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Study on heat transfer of ground heat exchanger based on wedgelet finite element method☆

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ABSTRACT

In order to maximize the economic benefit of ground source heat pump system, it is necessary to grasp the heat transfer rules of ground heat exchanger, the wedgelet finite element method is applied in analyzing heat transfer process of ground heat exchanger. First, existing researches on heat transfer analysis of ground heat exchanger and wavelet finite element method have been summarized. Second, the basic characteristics of wedgelet function are studied. Third, the wedgelet finite element model of analyzing heat transfer rules of ground heat exchanger is constructed using wedgelet function as interpolation function. Finally, the heat transfer simulation analysis of vertical U-type ground heat exchanger is carried out, and results show that the wedgelet finite element has higher precision and efficiency, and the effect of main affecting factors on heat transfer rules of ground heat exchanger is obtained.

1. Introduction

In recent years, the ground-source heat pump gets the rapid development. The ground-source heat pump has many advantages, such as good energy saving effect, environment protection effect, simple system, high performance coefficient. The ground-source heat pump system has higher energy efficiency relative to air source heat pump system, which contributes to reduce Carbon emission. However the high installation and drilling costs can impede the development of ground-source heat pump system. In order to maximize economic benefit, it is necessary to study the heat transfer of ground heat exchanger. The vertical U-type ground heat exchanger is used widely at present, which is the core technology and application basis of ground-source heat pump technology. The heat transfer of vertical U-type ground heat exchanger belongs to a very complex unsteady process. On the one hand, the burying pipe mode, underground hydrological parameter, backfill material, and ground meteorological parameters can affect the heat-transfer process of exchanger; on the other hand, the heat transfer process of ground heat exchanger can affect the operating characteristic of underground heat pump assembling unit. The geometry, coupled heat transfer between the fluid in tube and soil of vertical U-type ground heat exchanger are very complex, the current computer technology has difficulty in construct the precise model that simulates the all actual situations. The coupled model of heat transfer of fluid in tube and soil are constructed, and then the underground heat pump system simulation model coupled with ground heat pump system is also constructed.

The heat transfer process of ground heat exchanger has strong non-linearity, therefore the traditional numerical technology has difficulty in obtaining high computing precision and efficiency, it is significant to find out an effective means to carry out the heat transfer simulation analysis of vertical U-type ground heat exchanger. The wavelet finite element method is a new finite element approximation method, and the multi resolution thinking of wavelet function is induced into the traditional finite element method. The wavelet function is used as interpolating function, and the new finite approximation space can be obtained. The analysis scale can be changed randomly according to actual requirement of simulation analysis, and therefore the wavelet finite element method can be used to solve the nonlinear problems. In order to obtain better computing precision and efficiency, the wedgelet function is used as the interpolating function to construct the new finite element, the wedgelet function is different from wavelet function, which is defined directly in two dimensions, and therefore it has better performance in solving nonlinear problem. Then the wedgelet finite element model is established combing the traditional finite element method and the wedgelet theory, which can be applied to analyze the heat transfer rules of a vertical U-type ground heat exchanger.

2. Related research progress

In recent years, the heat transfer analysis of ground heat exchanger has been concerned by some scientists, and a lot of research results are obtained. Dasare R.R. and Saha S.K. (2015) carried out the numerical study of horizontal ground heat exchanger for high energy requirement applications, a mathematical model was constructed and validated, and thermal characteristics of different kinds of ground heat exchangers were predicted. Effects of different affecting factors on thermal

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performance of ground heat exchanger are obtained finally [1]. Naylor S. et al. proposed better designs of geothermal heat pump systems based on characterization of the spatiotemporal variability in soil thermal properties, and the ground heat exchanger costs can be reduced. The results show that the normal engineering practice of predicting thermal performances from soil type can be beneficial for optimal design of underground heat exchanger [2]. Chen J.H. et al. constructed the heat transfer model for vertical U-tube ground heat exchangers, and the different initial soil temperatures and physical properties at different depths are considered. And the theory model is verified by experimental analysis results, and the thermal performance of ground heat exchanger is obtained [3]. Jimin Kim et al. assessed the environment and economics for choose the optimal ground heat exchanger when the entering water temperature is considered. The basic information was established, and the main factors affecting ground heat exchanger characteristics were selected. The possible changes of the ground heat exchanger installation by considering entering water temperature were made. The life cycle cost was assessed finally [4]. Seok Yoon et al. proposed an experimental and a simulation analysis to evaluate thermal response test results from a precast high-strength concrete pile and a general traditional vertical type borehole with spiral coil type ground heat exchangers. The results showed that the infinite line source model can evaluate the ground thermal conductivity effectively [5]. Leroy Arny and Bernier Michel presented a new spiral coil ground heat exchanger model based on Green's function theory considering axial effects, and new input parameters, inlet fluid temperature and mass flow rate were presented. And the advantages of the new model were verified through a numerical analysis comparing with other conventional model [6]. Bottarelli M. et al. presented mixing phase change materials directly with backfill material for flat panel type ground heat exchanger, and the application was evaluated based on the numerical analysis, and the transient heat transfer was analyzed by effective heat capacity method, and the results showed that the employment of phase change materials could smooth thermal wave in the ground, and improved the performance of ground heat pump [7]. The heat transfer procession of ground heat exchanger is in unsteady state, and the conventional numerical algorithm has bigger error, therefore the advanced numerical analysis means should be used.

The wavelet finite element method is a new numerical tool of solving the nonlinear problem, which is applied in many engineering field. Mao Liu et al. studied the band structure of one-dimensional phononic crystals based on wavelet finite element method. The wavelet finite element formula was established by combining a slender beam element by B-spline wavelet on the interval, and the effectiveness of this model is verified based on numerical example [8]. Xue Xiaofeng et al. presented a multi-scale wavelet based numerical method. The amended Hermitian interpolation wavelet base could get transformation matrix, and then the amended Hermitian wavelet finite element was constructed, which was applied in wave propagation and load identification, and numerical analysis results showed that this method has higher precision and efficiency [9]. Bin Zhao studied temperature field changing rules of LNG tank under ultra-low temperature based on the Hermitian wavelet finite element method, and the results showed that the Hermitian wavelet finite element method had higher computing accuracy and efficiency than the traditional finite element method [10]. Samaratunga Dulip et al. analyzed the wave propagation in adhesively bonded composite joints based on the wavelet spectral finite element method. Daubechies that compactly supported wavelet scaling functions were applied in transforming the governing partial differential equations from time domain to frequency domain, and time domain analysis results for wave propagation in a lap joint were verified with the conventional finite element method, and the results showed that the new wavelet spectral finite element method has higher efficiency and correctness [11]. In order to improve effectiveness of the heat transfer analysis of ground heat exchanger, the wedgelet finite element method is used in this research, and the main reason is that the wedgelet transform has better approximation ability, which is applied in image processing. So far the wedgelet finite element method has not been put forward, therefore it explores the introduction of wedgelet function into the traditional finite element method.

3. Basic characteristics of wedgelet function

The wedgelet is the piecewise constant function defined in square S, which is divided by line l that runs through square S, and the two parts on both sides of line l are all constant. Every wedgelet function can describe the straight edge of local image region. The schematic diagram of the wedgelet function is shown in Fig. 1. As seen from Fig. 1, four parameters can denote the Wedgelet$(S_1, v_1, v_2, m_a, m_b)$, and the two crossing points between l and the boundary of square S can denote the position of line l, and the function values of two sides for line l are denoted by m_a and m_b respectively [12].

Although the wedgelet transform does not conclude orthogonal series, a single wedgelet is only selected for every sub block, and therefore the final approximation can be made up of two orthogonal parts. In order to control the performance of multi resolution transform, an update-first structure is used in this research, and the lifting wedgelet transform concludes the following three steps [13]:

Step 1 (Separation): during procession of presenting multi resolution wedgelet transform, some sub sets can be constructed through rectangular sampling, which are expressed as follows:

$$x_1[n,m] = x[2n,2m], \quad x_2[n,m] = x[2n,2m+1] \tag{1}$$

$$x_3[n,m] = x[2n+1,2m], \quad x_4[n,m] = x[2n+1,2m+1] \tag{2}$$

Step 2 (Updating): in order to control the performance of coarse approximation, Harr updating is used, and therefore every $x_1[n,m]$ can be replaced by a rough coefficient, and the corresponding expression is listed as follows:

$$c[n,m] = (x_1[n,m] + x_2[n,m] + x_3[n,m] + x_4[n,m])/4 \tag{3}$$

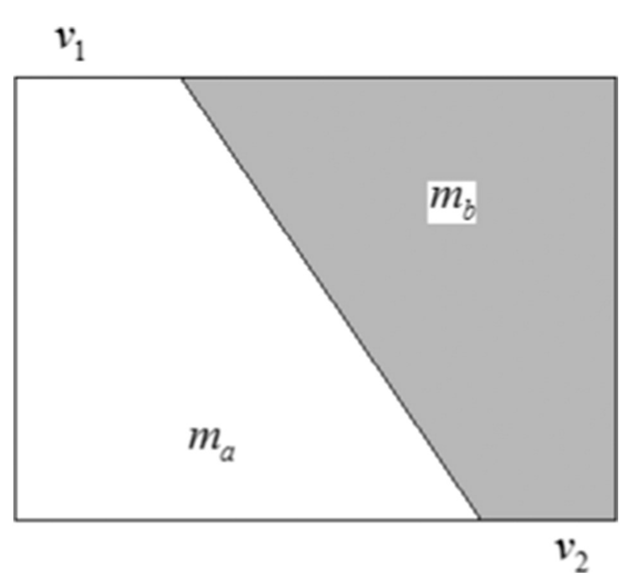

Fig. 1. Diagram of the wedgelet function.