmetry, only one half of the cross-section needed to be created. Thermal conductivity for materials was selected from the building material data library supplied with HEAT2.

The soil's effective thermal conductivity was calculated to be 0.9 W/(m.K) with volumetric heat capacity 1.75 MJ/(m3.K), following published guidelines (Balland 2005, Côté 2005, Farouki 1986). Heat transfer in many soils, including the sandy soil beneath the Sustainable Living Centre, occurs primarily through conduction. Other forms of heat transfer such as convection and radiation were accounted for in determining the effective thermal conductivity of a soil (Farouki 1986). Visually the site soil was highly uniform with depth and so thermal conductivity was also assumed to be uniform in both directions. Physical samples of the soil were not properly sealed, so direct measurements of thermal conductivity unavailable. The soil could still be tested using appropriate equipment.

Average daily outside temperature was modeled using the built-in sinus function in HEAT2. A mean temperature of 5°C was chosen with amplitude of +/- 10°C from the mean and a phase shift of three months. The function results in a curve that closely follows monthly average data from both satellite-derived meteorology and local temperature records (Stackhouse 2006, Minden 2007)

All other values of heat or temperature applied to the boundaries of the model (boundary conditions) were made adiabatic, meaning that no heat is to flow across the boundary. The heat source for the deposit tube was modeled as a stepwise linear time function of temperature, based on observed data from the system during its first month of operation, from building completion in late August until late September (Elfstrom 2006). In the simulation, the air collection system is run from April 1 to October 1, and then switched to an adiabatic boundary for the winter season until the following April 1.

The average ground temperature, which in a uniform soil starts at approximately 12 m deep, was unknown. For the model, the average air temperature of 5°C was used for the average deep ground temperature. Within a small range, a one degree average ground temperature rise results in approximately a one degree temperature increase at any given point. The two-dimensional ground temperature field was initialized by running 10 simulated years of ambient air temperature data on bare ground. If data exists for soil temperature with depth, this could be used to establish the initial temperature field and provide an accurate measurement of average ground temperature.

A computational mesh of 10,000 units was used (Figure2). Increasing the mesh size beyond this number slowed down calculation time and did not alter output.

3. Results

In the simulation, the AGS system increases floor surface temperature of the unheated building by 2–2.5°C (Figure3). This was less than expected. Stephens (2005) described a temperature increase in the Mica Peak residence of 7°C after three years, but this could be due to additional passive solar gain on the mass of the structure itself.

In an attempt to obtain higher temperatures the model was altered by bringing the heat deposit duct half the distance it originally was from the floor, and doubling the amount of collected heat. Additional insulation was added under the slab to dampen the surface temperature response. This resulted in raising the April average floor temperature only about 0.5°C, but also raised the average floor temperature at the October peak by 6°C.

The simulation also shows the shallow grade-beam foundation is kept free of reaching frost-forming temperatures by the shallow insulation skirt, never reaching zero degrees Celsius, with or without AGS (Figure4).

4. Conclusions

The HEAT2 manual suggests it may take 10 to 15 simulated years for transient calculations to reach a semi steady-state, year-on-year (Bloomberg, 2000). Furthermore, Stephens (2005) reports the unoccupied holding temperature of the Mica Peak residence increased about 2.8°C each winter for three winters. This type of 'charging' delay did not appear in the simulations. In fact, the modeled system very quickly stabilized within two simulated years, even from a uniform background temperature as a starting condition.

Further research is required to refine a modeling method for AGS heating systems to match the observed gains noted by Stephens. For example, the large sealed insulation skirt characteristic of AGS designs likely contribute to a slow reduction in soil moisture content beneath the building footprint. This will change the heat capacity and conductance of the soil over time, and may result in fewer losses from the heated mass.

This model investigated only the effects of the annualized geo-solar heating system for providing winter heat. A full building simulation including passive solar radiation absorption would predict the base indoor temperature of the otherwise unheated building.

Other well-insulated ground-coupled passive solar buildings in the same region never drop below 10°C (CMHC 2006). With the addition of a well-designed annualized geo-solar system, the minimum unoccupied winter floor surface temperature may then be 12–15°C with AGS, or even 18°C, based on Stephens' experience.

Annualized geo-solar implemented in a building with an airtight, highly insulated passive solar design should result in a true "net zero energy" self-heated shed, garage, or single-storey residential bungalow at a comfortable ambient temperature year-round.

Works Cited

Balland, Vincent and Arp, Paul A. "Modeling soil thermal conductivities over a wide range of conditions." Journal of Environmental Engineering and Science 4 (2005): 549–558

Blomberg, Thomas. HEAT2: A PC-program for heat transfer in two dimensions. Manual with brief theory and examples. Department of Building Physics, Lund University: Lund-Gothenburg Group for Computational Building Physics, 2000.

Côté, Jean and Konrad Jean-Marie. "A generalized thermal conductivity model for soils and construction materials." Canadian Geotechnical Journal 42.2 (2005): 443–458.

Design guide for frost-protected shallow foundations. U.S. Department of Housing and Urban Development; Office of Policy Development and Research, 1994.

Elfstrom, David. Records in personal construction journal. Aug. 2006.

Farouki, Omar T. Thermal properties of soils. Clausthal-Zellerfeld, Germany: Trans Tech Publications, 1986.

Hanks, Ronald John. Applied soil physics: Soil water and temperature applications. Castleton, New York: Springer-Verlag, 1992.

Low impact housing. Canada Mortgage and Housing Corporation. Aug. 2006. Accessed 20 April 2007. <http://www.cmhc.ca/en/inpr/bude/himu/loimho/upload/65039(w).pdf>.

Magwood, Chris and Elfstrom, David. Sustainable Living Centre at Kinark Outdoor Centre. 1 Dec. 2006. Fleming College and Kinark Outdoor Centre. Accessed 20 Apr. 2007. <http://www.sustainablebuilding2006.ca>.

Minden, Ontario, Canada. 8 Mar. 2006. Environment Canada National Climate Archive. Accessed 1 Apr. 2007. <http://climate.weatheroffice.ec.gc.ca/>

Stephens, Don. Annualized geo-solar heating as a sustainable residential-scale solution for temperate climates with less than ideal daily heating season solar availability. Sep. 2005. Global Sustainable Building Conference, Tokyo, Japan. Accessed 30 Apr. 2006. <http://www.greenershelter.org/TokyoPaper.pdf>.

Stackhouse, Paul W. and Whitlock, Charles H. Surface meteorology and Solar Energy (release 5.1). 8 Mar. 2006. NASA. Accessed 1 Apr. 2007. <http://eosweb.larc.nasa.gov/sse/>.