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Research paper

# Development of a novel spiral coil ground heat exchanger model considering axial effects

Arny Leroy*, Michel Bernier

*École Polytechnique de Montréal, Département de Génie Mécanique, Case Postale 6079, Succursale "Centre-Ville", Montréal, Québec H3C 3A7, Canada*

## HIGHLIGHTS

- A new spiral coil heat exchanger model was developed considering axial effects.
- The temperature response of the model varies with depth.
- A 2000 h simulation of the model with variable thermal loads is presented.
- A comparison to other models for constant and time-varying thermal loads is made.
- Importance to account for axial effects in spiral coil heat exchangers is evaluated.

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## ABSTRACT

This paper presents the development of a novel spiral heat source model based on the Green's function method that takes into account axial effects. This new model is based on the principle of spatial superposition of heat sources to model the varying thermal response in spiral coil heat exchangers (SCHE) as a function of depth. It also proposes new input parameters, inlet fluid temperature and mass flow rate instead of heat transfer rate, which is now obtained by performing an iterative process. To perform simulations of time-varying thermal loads, a temporal superposition along with an aggregation algorithm is developed. The new model is compared to other models for both constant and variable loads to evaluate the importance of taking into account axial effects and the variation of the thermal response with depth in SCHEs.

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## 1. Introduction

The increasing interest in renewable energy has led to a wider adoption of ground-coupled heat pumps (GCHP) systems in residential and commercial buildings [1]. GCHP systems are designed to exchange heat between the ground and a building in which temperature needs to be controlled.

GCHP systems usually consist in a heat pump connected to a closed-loop ground heat exchanger (GHE) in which circulates a heat carrier fluid. Vertical boreholes GHE such as vertical U-tubes have been more widely adopted [2] than horizontal GHE in GCHP systems in urban areas where available land area is limited. However, vertical depth of boreholes can reach up to 120 m [3] when land area is limited, resulting in relatively high drilling costs.

Because of limited heat transfer area and air chocking that may occur in U-tubes GHE [4], a new solution consisting in a spiral coil heat exchangers (SCHE) has been explored lately [4–8]. Fig. 1 illustrates a GCHP system equipped with an SCHE for residential building. Starting from the heat pump, the heat carrier fluid flows down into the spiral coil pipe to its deepest end. The fluid then returns to the heat pump via a vertical returning pipe typically located in the center of the spiral. SCHEs increase the available heat transfer area compared to traditional U-tube boreholes with the same depth thus reducing drilling and installation costs as well as air chocking in pipes [4].

Before installing a GCHP system, it is crucial to evaluate the total pipe length, costs and energy savings of such a system [9]. A thorough dimensioning of the system is thus needed to ensure optimal performances within the constraints of the permissible minimum and maximum inlet fluid temperatures to the heat pump [9]. Oversizing the system increases its initial costs while undersizing decreases the heat pump coefficient of performance (COP)

* Corresponding author. Tel.: +1 514 998 9536.
*E-mail address:* arny.leroy@polymtl.ca (A. Leroy).

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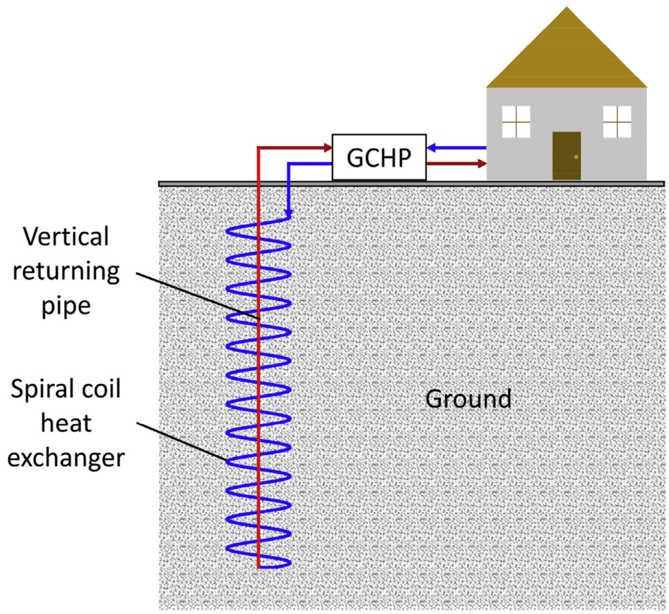


**Fig. 1.** Example of GCHP system equipped with an SCHE for residential building.

[10,11] as well as its capacity to meet the building's energetic demand.

Because of the complexity and of the recent introduction of SCHEs, there is a limited number of analytical models and experimental validations in the literature.

At first, the infinite line source [12] and the infinite hollow cylinder source [13] models were developed to model conventional boreholes with U-tubes. A finite line source was also proposed by Zeng et al. [14] to better represent long-term temperature response. While these models may be used for conventional vertical boreholes, they are not well-suited for SCHE. This is because they usually have a larger radius/depth ratio and more complex geometry compared to conventional boreholes with U-tubes. Therefore, previous models used for vertical boreholes are not appropriate for detailed modeling of SCHE.

In order to simulate heat transfer in an SCHE, Man et al. [15] first presented a new solid cylindrical heat source model derived by means of the Green's function method. It assumes that the spiral coil can be modeled as a continuous cylindrical heat source. Unlike the hollow cylindrical source model, the inner part of the SCHE is also filled with the same medium (ground soil) as outside of the SCHE. However, this model fails to take into account the real geometry of the SCHE.

A ring-coil source model was developed by Cui et al. [5] using the cylindrical source model. It simplifies the spiral as a set of separated rings located on the cylindrical surface. In comparison with the solid cylindrical heat source model, the ring-coil model takes into account the discontinuity of the heat source as well as the impact of the coil pitch. However, while the ring-coil source model is an improvement over Man et al.'s [15] model, it stills differs significantly from the real conditions and geometry of spiral coil pipes.

A further improvement was proposed by Man et al. [4] in the form of a spiral heat source model. The analytical solution is developed using Green's function to evaluate the heat transfer around a spiral coil heat source of finite and infinite length. While representing more adequately the real conditions of the spiral, the analytical model assumes that the spiral line heat source emits heat at a constant heating rate per length of heat source. Furthermore, this model imposes the heating rate per unit length of heat source as an input parameter for the model. Moreover, the spiral heat source model is presented with a double integral and a singularity $1/(Fo-Fo')^{\frac{3}{2}}$, which leads to important computational problems. Man et al. [4] also presented a temporal superposition scheme using the $p$-function and the $q$-function.

Park et al. [7] addressed the problem of singularity by expressing the analytical solution of the spiral heat source model using the error function. They also validated their analytical model with experimental test measurements. While the analytical solution of the spiral source model is in good agreement with experimental results, the latter were only compared for a short period of 25 h and temperatures were measured at too few coordinates to validate axial effects.

Previous approaches use idealized heat source models by considering a constant heat flux or pipe wall temperature along the heat exchanger pipe. These assumptions do not reflect reality and may significantly miscalculate the evolution of the temperature response, as presented by Ghasemi-Fare and Basu [16] in the case of a U-tube type PGHE. Further research is thus necessary to take into account axial effects along the spiral heat source and modify the input parameters to better reflect real conditions.

This paper describes the development of a novel contribution to previously developed spiral heat source models. The solution is developed using spatial superposition of the spiral heat source model to take into account axial effects in the vertical direction. An iterative method is also proposed to account for new input conditions. Finally, the new model is compared to the spiral heat source model [4,7] for constant and variable loads to evaluate the significance of axial effects on SCHE.

## 2. Previous models

Due to the complexity of the spiral coil spatial geometry, previous models have been attempting to use analytical models that represent the geometry as precisely as possible while minimizing computation time.

Green's function theory has been used in past spiral coil models because of its analytical nature and its convenience in solving heat conduction problems with boundary values. Green's function calculates the temperature response in a medium at a given coordinate $P(r,\varphi,z)$ and time $\tau$ caused by a heat source of coordinates $P'(r',\varphi',z')$ starting at time $\tau'$. Time $\tau$ (point $P$ time reference) is usually equal to $\tau'$ (heat source $P'$ time reference) in current models. The influence of a point heat source $P'(r',\varphi',z')$ on a coordinate $P(r,\varphi,z)$ is illustrated in Fig. 2a and given by Eq. (1). The function $h(r,\varphi,z,\tau;r',\varphi',z',\tau')$ in Eq. (1) is referred as the $h$-factor.

$$h(r,\varphi,z,\tau;r',\varphi',z',\tau')=\frac{1}{8[\pi\alpha(\tau-\tau')]^{\frac{3}{2}}}\cdot\exp\left[-\frac{(\mathrm{r}\cdot\cos(\varphi)-\mathrm{r}\cdot\cos(\varphi'))^2+(\mathrm{r}\cdot\sin(\varphi)-\mathrm{r}\cdot\sin(\varphi'))^2+(\mathrm{z}-\mathrm{z}')^2}{4\alpha(\tau-\tau')}\right] \quad (1)$$

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