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Heat transfer analysis of single screw compressor under oil atomization based on fuzzy random wavelet finite element method☆

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ABSTRACT

Oil atomization is an effective enhanced heat transfer method for single screw compressor, which can make the compression process of single screw compressor be close to the isothermal process, then the working efficiency can be improved. In order to obtain optimal atomization technology effectively, the heat transfer of single screw compressor is analyzed based on fuzzy random wavelet finite element method. Firstly, the relating researching progresses are summarized. Secondly, the heat transfer governing equation of single screw compressor is constructed based on large eddy simulation technology. Thirdly, the heat transfer wavelet finite element model of single screw compressor is established through using Hermitian wavelet function, and then the fuzzy random Hermitian wavelet finite element mode is established based on λ level set theory. Finally, the heat transfer rules of single screw compressor is obtained based on simulation analysis, the effect of atomization on heat transfer of single screw compressor is obtained, results can offer effective theoretical guidance for designing the novel atomization system for single screw compressor.

1. Introduction

The oil is often injected into working capacity to play the role of lubrication, cooling and sealing in single screw compressor working process. Heat exchange between oil and gas in compression process can reduce power consumption, which can affect the performance of single screw compressor, and therefore the exhaust temperature of single screw compressor with oil injection is higher than that of piston compressor under the same working condition. The heat exchange should be enhanced to make the compression process be more close to the theoretical isothermal process, and then the power can be saved. When the oil in mixed status enters into working capacity of single screw compressor and attaches to the metal wall, the heat transfer area is little, and there is almost no cooling effect, and the compression process is still close to adiabatic status. On the contrary, the oil is injected into the single screw compressor after atomization, and the compression process index is expected to greatly reduce. Therefore, the oil should have a bigger surface to enhance the heat exchange when the amount of oil is the same, that is, the atomization should be carried out for oil to make it suspend in the air in particle shape, then the exhaust temperature can reduce, and the working efficiency can be improved, and the manufacturing cost can be reduced, and the use range of single screw compressor can be expanded.

The heat transfer procession between lubrication oil and gas of single screw compressor has strong nonlinearity during compression process of single screw compressor, the traditional finite element method cannot obtain high computing precision and efficiency, and therefore it is necessary to find out an advanced numerical analysis method. The wavelet finite element method using the wavelet function as interpolating function, the multi resolution character can be used effectively, therefore the wavelet finite method has good stability and high computing precision and efficiency, which can be applied in heat transfer of single screw compressor. In addition, the heat transfer analysis generally is carried out based on certainty model that considers all kinds of factors as certainty quantity, however the affecting factors of heat transfer between oil and gas are uncertain in actual compression process of single screw compressor such as physical characteristic parameters of materials, boundary conditions, and thermal load. The fuzzy finite element method is an effective tool for analyzing the effect of fuzzy factors on the heat transfer of single screw compressor, which can reflect the actual heat transfer rules of single screw compressor. In order to improve the effectiveness of heat transfer analysis of single screw compressor, the wavelet finite element method can be combined with fuzzy finite element method to construct fuzzy wavelet finite element method, which is applied in the heat transfer simulation analysis of single screw compressor.

2. Related research progress

In recent years, the heat transfer of compressor has been concerned by many scientists, and some excellent achievements have been

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obtained. Changhyun Baek et al. studied the heating performances of the vapor injection CO_2 cycles and sub-cooler vapor injection cycles when the cylinder volume ratio of twin rotary compressor was different, and results offered effective guidance for designing and operating the twin rotary compressor [1]. Bo Yan et al. carried out an experimental investigation on heat transfer with porous inserts during compression and expansion of a liquid piston compressor, and the changing rules of power density and efficiency of compressor were obtained, and results provided the theoretical guidance for choosing proper compressor types for working environment with different compression ratios and efficiency requirement [2]. Arjomand Kermani N. and Rokni M. studied the heat transfer phenomena inside the compression chamber based on thermodynamic model, and the temperature distribution of the system was obtained, and the sensitivity analysis showed that the total heat transfer coefficients at the interface and wall played an important role on reducing the hydrogen temperature [3]. Sharapov I.I. et al. studied the heat exchange of rotary compressors with external and internal compressions, and the implemented methods were established for measuring time varying temperatures of gas and walls of working chamber of the rotary compressor, and the experiments and simulations were carried out for analyzing the heat exchange of rotary compressor [4]. Lili Gu et al. studied the effect of heat transfer on the centrifugal compressor performance based on computational fluid dynamics techniques, the heat transfer influences were investigated on the compressor performance at design point and other operation points, and the analysis results could offer a theoretical basis for taking heat transfer controlling measurements to improve the efficiency of compressor [5]. The single screw compressor was also a concernof some scientists, and the main research contents conclude areas including mathematical model of the meshing principles of meshing pair, dynamic characteristics of gate rotor and screw rotor, performance analysis of single screw compressor, thermal deformation analysis of main components and so on. So far the related studies on the heat transfer of single screw compressor under oil atomization are relatively less, therefore it is necessary to carry out relating researches.

In order to improve effectiveness of heat transfer analysis of single screw compressor with high nonlinearity, the wavelet finite element method can be applied in analyzing the heat transfer of single screw compressor because it has an advantage in solving the nonlinear problem. The wavelet finite element method has been applied in many fields successfully, and some excellent achievements have been obtained. Samaratunga, D. et al. constructed wavelet spectral finite element model for analyzing the wave propagation in anisotropic composite laminate with a transverse surface crack, and numerical analysis results illustrated that the wavelet spectral finite element model can obtain higher computing accuracy and efficiency [6]. Zuo Hao et al. analyzed static and free vibration problems of laminated composite plates based on the B-spline wave finite element method, and numerical experiments, and the wavelet-based BSWI element were constructed based on the principle of minimum total potential energy, and numerical analysis results showed that the wavelet finite element method was an effective, accurate and stable tool of analyzing the static and free vibration analysis of laminated composite plates [7]. Zhao Bin studied the temperature field of LNG tank under ultra-low temperature based on Hermitian wavelet finite element method, and the theoretical model of Hermitian wavelet finite element model of analyzing temperature field of LNG tank was constructed, and simulation results showed that the Hermitian wavelet finite element method had higher computing accuracy and efficiency [8]. Khulief Yehia A studied the effect of wall-thinning on the natural frequencies of fiber-reinforced polymer pipe based on wavelet-based finite element method, and a new set of Hermite shape functions was proposed, and the simulation and experimental results showed that effectiveness of wavelet-based finite element method [9]. Yaghmaie Reza et al. proposed a new wavelet finite element model of analyzing the coupling transient electromagnetic and dynamic fields in a vibration substrate undergoing finite deformation, and the computing efficiency was enhanced than traditional finite element method, and the effectiveness of this new method was verified through numerical analysis [10]. As seen from current achievements, the wavelet finite element method has an advantage in solving nonlinear problems, and therefore it can be applied in heat transfer of single screw compressor.

In addition, the effect of fuzzy affecting factors on heat transfer between oil and gas under oil atomization should be considered for improving the correctness of simulation analysis, fuzzy finite element method has been also applied in many engineering fields, and some achievements have been obtained. Nayak S. and Chakraverty S. proposed the modified form of fuzzy finite element method for solving the conjugate heat transfer considering the uncertainty parameters. The fuzzy numbers were changed into intervals through alpha cut, and the simulation of heat transfer problem for a square plate was carried out, and the results showed the effectiveness of the fuzzy finite element method [11]. Wang C et al. presented the fuzzy stochastic finite element method through combing the perturbation theory and moment method, the fuzzy parameters were equivalently decomposed into interval variables based on the level cut method, and the probabilistic characteristics of the uncertain temperature field were calculated effectively, and the effectiveness of the fuzzy finite element method had been verified through numerical simulations [12]. Massa F. et al. proposed a new method of solving the mechanical frictionless contact problem using a fuzzy logic controller. The nonlinear problem could be decomposed into a set of linear problems, which can be solved by finite element method, then the computing time and precision of analysis were improved [13]. The fuzzy finite element method can obtain the correct analysis results of engineering problems because the uncertain factors are considered, therefore it is feasible to combine the fuzzy finite element method and the wavelet finite element method for analyzing the heat transfer between oil and gas of the single screw compressor.

3. Heat transfer governing equation of single screw compressor

The heat transfer of single screw compressor is turbulence problem, and therefore the large eddy simulation (LES) is applied in simulation computation. In the large eddy simulation method, each variable is divided into two parts by the filter function, which concludes large scale mean component $\overline{\phi}$ and small scale component ϕ', where $\overline{\phi}$ is calculated by the following expression [14]:

$$\overline{\phi} = \int_D \phi G(x, x')dx' \tag{1}$$

where x' denotes the spatial coordinate in the actual flow area, x denotes spatial coordinate on the large scale space after filtering, and $G(x,x')$ denotes the filtering function.

The Navier–Stokes in transient state through filtering process based on expression (1) is expressed as follows [15]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \overline{u}_i) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \overline{u}_i) + \frac{\partial}{\partial x_j}(\rho \overline{u}_i \overline{u}_j) = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \overline{u}_i}{\partial x_j}\right) - \frac{\partial \overline{\tau}_{ij}}{\partial x_j} \tag{3}$$

where ρ denotes the medium density, kg/m^3; $\overline{u}_i$ and $\overline{u}_j$ are filtered horizontal and vertical velocities, m/s; $\overline{p}$ denotes the filtered pressure, MPa; t denotes time, s; $\overline{\tau}_{ij}$ denotes the subgrid scale turbulence stress term, μ denotes the motion viscosity coefficient, and mm^2/s.

The subgrid stress is expressed as follows based on Smagorinsky–Lilly model [16]:

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t \overline{S}_{ij} \tag{4}$$