Applicability of Related Data, Algorithms, and Models to the Simulation of Ground-Coupled Residential Hot Water Piping in California

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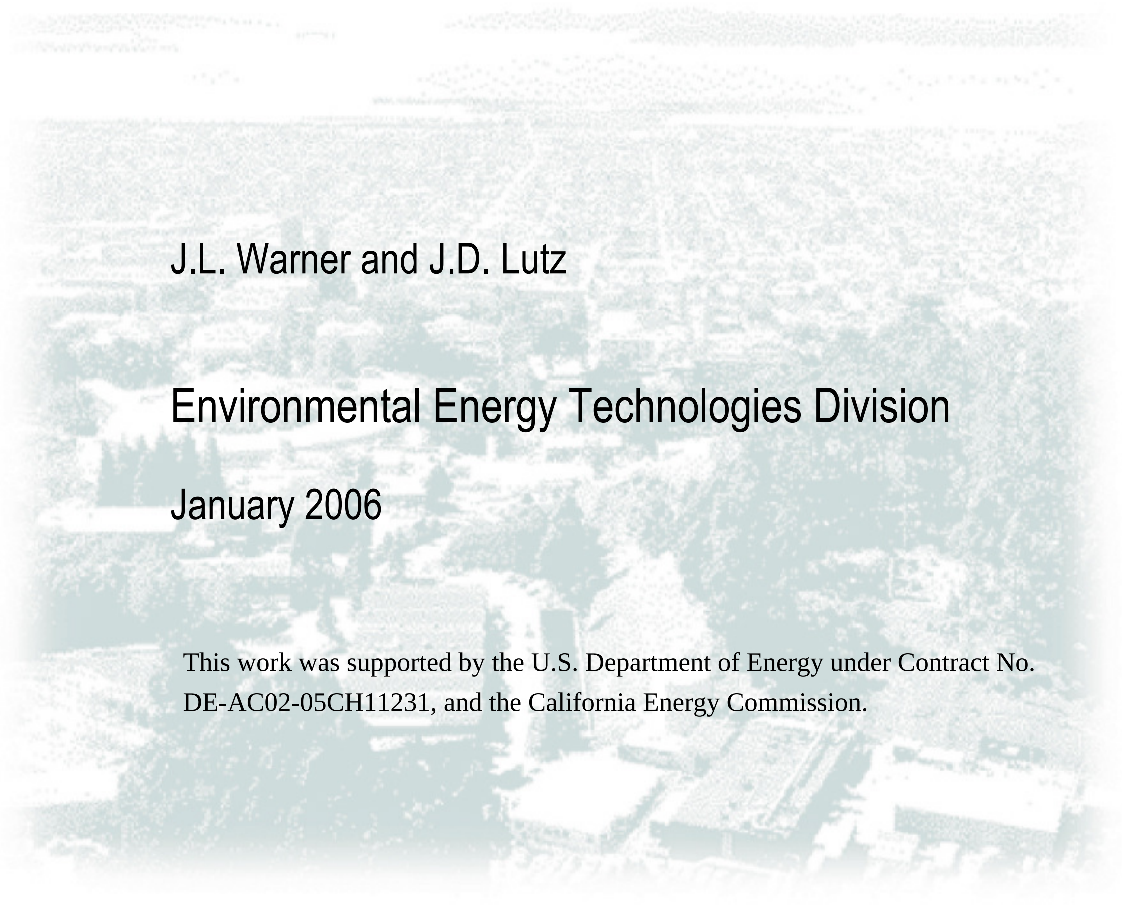

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Abstract

Residential water heating is an important consideration in California's building energy efficiency standard. Explicit treatment of ground-coupled hot water piping is one of several planned improvements to the standard. The properties of water, piping, insulation, backfill materials, concrete slabs, and soil, their interactions, and their variations with temperature and over time are important considerations in the required supporting analysis. Heat transfer algorithms and models devised for generalized, hot water distribution system, ground-source heat pump and ground heat exchanger, nuclear waste repository, buried oil pipeline, and underground electricity transmission cable applications can be adapted to the simulation of under-slab water piping. A numerical model that permits detailed examination of and broad variations in many inputs while employing a technique to conserve computer run time is recommended.

1. Introduction

California's Title 24 standard for residential energy efficiency (CEC 2004; CEC 2005) is scheduled for revision in 2008. Among many improvements will be the more detailed and realistic treatment of residential water heating systems. Hot water distribution piping is often placed under slab floors in California residences. Proper determination of the instantaneous and seasonal thermal efficiency of this distribution system configuration is to be an important component of the improved water heating directive. An appropriate model must be developed for this purpose.

2. Analytical Requirements for the Model

Many factors affect the thermal efficiency of under-slab hot water distribution piping. The factors that should be accounted for in a rigorous system model are summarized below.

- The hot water temperature, thermal conductivity, density, specific heat, and flow rate are important parameters in any distribution system model. Variations in the thermal properties with temperature must be considered.

- Copper, polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), high-density polyethylene (HDPE), polypropylene, and polybutylene can be used for under-slab hot water distribution piping. Various types of insulation can be placed around the piping. Thermal conductivity, density, and specific heat values of the piping and insulation, and their variations as functions of temperature, if significant, are important model inputs.

- Piping length, wall thickness, and friction factor affect distribution system efficiency. Typical under-slab hot water piping has short vertical lengths at the inlet and outlet locations, and a much longer horizontal length between them. Although it is tempting to disregard the short inlet and outlet segments to simplify a model, these components are important because of the heat losses and resistances to fluid flow that they comprise.

- Fine gravel, sand, cementitious grout, clay, and loam can be used as backfill around the hot water piping and directly under the slab. The thermal properties of the backfill materials in both of these locations, as well as those of the concrete slab and surrounding soil, must be taken into account. The base temperatures of these materials vary with time of year, and their properties vary with moisture content. Additionally, the model must consider the presence and migration of groundwater, which dramatically affects the thermal properties of soil. The model must also treat the vertical asymmetry of the materials involved; in particular, it must incorporate the thermal reservoir effect of the soil or ground below the piping and the convective pool of the large air space above the slab.

- Hot water, unlike heating, cooling, and ventilation, demand derives from multiple end uses. Consequently, it exhibits complex temporal variations—hourly, daily, seasonal, etc. The resulting water draw patterns drive cyclical, sporadic, and transient piping heat losses that must be characterized accurately to determine distribution system efficiency for any time interval of interest. The most useful model will be one that permits wide variability in the calculational time step.

- The heated water remaining in the piping after a given hot water draw event is left to reach thermal equilibrium with its surroundings. Depending on the water temperature, piping, backfill, slab, and soil properties and configuration, and timing of the next draw event, this equilibrium might or might not be reached. Thus, the temperature of the residual water encountered by the next flux of hot water is highly variable. To further complicate the model requirements, any one of the following interactions between the next flux of hot water and the residual water might occur: (1) the hot water might drive the residual water through the piping ahead of it; (2) the hot water might mix with the residual water; or (3) the hot water might flow over the residual water, with accompanying conductive and convective heat exchange. Furthermore, due to the combined influences of all variables under consideration, this interaction might be different for each time step (draw event).

3. Related Data

Many material properties and variations that could be used in an under-slab piping model have been published in the technical literature.

Lide (2005) tabulated the thermal properties of water as functions of temperature.

ASHRAE (2005) tabulated the typical thermal properties of a few piping materials, some common types of insulation, many common varieties of concrete and similar materials, and a few earth materials.

The thermal properties of selected piping, concrete, soil, and rock samples were measured or compiled by Mei and Baxter (1986).

The effective resistances of some high-density polyethylene pipes were reported by Remund (1999). Some backfill thermal conductivities were also measured in the laboratory and field in the same study.

Allan and Kavanaugh (1999) measured and reported the thermal conductivities of several varieties of cementitious grout that can be used as backfill in ground-source heat pump installations. They used a thermal conductivity meter in the hot wire method, a transient method that surmounts the problem of initial moisture migration or drying in materials, to test grout samples. This test method can be used to determine the thermal conductivities of other materials involved in an under-slab piping model.

Beier and Smith (2002) used a combination of measurements of ground-source heat pump boreholes and a line-source model of the boreholes to estimate several backfill and soil thermal conductivities.

Empirical and theoretical models were used to determine the thermal conductivities of idealized gravel, sand, silt, clay, and peat (Misra et al. 1995).

Thermal properties of various soil and rock types were provided by Bose (1988) and Chiasson et al. (2000).

Witte et al. (2002) determined thermal properties of various soil types using three methods: (1) interpretation of data from the technical literature; (2) measurements using a transient probe in a ground-source heat pump borehole; and (3) simulations using the two-dimensional finite volume model of Yavuzturk et al. (1999).

As suggested by many of the referenced authors, the thermal properties of inhomogeneous localized geological media are important in ground-coupled building system models but are difficult to obtain or determine. Without adequate data of this type, an under-slab hot water piping model will suffer from inaccuracy.

4. Related Algorithms and Models

Many published heat transfer algorithms and models for application to generalized problems, hot water distribution systems, ground-source heat pumps and ground heat exchangers, nuclear waste repositories, buried oil pipelines, and underground electricity transmission cables could be adapted to the analysis of under-slab hot water piping.

4.1. Generalized Heat Transfer Problems

Solutions have been derived for many generalized heat transfer problems. Certain of these solutions are applicable to the case of under-slab piping.

Carslaw and Jaeger (1947) derived a solution for radial heat flow from an idealized cylindrical source of infinite length, which could be taken to represent a hot water pipe.

Ingersoll et al. (1954) solved the simpler, one-dimensional case of heat flow from an idealized linear source of infinite length. This approach cannot consider the geometric characteristics of a real piping installation.

Both of the aforementioned approaches have been used in models of systems that have commonalities with under-slab hot water piping.

4.2. Hot Water Distribution Systems

Baskin et al. (2004) employed a finite element model to evaluate and compare characteristics of residential hot water distribution systems, including those placed under slab floors. The model can handle up to 50 piping segments and considers piping with or without insulation. It treats the flow of water through the pipe in one (axial) dimension and the flow of heat through the piping wall and insulation in two (radial) dimensions. A finite and uniform radial thickness of material is permitted. The outermost radial surface is held at a user-selected constant temperature during hot water system operation. Therefore, the model is indifferent to the case in which one side of the piping has different surroundings from the others, as with an under-slab configuration. The simulation time is relatively brief—one day—but can include any number of hot water draw events.

4.3. Ground-Coupled Heat Pumps and Ground Heat Exchangers

The increasing interest in ground-coupled heat pumps as energy-efficient heating and cooling systems has spawned the development of numerous models for more accurate analysis of ground heat exchangers. These models are relevant to the under-slab hot water piping problem in that both involve water properties, piping properties, backfill properties, soil or ground properties, soil moisture and groundwater effects, water circulation patterns, and residual water effects. However, a hot water piping model need not consider thermal interferences like those between the legs or coils of U-tubes or helical heat exchangers.

Doughty et al. (1991), Nir et al. (1992), and Doughty et al. (1993) produced a numerical model and conducted field tests for a unique helical ground heat exchanger that could be linked to a ground-source heat pump or solar collectors. For simplicity, the heat exchanger is viewed as a cylindrical annulus and heat flow in the surrounding soil as purely conductive. The finite-difference model considers the annulus using a two-dimensional axisymmetric mesh with a large radial extent to represent an infinite medium. The vertical central input conduit is also an explicit part of the model.

Deerman and Kavanaugh (1991) modeled U-tube heat exchangers for ground-source heat pumps using the cylindrical source solution of Carslaw and Jaeger (1947). In this solution, a U-tube must be treated as a single pipe with an equivalent diameter. This model incorporates several other idealizations and simplifying assumptions, including the omission of treatment of soil moisture and groundwater.

Rottmayer et al. (1997) also modeled U-tube heat exchangers but utilized a three-dimensional finite-difference method. Thus, U-tubes can be treated more realistically, without the use of equivalent diameters. Because of the symmetry of a U-tube about a vertical plane, only half of the configuration is explicitly modeled. The half-cylinder is divided into a network of axial, radial, and circumferential sections. However, heat flow is simulated only in the radial and circumferential directions in the surrounding medium; vertical heat transfer is assumed not to occur. The heat capacities of the piping and backfill are considered small relative to that of the surrounding geological media and are, therefore, neglected. Like the model of Deerman and Kavanaugh (1991), this model does not examine the effects of soil moisture and groundwater.

Yavuzturk et al. (1999) and Yavuzturk and Spitler (1999) developed a two-dimensional finite volume approach and its outgrowth, a response factor model, for U-tube heat exchangers. The response factor model captures the short time scales necessary for analyzing shorter-term field data and for performing annual energy simulations with hourly or shorter time steps. It was validated against measured data from a building conditioned by a ground-source heat pump (Yavuzturk and Spitler 2001).

An improved linear source model for ground heat exchangers was proposed by Diao et al. (2004). An explicit solution that more accurately represents system temperature responses for long time steps was developed.

In contrast to the other efforts described above, Chiasson et al. (2000) developed a preliminary model for ground heat transfer that includes the effects of groundwater flow. Specifically, this numerical model treats heat transfer through solids by conduction, liquids by conduction, and liquids by advection. The finite element mesh consists of triangular elements that are most closely spaced around the U-tube heat exchanger of the ground-source heat pump to be modeled. Separate boundary conditions are imposed for the heat and mass transfer problems. Sample results from the model suggest that groundwater flow has a significant effect on ground heat exchanger performance only in highly porous or permeable geological media.

Bernier et al. (2004) contributed an algorithm that systematically aggregates previous time steps that do not markedly influence the current time step in a simulation, while still permitting more recent time steps to have greater effects. Computational time is conserved, with little, if any, reduction in simulation accuracy. This approach can be applied to modeling hot water distribution systems, for which long-past water draw events have little effect on more recent events.

4.4. Nuclear Waste Repositories

Underground fluid flow in the vicinity of a heat-releasing nuclear waste package can assume a roughly cylindrical pattern and involve phase change, creating a somewhat analogous situation to that of under-slab hot water piping.

Doughty and Pruess (1988, 1990, 1991, 1992) produced various forms of a mathematical model describing the multi-phase mass and heat transfer that not uncommonly surround nuclear waste repositories. The primary purpose of this model is the establishment of the local temperature and pressure conditions under which various phases will occur, rather than the quantification of heat flows. Therefore, it is not the best alternative for modeling under-slab piping.

4.5. Buried Oil Pipelines

Buried oil pipelines are also analogous in many ways to under-slab hot water piping, but are relieved of the complexities of backfill and slab materials. Additionally, pipeline oil is at a much lower temperature than is building service hot water, greatly reducing the temperature difference between the fluid and its surroundings that drives heat loss.

A steady-state heat transfer coefficient that incorporates only the more important mechanisms of conduction and convection was derived for buried submarine pipeline oil flow (Loch 2000). Calculated values of this coefficient suggest that burial adds insulating value to oil pipelines, a benefit that eludes under-slab piping. This simplified derivation is probably of limited use in treating hot water piping more accurately.

4.6. Underground Electricity Transmission Cables

Electricity transmission cables differ from hot water piping in that they experience both thermal and electrical losses. Thus, models developed to quantify cable losses can be quite complicated.

Kovac et al. (2006) devised a numerical model for combined electricity and heat losses in underground cables with solid sheaths. This model employs the filament method, wherein conductors and sheaths are represented by numerous smaller filaments in a finite and infinite element mesh. It is almost certainly too complex, with integral treatment of electrical losses, to be applied to the problem of under-slab hot water piping.

5. Recommendations

Following are summary recommendations for an appropriate model for under-slab hot water distribution piping in support of an improved energy efficiency standard.

- The model should capture all significant properties and characteristics of materials and components of under-slab piping configurations.

- Transient effects and interactions should be treated explicitly in the model.

- A numerical (e.g., finite element, finite-difference, or response factor) model is preferable to a purely analytical (e.g., cylindrical source or linear source) model.

- The model should be capable of longer-term (e.g., annual) simulations.

- To conserve computer run time, the model should employ a technique to aggregate past time steps (water draw events) that do not markedly influence each succeeding time step (water draw event) in the simulation.

Acknowledgments

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Attachment A

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