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Thermal coupling between a helical pipe and a conducting volume

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ABSTRACT

Here we document the effect of flow configuration on the heat transfer performance of a helically shaped pipe embedded in a cylindrical conducting volume. The helix is wrapped on an imaginary cylinder. Several configurations of helices with fixed volume of fluid are considered. We found the optimal spacings between the helical turns such that the volumetric heat transfer rate is maximal. Next, we extended the study by varying the volume (length) of the embedded pipe. We found that the optimized features of the heat transfer architecture are robust with respect to changes in several physical parameters. We compared the performance for both helical 3D and 2D designs. We found that the 2D designs offer greater heat transfer density than the 3D designs.

1. Introduction

Flow systems in nature generate shape and structure have freedom to morph, and over time they evolve into progressive architectures that facilitate movement and provide easier access to what flows. Recent work in physics has shown that the generation and evolution of flow configuration in nature is governed by the constructal law [1–3]. Thermodynamically, resistances are imperfections (sources of irreversibility) distributed over the flow volume. Imperfections cannot be eliminated, but can be redistributed in order to facilitate the global flow. The only way to redistribute the imperfections is to have freedom to vary the flow organization. Research during the past decade (reviewed in [2,3]) showed that the organization of all the flow designs that occur in nature and engineering is the governing factor in design performance.

Heating and air conditioning are technologies that have played a key role in increasing economic activity during the past century [1]. Geothermal heat pumps have spread rapidly in many countries since 1980s. One design consists of using a borehole heat pump, which can be utilized economically by drawing heat from low temperature sources [4–23]. There are two types of ground heat exchangers: open and closed. The open system is a direct heat exchanger between the ground and the medium. The closed system is of the indirect type, with pipes buried horizontally or vertically. The choice of horizontal versus vertical ground heat exchangers depends on the condition of the surrounding soil.

In our previous paper we considered the effect of flow configuration on the heat transfer performance of a spiral shaped pipe embedded in a cylindrical conducting volume [24]. The objective was to find the optimum spacing between spiral pipes, and the spacing between spiral turns. The method developed in the previous paper can be extended to the optimization of geometry in more complicated configurations of ground coupled heat exchangers.

In this paper we consider the fundamental configuration of time-dependent heat transfer between helical pipes and a conducting volume that functions as heat source or sink. The objective is to find the optimum geometry of the helical pipe. The fundamental aspect is the focus on the relation between the morphing of the system configuration and the improvements in the global performance of the complex flow system, in accord with constructal design. In a recent paper we examined the effect of geometry when the pipe helix is in a plane. In the present study, we consider the same question in the optimization of a helical configuration in three dimensions.

2. Model

Consider the heat transfer performance of an embedded helical heat exchanger. As shown in Figs. 1 and 2, the heat flow system has two domains, one fluid and the other solid: an isothermal helical pipe with fixed diameter D_0 and length L_h, and a fixed solid volume with cylindrical shape of diameter D with height $H = D$. The

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Nomenclature

A_c	cylinder cross-sectional area, m^2
D	diameter or cylinder, m
D_0	pipe diameter, m
H	height, m
L_h	helix length, m
n	number of turns
r	radial coordinate, m
S_a	axial spacing between turns, m
S_H	horizontal spacing, m
t	time, s
T_c	initial temperature, K
T_h	pipe temperature, K
V_c	volume of cylinder, m^3
V_h	volume of helix, m^3
z	coordinate, m
Greek symbols	
α	thermal diffusivity, m^2/s
β	pitch angle, rad
θ	angle, rad
ε	dimensionless spacing S_a/H
ζ	dimensionless spacing S_H/D
Subscripts	
*	dimensionless
avg	volume averaged

geometry of the helix can be described in terms of the diameter D_h, axial spacing between the turns S_a, and the number of turns n. The total axial length of the helix is $H_h = n\,S_a$, and its circumference is $C_r = \pi D_h$. The axial spacing between the turns can be estimated as

$$S_a = \frac{L_h}{n}\sin\beta = \frac{\pi D_h}{n}\tan\beta \tag{1}$$

where L_h is the total length of the helical pipe, and β is the pitch angle. In order to estimate the amount of material needed to make the helical pipe, the total length of the helical pipe L_h indicated by Eq. (1) is

$$L_h = n\left(S_a^2 + \pi^2 D_h^2\right)^{1/2} \tag{2}$$

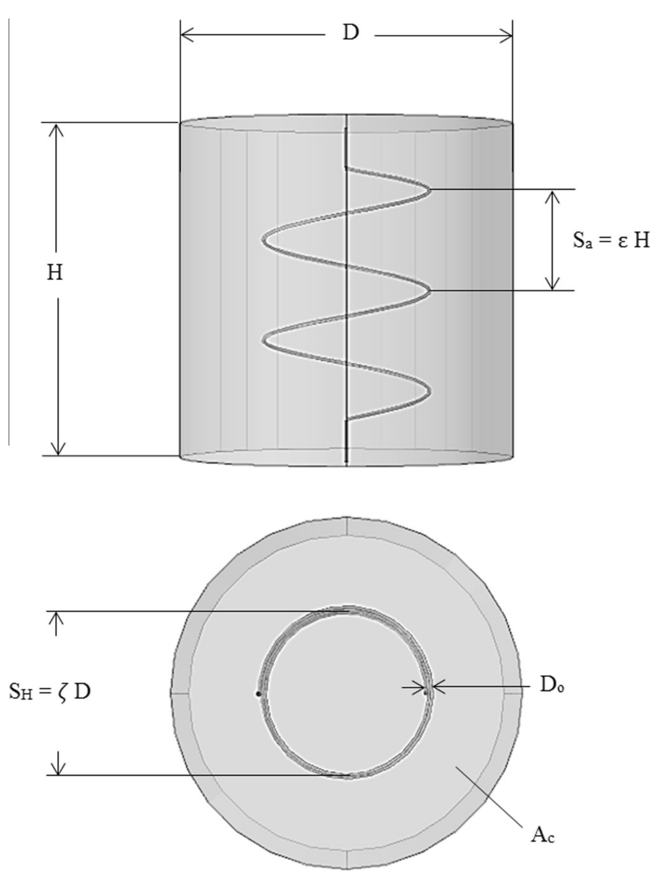

Fig. 1. The geometry of helical pipe embedded in a cylindrical volume.

The total volume of the helical pipe is $V_h = A_h \times L_h = \frac{\pi}{4}D_0^2 L_h$, where A_h is the helix cross-sectional area and D_0 is the pipe diameter.

The helical pipe is buried in a solid body with cylindrical shape of volume $V_c = A_c \times H = \frac{\pi}{4}D^2 H$, where A_c is the cylinder cross-sectional area. The external boundary of the solid cylindrical volume is insulated. The initial temperature of the body (T_c) is higher than the temperature of the helical pipe (T_h).

Transient heat conduction in the cylindrical volume was simulated using a finite element software package [25]. The conservation of energy in the solid is governed by

$$\frac{\partial T}{\partial t} = \alpha\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2}\right] \tag{3}$$

where r, θ and z are defined in Fig. 2, and α is the thermal diffusivity of the solid. Eq. (3) can be written in dimensionless form by using the dimensionless variables

$$r_* = \frac{r}{D}, \quad z_* = \frac{z}{D}$$

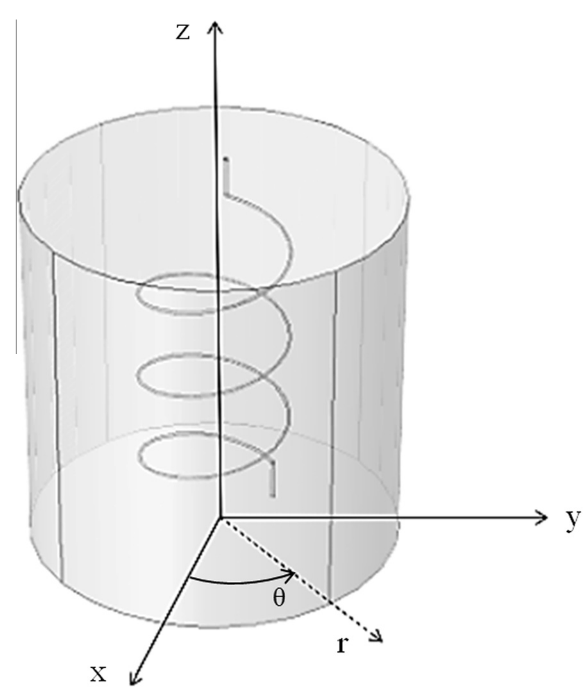

Fig. 2. The coordinates of the flow system of Fig. 1.