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GEOTHERMAL HEAT PUMPS: Design Tools and Simulation Software

Jeff D. Spitler
Oklahome State University

KEY WORDS

heat pumps, geothermal heat pumps, ground source heat pump systems, ground coupled heat pump systems, ground loop heat exchangers, boreholes, BLAST (Building Loads Analysis and Systems Thermodynamics)

PROJECT BACKGROUND AND STATUS

The primary focus of work during the first phase period has been the development of a method for developing new configuration data on the fly. in order to accomplish this several different approaches involving the use of transfer functions have been investigated. Two approaches have been moderately successful, a heuristic transfer function and a Box-Jenkins approach. The two approaches are discussed below.

The primary focus of work during the second period has been the development of short time-step methods and their superposition with potential long time-step models such as the transfer function approaches reported. A two-dimensional borehole model based on short time-step transients has been investigated. A preliminary model validation has been performed with good results.

PROJECT OBJECTIVES

The general objective of this project is to expedite the selection and design of ground-loop heat exchangers for commercial-building ground source heat pump systems. In order to accomplish this, improvements in the currently available design tools and methods are necessary. The specific objectives are listed below:

- Continued integration and technical support of existing ground loop heat exchanger models with water loop heat pump system models (which originally were for boilers and cooling towers, such as BLAST, Trane Software, etc.).
- Develop techniques using short time-step methods to evaluate hourly temperature for studying time-of-day variations.
- Development of models for borehole thermal testing which takes into consideration variationa in load inputs.

APPROACH

TRANSFER FUNCTION APPROACH TO DEVELOPING NEW CONFIGURATION DATA

Heuristic Approach

As a preliminary step, the following approach has been taken to simulate the average borehole temperatures over an extended period of time. The average temperature of a given single borehole (output) at the end of a month is assumed to be a function of past average borehole temperatures (inputs), a function of heat transferred (also inputs) within the borehole and a function of the constant far field temperature. At the start of the heat pump operation, the initial borehole temperature is set to be constant and equal to the specified far field temperature. The general equation for the average borehole temperature for a given month then can be expressed as follows:

$$T_i=AT_{i-1}+BT_{i-2}+CT_{i-3}+\ldots.+NT_{i-n}+(\mathtt{Coeff.})T_{FarField}+A'q_i+B'q_{i-1}+C'q_{i-2}+N'q_{i-n}$$

where

T_i = The average borehole temperature at the end of month i.
T_{i-n} = The average borehole temperature at the end of month i-n.
q_i = The average heat flux per unit time and length of the heat exchanger pipe at the end of month i.
q_{i-n} = The average heat flux per unit time and length of the heat exchanger pipe at the end of month i-n.
A,B,C,.....N,A',B',C'...N' = Transfer function coefficients.
$T_{FarField}$ = Constant far field temperature.

A number of combinations of different numbers and types of tranfer function terms have been evaluated. To date, the best results have been obtained by incorporating 13 coefficients into the transfer function modified as follows:

$$T_i=AT_{i-1}+BT_{i-2}+CT_{i-3}+DT_{i-4}+ET_{i-5}+FT_{FarField}+A'q_i+B'q_{i-1}+C'q_{i-2}+D'q_{i-3}+E'q_{i-4}+K\sum_{j=1}^{i} q_j+\frac{L}{i}\sum_{j=1}^{i} T_j$$

Figure 1 shows the close conformity of results obtained using the 13 coefficient transfer function with two more detailed methods.

Box-Jenkins Transfer Function Modeling

The second approach involved the use of a Box-Jenkins transfer function for forecating single borehole temperatures.

A multivariate transfer function analysis is required since the Box-Jenkins transfer function model refers to a model that describes the current value of a time series data set (the output series) on the basis of past values of this series and past and present values of one or more related time series (input series). In the analysis at hand, the monthly heat flux terms and past average borehole temperature observations represent the input series based on which forecasts are made for current and future average borehole temperatures.

In addition, this statistical model is applicable since no dramatic fluctuations and interventions in the input data series are expected. In fact, the assumption is made that one of the input series (the monthly heat flux terms) repeats itself seasonally for the duration of the of the forecasting period. In general, the applicability of a Box-Jenkins type forecasting may be questioned for long-term forecasts in cases where the time series data set itself and inputs that influence the data set display strong fluctuation patterns since this method is primarily used for relatively short-term forecating. Box and Jenkins (1976) basically recommend as a rule of thumb that to forecast a single season an input series of three seasons be used.

A univariate model that is only based on past average borehole temperatures is also developed. Such a model does not consider any past or present values of any input time series in a borehole. Even though a multivariate model is theoretically expected to produce better forecasts, simply because more information on the data set is available than just its past values, Pankratz (1983) states that some analysts argue that univariate models frequently approach or exceed the forecating accuracy of multiple-series models in practice. Works of Cooper (1972), Naylor et al. (1972), and Nelson (1973) should be consulted for further studies that discuss and compare the accuracy of multivariate and univariate models.

The univariate Box-Jenkins auto-regressive integrated moving average modelling (UBJ-ARIMA) procedure is based on initially estimating the auto-correlation and the partial auto-correlation behavior of a given time series data set and comparing these to theroretical auto-correlation and partial auto-correlation functions for auto-regressive and/or moving average models. Once a consistency is observed between the estimated and theoretical functions of auto-correlation, the error terms (the residuals) are investigated in regards to their auto-dependency and distribution behavior. If the error terms are in fact independent and normally distributed, the model is fitted to the data.

The multivariate transfer function model is based on a three-step procedure: identification, estimation and diagnostic checking (Pankratz, 1983; Box and Jenkins, 1976). In the identification stage, an UBJ-ARIMA model is identified to describe the input series. based on this UBJ-ARIMA model, a preliminary transfer function model is identified that describes the output series (monthly average borehole temperature values) in the estimation stage. Finally, a transfer function model is determined using the statistical residuals of the preliminary model that describe the error structure of the preliminary model.

The general form of the multivariate transfer function equation is defined as follows (Box and Jenkins, 1976):

$$Z_t=\mu+\frac{\omega(B)}{\delta(B)}B^b Z_t^{(x)}+\eta_t$$

where

Z_t = Output series
μ = Mean of the output series
$\omega(B)$ = The so-called numerator function denoting the order of differencing for the input series.
$\delta(B)$ = The so-called denominator function denoting the order of differencing for the output series.
$Z_t^{(x)}$ = Input series
η_t = Error term
B = Backshift operator

The multivariate Box-Jenkins transfer function modeling and the univariate Box-Jenkins ARIMA modeling were performed on all six different building load configurations using 48 monthly temperature observations obtained from the Hart and Couvillion line source solution.

The analysis of the multivariate model was compared with the univariate model. No significant deviations were observed. The modeling was performed using the SAS and SYSTAT software packages. The average borehole temperature forecast results of the Box-Jenkins analysis were compared to the Hart and Couvillion line source solution results and compared very well, e.g., see Figure 2.

SHORT TIME-STEP MODEL AND ANALYSIS

the model for predicting the short time-step ground loop heat exchanger behavior is based on a two dimensional, transient finite volume (numerical) model.

The numerical model developed to represent the borehole, U-tube, grout and the surrounding soil has the following features:

- Two-dimensional, transient finite volume model in cylindrical coordinates. The approximate grid is shown in Figure 3.
- Intermediate grid coarseness - the numerical model is developed as a computer program which incorporates an automated yet constrained grid generation routine using the borehole geometry as input.
- Implicit, 5 minute time-steps.
- The pipe geometry is represented as a "pie-slice-shaped" sector.
- The model takes advantage of the symmetry in the Theta-direction of the borehole domain as shown in Figure 3 to set zero flux boundary condition in that direction. The boundary condition in the r-direction also states that no heat exchange is taking place at a far enough distance from the center of the borehole domain.
- The simulation takes about 11 seconds on PentiumPro/200 for a 12 hour test at 5 minute intervals.

The numerical model is still being refined, though it seems to work fairly well at present. The model is adaptable to user-defined pipe and borehole geometries as well as grout types. Planned refinements are mainly in the area of model optimization (improved modeling of the convective heat transfer, improved handling of undistributed ground temperature adjustments) and computer program code optimization.

Some preliminary attempts at experimental validation of the model have been made. Several experimental tests have been performed at the Oaklahoma State University "Site A"-field. The tests simulated continuous and cyclic system operations. Figure 4 shows a comparison between the temperature predicted by the numerical model and the experimentally determined temperatures for the on/off cycling simulation. This is somewhat of a "torture" test of the model likely to yield worst-case results. The results yield a relatively good match even for this case of strong load fluctuations. Figure 5 shows a comparison between numerical and experimental temperatures for the continuous system operation simulation.

Currently available system design and simulation models such as the line source or cylinder source models work relatively well for long time-steps, say monthly or weekly time steps. However, the accuracy of the models decreases dramatically as these models are applied for short time-steps (hourly or less). Conversely, the numerical model described above works very well when applied to short time-steps, but would be infeasible to apply for each borehole in a large borehole field.

One appraoch to solving the problem is to superimpose a long time-step solution which can represent the borehole-to-borehole interaction and long-term heat build-up in the borehole field with a short time-step solution of a single borehole which can represent the hour-by-hour variations in temperature. In other words, the numerical model is being superimposed onto the transfer function model to combine short and long time-step system behavior. The research in this area is still ongoing. More details and results on this issue will be filed with the next progress report.

RESEARCH RESULTS

Several important results have been obtained:

- The Heuristic Approach using the 13 coefficient transfer function conforms closely with results obtained from two other detailed models.
- The average borehole temperature forecast results of the Box-Jenkins analysis were compared to the Hart and Couvillion line source solution results and compared very well.
- The short time-step model results yield a relatively good match between temperature and time when compared to experimental data even for the case of strong load fluctuation.
- The short time-step model was applied to a single borehole, but a superposition method combining transfer functions and numerical models is required for multiple boreholes.

FUTURE PLANS

Future plans include a number of further refinements to the design tools both in convenience and accuracy. The improvements in accuracy will primarily be aimed at allowing better comparisons to be made and allowing additional system features to be investigated. These tools will be valuable in the design of auxilliary systems such as ice melt and refrigeration loads which has the potential to reduce first cost and operating costs.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

A continuing wide variety of industry interest has been expressed, primarily in the improved tolls for design of ground loop heat exchangers. The methods have been transferred to the BLAST program through the BLAST Support Office. In addition, the TRANE Corporation has funded the interfacing of files between their commercial software programs and GLHEPRO and industry use has demonstrated that the interface improves operator speed and confidence.

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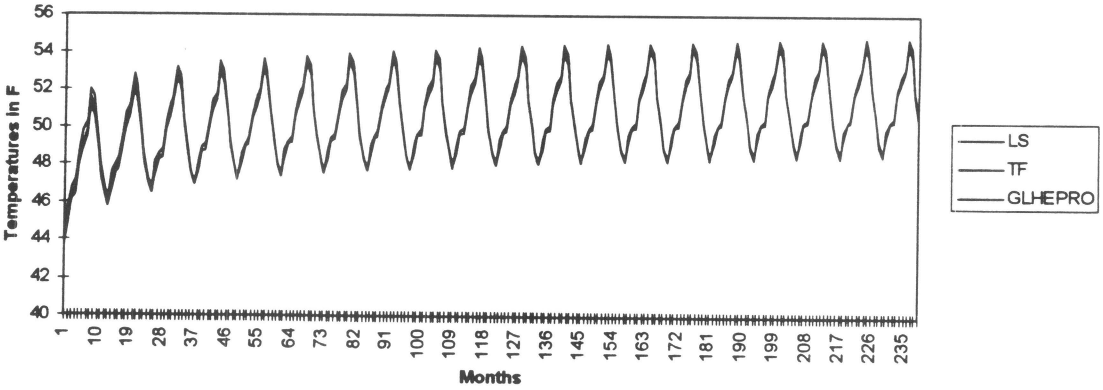

Figure 1. Borehole temperatures for a heavily cooling dominated building.

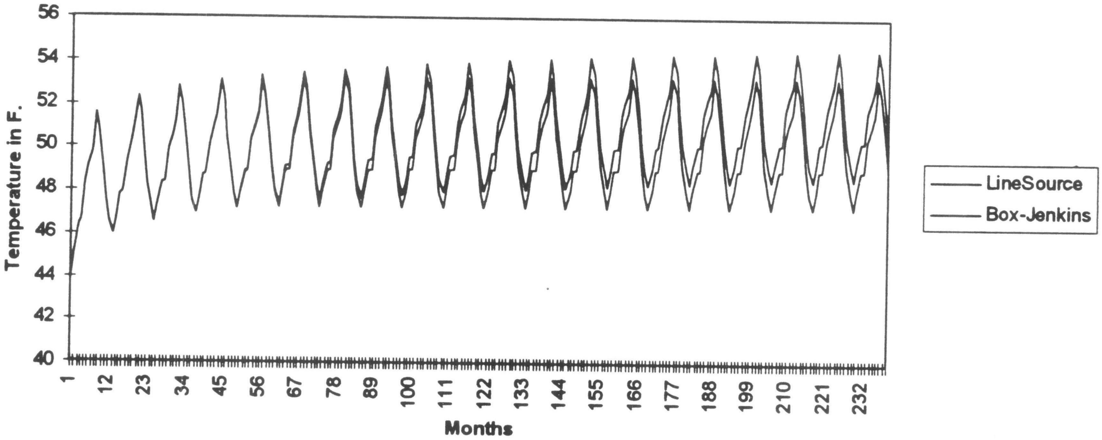

Figure 2. Average borehole temperature forecasts using Box-Jenkins analysis for a heavily cooling dominated building.

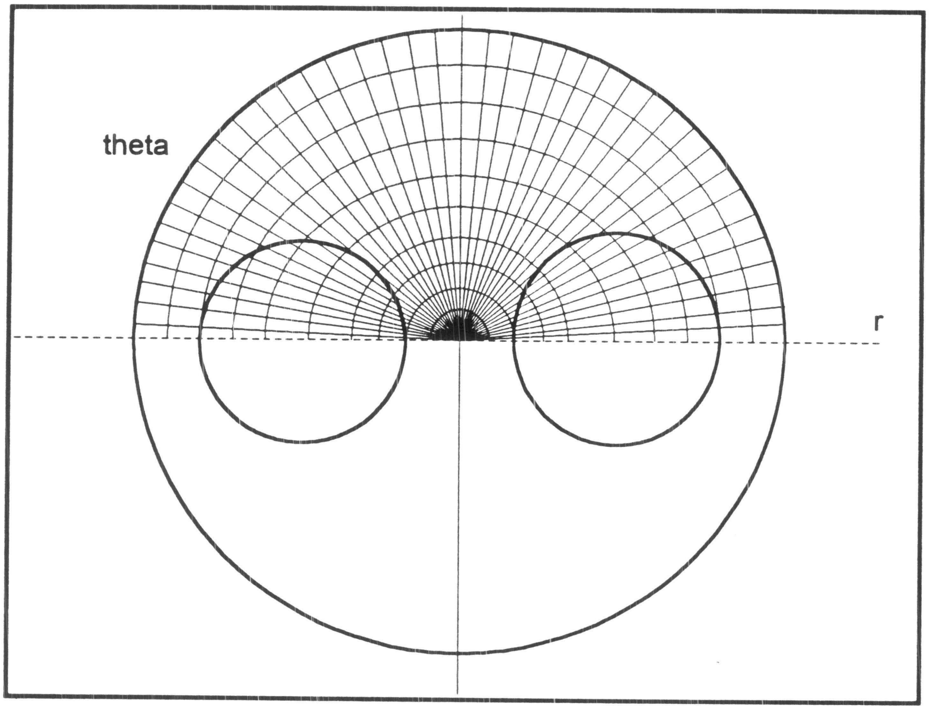

Figure 3. Numerical Grid - The U-tube legs are presented with a group of cells approximating the pipe area to the area of a "pie-slice-shaped"sector.

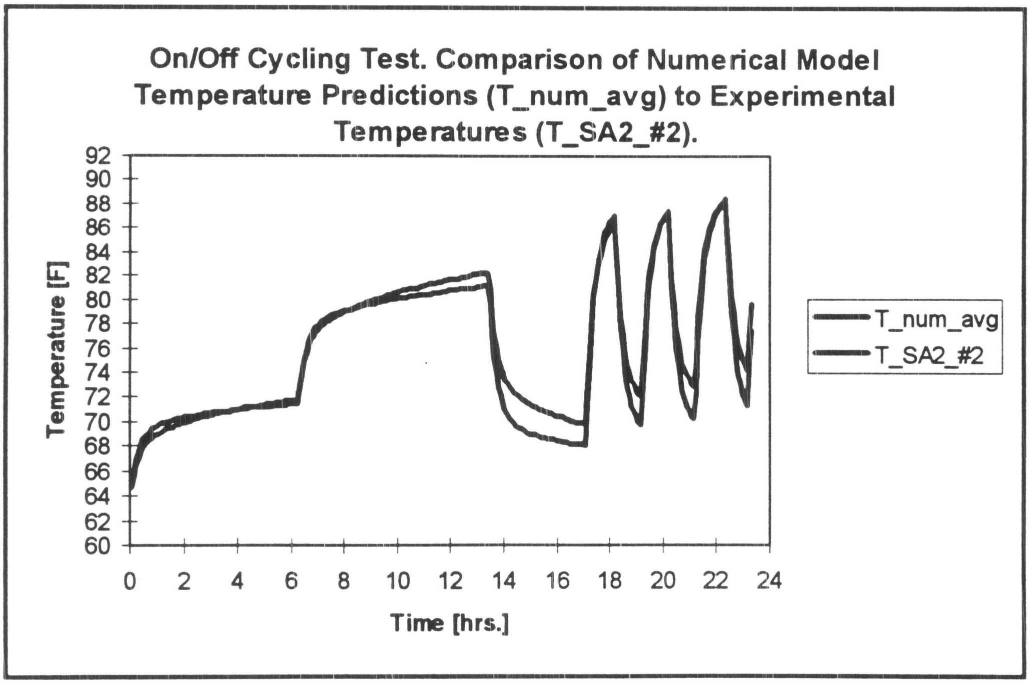

Figure 4. Cycling tests at Oklahoma State University site A, vertical borehole #2.

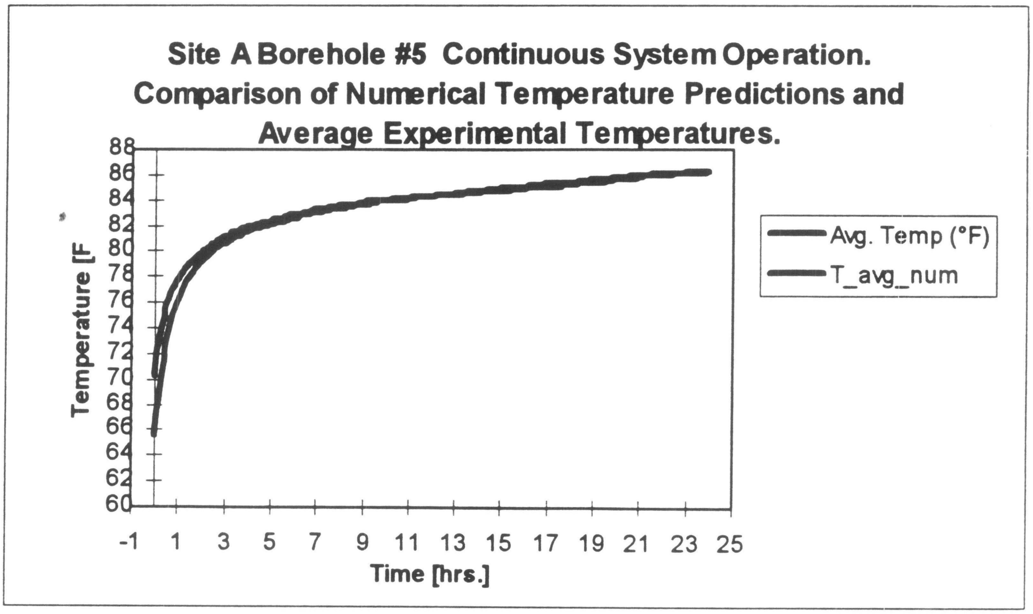

Figure 5. Continuous system operation simulation at Oklahoma State University site A, vertical borehole #5.