ABSTRACT

Wide spread use of distributed, small scale energy technologies can help bring balance to a nations' energy portfolio over reliant on foreign petroleum resources. The Pennsylvania Alternative Energy Portfolio Standards Act of 2004 lists demand side management, energy efficiency and load management programs and technologies among resources eligible for participation in Pennsylvania's alternative energy market. Ground source heat pumps, often referred to as geothermal heat pumps, offer an attractive option for heating and cooling residential and commercial buildings owing to their higher energy efficiency compared with conventional systems. The ability to predict both the long-term and short-term behavior of ground loop heat exchangers is critical to the design and energy analysis of ground source heat pump systems. For detailed analysis and accurate simulation of the transient heat transfer in vertical ground loop heat exchangers, a numerical model is developed. The model couples equations for momentum balance with that of energy balance to study the convective heat transfer of water flowing through a pipe, the wall of the pipe, and the grout surrounding the pipe. Real-time data obtained from an interoperable web accessible control system controlling a commercial ground-source heat pump system is used to help formulate, solve, and validate the model then provides the basis for a parametric study described herein.

INTRODUCTION

Wide spread use of distributed, small scale energy technologies can help bring balance to a nations' energy portfolio over reliant on foreign petroleum resources. Examples of such low-exergy systems include fuel cells, high efficiency combined heat and power systems, and geothermal heat pump systems. [1-4] This genre of integrated energy systems [5] can combine with disparate economic, social, and technology based disciplines to enhance the stability of local ecosystems. [6] Internet based monitoring and control system technology has developed which can improve ecosystem stability by providing real-time feedback for system optimization. [7-9] Enhanced understanding of environmental problems relating to energy use presents a high-priority need and urgent challenge; both to allow problems to be addressed and to ensure the potential solutions are beneficial for the economy, the energy and energy system itself. New understanding using the most sophisticated theories need developed. These theories can then be employed to further analyze and direct integrated energy system development. [10] Recently, several states in the USA have implemented new policies to catalyze fundamental development in these areas.

On September 29, 2005 the Pennsylvania Public Utility Commission (PUC) issued a Final Order approving developed standards to track and verify demand management, energy efficiency, and load management programs and technologies. In so doing, they fulfilled a major commitment towards implementation of the Pennsylvania Alternative Energy Portfolio Standards Act. [11] The Alternative Energy Portfolio Standards Act of 2004, ("Act 213" or the "Act"), includes demand side management, energy efficiency and load management programs and technologies ("DSM/EE") among resources eligible for participation in Pennsylvania's alternative energy market. [12] The Act categorizes energy efficiency technologies as a Tier II alternative energy source. As such, these technologies qualify for new renewable energy credits - new tradable commodities. Water source heat pumps fall under this criteria. Such commercial heat pumps are typically coupled with ground source heat pump systems, also known as geothermal or geoexchange heat pump systems.

Ground source heat pumps (GSHPs), often referred to as geothermal heat pumps (GHPs), offer an attractive option for heating and cooling residential and commercial buildings owing to their higher energy efficiency compared with conventional systems. [13] The origin of this heat is linked with the internal structure of our planet and the physical processes occurring there. [14] Vertical ground heat exchangers reject or absorb heat to or from the ground. Components of the ground system include the ground heat exchanger or wells, run-outs, headers, manifolds, flow control valves, pumps, variable speed drives and strainers. [15] This paper presents a computer modeling study of the convective heat transfer which takes place in a geothermal heat exchange well.

The ability to predict both the long-term and short-term behavior of ground loop heat exchangers is critical to the design and energy analysis of ground source heat pump systems. [16] For detailed analysis and accurate simulation of the transient heat transfer in vertical ground loop heat exchangers, a numerical model is developed. The model is based on a two-dimensional, finite element method developed using Comsol Multiphysics. [17] The model couples equations for momentum balance with that of energy balance to study the convective heat transfer of water flowing through a pipe, the wall of the pipe, and the grout surrounding the pipe. [18] [19] [20] Real-time data obtained from an interoperable web accessible control system used to control a commercial ground-source heat pump system in Ambridge, PA is used as part of the formulation, solution, validation and parametric study described herein.

GOVERNING EQUATIONS

In this example, energy transport by convection and conduction is studied. Such a system can be found in a geothermal heat exchanger. This system is depicted in Figure 1-1. The fluid flow enters the heat exchanger from the top and is heated (or cooled) as it passes through the U-Tube. The fluid then leaves from the top and travels back into the water-to-water and water-to-air heat pumps for heating or cooling the indoor building environment.

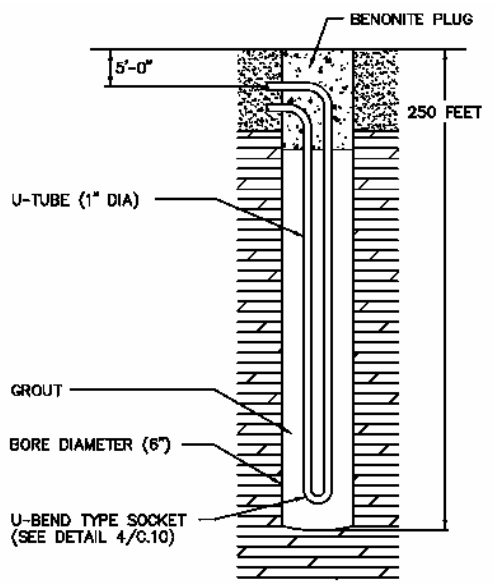

Figure 2-1: Sketch of geothermal heat exchanger.

TEST BORE DATA TABLE	
DEPTH (FT)	MATERIAL
0-45	SAND
46-110	COAL SEAM W/SAND AND GRAVEL
110-146	COARSE SAND AND GRAVEL
146-200	SOFT GRAY SHALE W/SS STREAKS
200-250	GRAY SANDSTONE W/SHALE STREAKS

Figure 2-2: Soil types obtained from test well

For simplicity, the modeled system is assumed to have only one pipe running down the central axis of the well. With this assumption only half of the well needs treated, and calculations can be performed on a typical PC. The velocity is varied, using the parametric solver (from $5x10^{-4}$ to $6.5x10^{-3}$ ms^{-1}) in order to study the effect of flow variation occurring over the length of the tube at higher velocities. The varying soil types listed in Figure 1-2, for this example, are considered to be uniform.

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The equations for the momentum balance are the Navier-Stokes equations in 2D, assuming symmetry also along the length of the tube.

$$-\nabla \cdot \eta(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} + \nabla p = 0$$
$$\nabla \cdot \mathbf{u} = 0$$

where η denotes the dynamic viscosity (kg m^{-1} s^{-1}), u the velocity vector (m s^{-1}), ρ the density of the fluid (kg m^{-3}), and p denotes the pressure (Pa). The heat flux is given by conduction and convection and the resulting energy balance is:

$$\nabla \cdot (-k\nabla T + \rho C_p T\mathbf{u}) = 0$$

Here T denotes temperature (K), k denotes the thermal conductivity (J s^{-1} m^{-1} K^{-1}), and C_p the heat capacity of water (J kg^{-1} K^{-1}). At the inlet, we know the velocity and temperature of the fluid:

$$\mathbf{u} \cdot \mathbf{n} = u_0$$
$$T = T_0$$

At the outlet we set the pressure to a constant value and we state that the velocity components tangential to the outlet are zero. For the energy balance we neglect the conductive heat flux in the main direction of the flow at the outlet. This implies that the transport of heat out of the system is dominated by convection.

$$\mathbf{q} \cdot \mathbf{n} = \rho C_p T\mathbf{u} \cdot \mathbf{n}$$

At the surface of the tube we specify no-slip conditions for Navier-Stokes and we set a constant temperature.

$$\mathbf{u} = \bar{0}$$
$$T = T_1$$

At the vertical boundaries we assume symmetry for all variables.

FORMULATION

The model is viewed as a series of three rectangles depicting water flowing through the tube (R1), heat transfer thru the wall of the PVC tube (R2), and heat transfer through the mortar which fills all voids between the tubes and the outer diameter of the 6” drilled well. Model subdomain regions and corresponding thermal properties of each region are shown in Figure 2-3. Values indicated for heat capacity of PVC and concrete are estimated values. Water temperature entering the tube is variable depending on load requirements of building. The load requirements are affected by weather conditions, occupancy and building envelope.

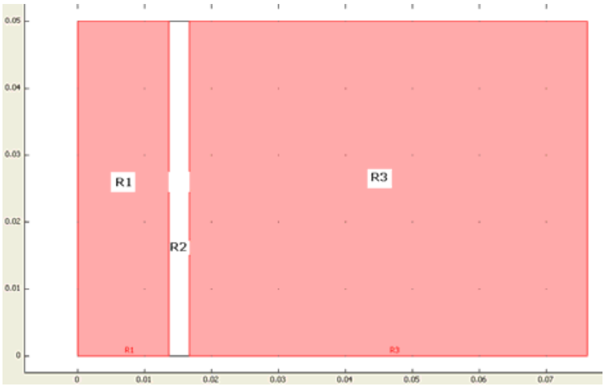

Figure 2-3: Geothermal model subdomain settings

Thermal Properties: **Water**

eta	1.00E-03	Dynamic Viscocity	(kg m-1 s-1)
rho	1.00E+03	Density	(kg-3)
Cp	4.20E+03	Heat Capacity	(J kg-1 K-1)
k	0.6	Thermal Conductivity	(J s-1 m- K-1)
Tin	301.8	Temperature entering	(K)
Tw	284.3	Temperature wall	(K)

Thermal Properties: **PVC**

eta	1.00E+00	Dynamic Viscocity	(kg m-1 s-1)
rho	1.76E+03	Density	(kg-3)
Cp	3.20E+02	Heat Capacity	(J kg-1 K-1)
k	0.1	Thermal Conductivity	(J s-1 m- K-1)

Thermal Properties: **Concrete**

eta	1.00E+00	Dynamic Viscocity	(kg m-1 s-1)
rho	2.30E+03	Density	(kg-3)
Cp	1.28E+03	Heat Capacity	(J kg-1 K-1)
k	1.8	Thermal Conductivity	(J s-1 m- K-1)

Boundaries settings have been defined at the perimeters of each subdomain for both the Navier-Stokes and conduction-convection equations. The coupling of the equations to the sub-domains was not intuitive. Many iterations of modeling were tried to find the right mix of boundary conditions to make the model run. The settings indicated develop a model which runs and can be explained. However, additional variations to the boundary may be explored to further develop a model which more accurately describes actual field installed conditions.

Incompressible Navier-Stokes

Boundary	1	2	3	4	5	6	7	8	9	10
Type	S/S	I/O	Nf/P		NS	Nf/P		NS	Nf/P	S/S
u		0								
v		v0								
p			0							

Notes: S/S: Slip/Symmetry
I/O: Inflow/Outflow Velocity
Nf/P: Normal flow/Pressure
NS: No-Slip

Convection and Conduction

Boundary	1	2	3	4	5	6	7	8	9	10
Type	TI	T	CF		TI	TI		TI	TI	T
T		Tin								Tw

Notes: TI: Thermal Insulation
T: Temperature
HF: Heat Flux
CF: Convective Flux

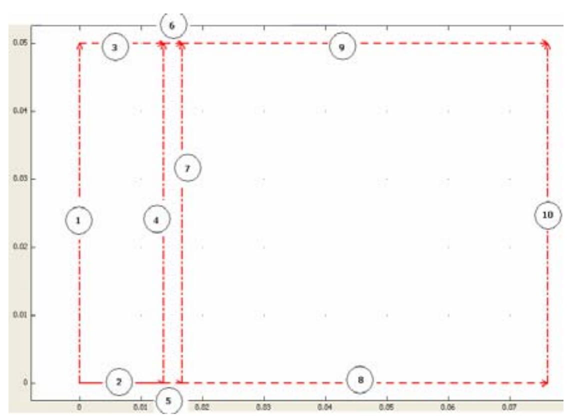

Figure 2-4: Geothermal model boundary settings

Boundary #10 is that of the interface between the soil and motor. Here the temperature of the ‘wall’ (Tw) is assumed to be a constant 52F (298.3K). In reality this temperature can vary based on actual soil types. Soil types for this well are know, and were shown in Figure 2.2.

SOLUTION

Figures 2-5 thru 8 are color plots of temperature gradients at increasing inlet velocities. These plots also show y-velocity contours along the vertical boundary at the tube surface.

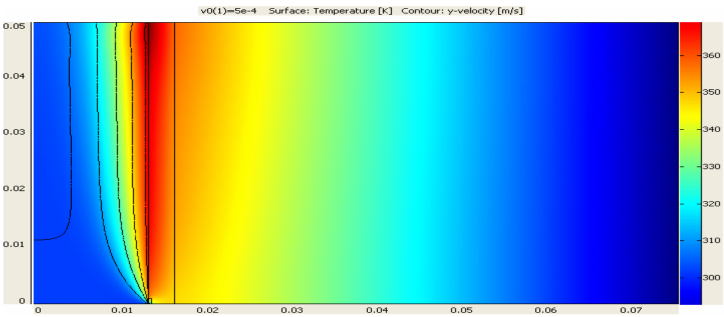

Figure 2-5: Vertical velocity is 0.0005 m/s

The inlet water temperature (Tin) is held constant for each plot, as is the temperature of the earth (Tw). Here (figure 2-5) we note there is a uniform temperature gradient thru the mortar thickness. The gradient becomes uniform in the wall of the pipe due to the varying material properties.

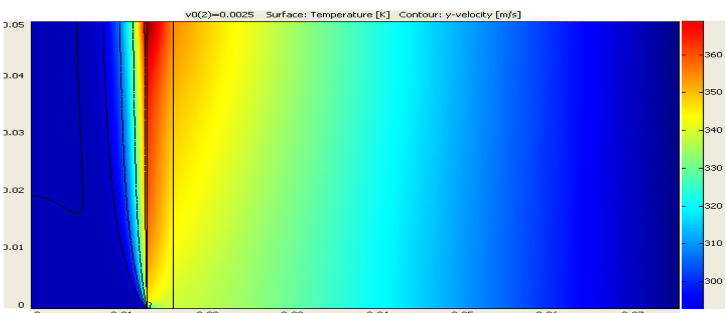

Figure 2-6: Vertical velocity is 0.0025 m/s

As the velocity increases, there is a corresponding decrease in the temperature gradient across the column of water. The velocity contours narrow. The convective heat transfer between the water flow and the tube wall decreases. Notice the red area in the wall is rising with increased velocity.

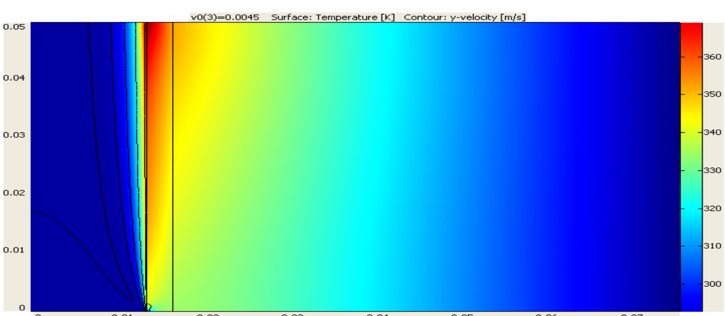

Figure 2-7: Vertical velocity is 0.0045 m/s

The heat convection between water and tube wall continues to 'wash out' as velocity continues to increase. The temperature gradient in the mortar continues to show a high uniformity, however the impact of reduced convective heat transfer between outside wall of tube and mortar is pronounced.

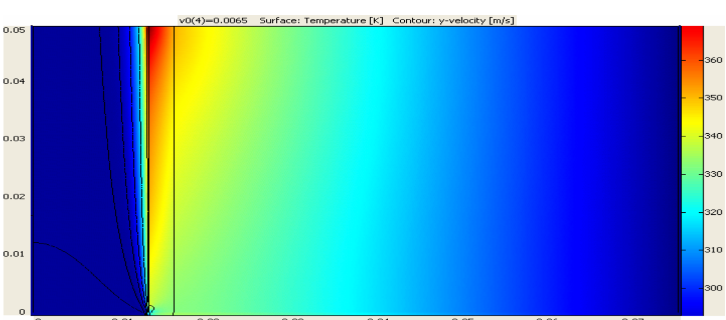

Figure 2-8: Vertical velocity is 0.0065 m/s

Finally, the percent of 'lost' heat transfer becomes significant. At constant volume, this translates into a system with poor overall performance. Well designed systems use variable speed drives to vary the flow with the ever changing load on the entire building. The well field design must be sized to meet greatest of the coolest or heating load.

VALIDATION

The developed numerical model is run to generate an output to determine if effective convective heat transfer is occurring between water transfer medium and the surround geoexchange environment. Thru an iterative process, the numerical model was edited to generate results compatible with ‘field’ observation. Additionally, model development led to a better understanding of the dynamic effects imparted to the system by operation and maintenance activities, building response to changing weather conditions, and use of the building by both employees and general public.

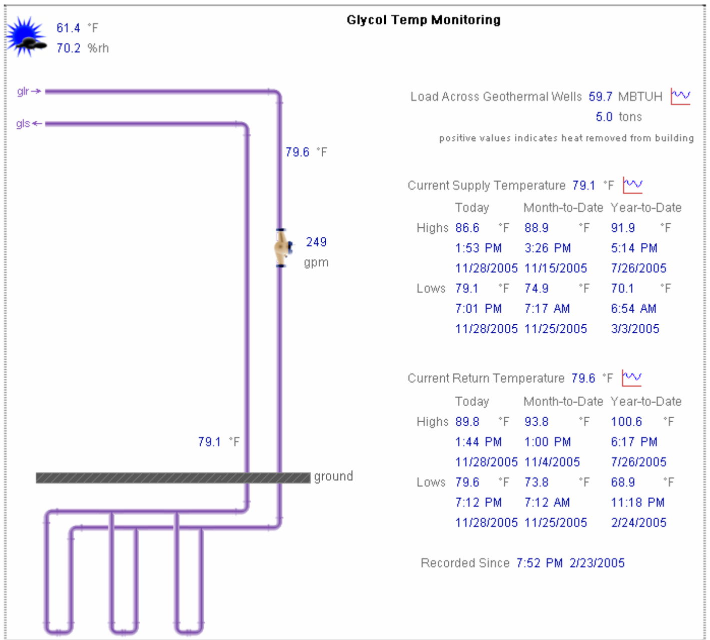

Fig 3-1: Real-Time iWACS graphics (11/28/2005 7:26:04 PM EST)

Figure 3-1 is a snap-shot in time of real-time data obtained from an interoperable web accessible control system (iWACS) used to control a commercial ground-source heat pump system in Ambridge, PA. The well field was constructed under a parking lot. Supply and return water from the ground loop enter the building through supply and return water pipes. Individual components of the well field outside building envelope are not accessible. The control logic (not shown) and graphics are under a continuous commissioning program designed to optimize user efficiency and system performance. Values obtained from this system were used to define boundaries in modeled system.

The well field is comprised of 54 geothermal wells piped in a parallel configuration. The variable speed drive (VSD) was set to 100% thereby generating a maximum flow rate of 360gpm (0.255 M/S). This equates to 4.81e-3 M/S flow through each well. This correlates with Figure 2.7 velocity contours and convective heat flow. Input temperature (Tin) for modeling purposes was 83.6F (301.8K). Supply and return temperature history (figure 3-0) shows a temperature swing from 68.8F (293.6K) to 100.6F (311.3K).

Figure 3-2 is model output set to the lowest recorded Tin, 68.8F (293.6k) over the last 10 months. This figure is almost identical to Figure 2-7 where Tin was set to 83.6F (301.8K) as same (maximum) velocity. Model indicates maximum performance would be reached at a lower VSD setting. IWACS control logic and graphics will be edited to match GPM history with that of temperature history. This will provide better visualization of actual well performance under variable load conditions.

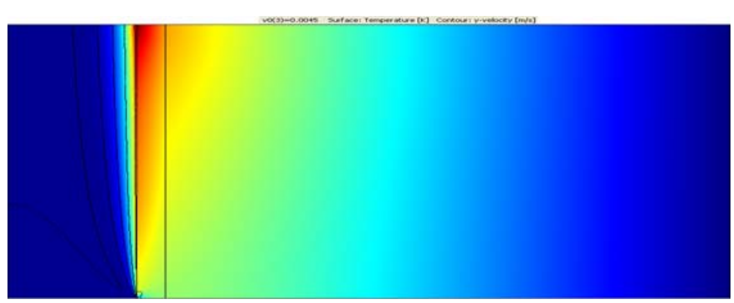

Fig. 3-2: Revised model output: Vy/Thermograph

PARAMETRIC STUDY

Discussion centering on model solution presented output of varying flow through tubes while holding the input temperature of the system constant. Previous discussion of model validation touched on the effect of holding the input velocity constant while varying the input temperature. It was shown that velocity of water in the geoexchange piping has the single greatest impact on the convective heat transfer between the ground and the circulating water. The visualization capabilities provided by modeling output is most helpful in this case study due to the well location under the parking lot. This design decision was based on least cost when several well piping options were considered. More expensive piping options allowed for increasing access within the building or manholes to the individual run-outs of each well head.

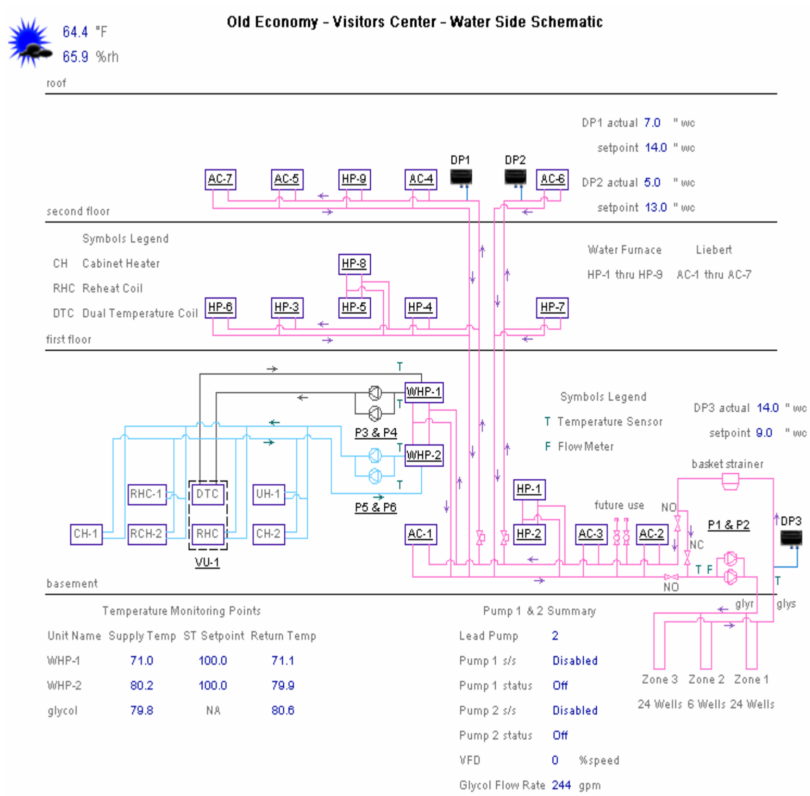

Fig 4-1: Real-Time iWACS graphics (11/28/2005 10:32 PM EST)

Figure 4-1 depicts mechanical equipment, located inside the building, interacting with the underground thermo-wells. The graphic shows a flow of 244gpm while the motor drive speed is zero. The flow has been field verified. The variable speed drive unit was disabled in the field to 'fix' unknown yet perceived problems in the well field. Corrective action has been initiated as of this writing. Improved visualization techniques are helpful to iWACS system operators and users in order to reach project goals. These goals are to maximize system efficiency under all operating conditions while maintaining the highest level of human comfort and the best possible indoor environment for the building occupants and stored material.

In addition to the two water-to-water heat pumps, ground source water is distributed to numerous water-to-air heat pumps throughout the building (see pink water piping in figure 4-1). As additional field data is collected on this system it will be used to further develop the convective ground source heat exchange model in a manner to enhance understanding of the unique features of this particular well field system.

CONCLUSIONS

The flow of water through the pipe in a geoexchange well is modeled at 0.05, 0.25 0.45 and 0.65 cm/s in order to study the effect of flow variation occurring over the length of the tube as velocities increase. The temperature of the surrounding earth is assumed to be 284.3K. The temperature of water entering the model at the bottom is 301.8K. At these conditions the model indicates the water is losing heat to the ground through the wall of the tube and intermediary mixture of mortar. As the velocity of the fluid moving through the pipe increases, the amount of heat transferred from the fluid to the surroundings decreases. This process is clearly shown in the series of four thermographs of Figures 2.5 thru 2.8. The overall geothermal system, including the inside mechanical equipment, performing in this manner would be considered to be cooling the building.

The interoperable web accessible control system used to remotely view the geothermal system provides detailed information pertaining to the status of many pieces of mechanical equipment working together in the building. This dynamic view of building information indicates the geoexchange well field cycles between cooling and heating loads many times over the course of twenty-four hours in the winter months of western Pennsylvania. Cooling scenarios have been described in this study. Additional model development work can be performed to show model performance when inlet water temperatures is below that of the earth temperature. However, historical data collected to date indicates the actual temperature of the water entering the well has not fallen below the ground temperature used.

When the variable inputs to the developed model are changed to reflect described system operating in cooling mode, thermographic profiles can be generated which indicates an obvious flow of temperature being drawn from the earth into the water stream. A series of thermographs were generated and compared when holding the flow at it minimum value (0.05cm/s). These thermographs (not shown) show a clear movement of temperature gradient from the earth toward the lower temperature water in the pipe. However, when the flow is increased as per cooling scenario, the temperature scale, shown to the right of the thermograph, doubles, triple then quadruples. This phenomenon needs further study.

The phenomenon may be indication there is a fundamental error in the correlation of the Navier-Stokes equations with the convection/conduction equations used. On the other hand, it may also be a clear indication of an error in the programming of the software. Since the model shows strong correlation to results observed and expected as part of the parametric study, the software company will be contacted for an explanation of how their legends and scales are generated.

Regardless, the flow in the tube is definitely shedding heat to its surroundings as it flows when Tin is higher than Tw. Likewise it is definitely picking up heat, from the pipe wall, when Tin is lower then Tw. And, changing the flow of water through the pipe has a very discernable effect on amount of heat transferred between the water and pipe wall.

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