J Therm Anal Calorim (2012) 110:1013–1019
DOI 10.1007/s10973-011-1990-y

Study on temperature field change regularity of crude oil in seabed pipeline

A method combing finite element analysis with curvelet transform

Bin Zhao

Received: 14 September 2011 / Accepted: 11 October 2011 / Published online: 1 November 2011

Abstract The temperature distributions of the crude oil in the seabed pipeline is important for its operation, and the application of the traditional finite element method and curvelet transform on its temperature are described in this study. First, the basic theories of the curvelet transform are analyzed. Second, the finite element model of the crude oil in the seabed pipeline based on curvelet transform is constructed. Third, the computing model of the crude oil in the seabed pipeline is established, and then the temperature changing rules of the crude oil in the seabed pipeline are obtained. The results show that the method of combining traditional finite element method and curvelet transform is more efficient than the traditional finite element method with ANSYS software, and the solidification time of the crude oil in the seabed pipeline is obtained. Finally, the effect of the insulation layer on the solidification time is analyzed.

Keywords Temperature field · Crude oil · Solidification time · Curvelet transform · Finite element method

During the process of the offshore development, seabed pipeline is an important infrastructural facility with huge investment, and its safety should be ensured. The seabed pipeline may stop transporting the crude oil during operation, and the temperature of the crude oil in the seabed pipeline will drop after the stoppage of the transportation operation. As a result, the phenomena of the solidification and wax precipitation may occur, which will present much difficulty and risk during the startup operation.

B. Zhao (✉)
School of Mechanical Engineering, Liaoning Shihua University, Fushun 113001, China
e-mail: zbzbz0203288@163.com

Higher viscous crude oil has been used in the seabed pipeline recently, which is readily coagulated. This kind of crude oil has high viscosity and poor fluidity under the normal temperature, which is unfavorable for long-distance transportation. In order to improve the fluidity of the crude oil, the viscosity of the crude oil is reduced using the thermal-insulating and heating techniques. Therefore, it is important to analyze the temperature changing rules of the crude oil in the seabed pipeline for setting the maximum allowable solidifying time for shutting down and restarting pipeline. Thus, the study on the temperature varying rule of the crude oil in the pipeline is truly significant.

The temperature field calculation of the crude oil has greatly attracted the attention of scientists. An unstructured volume method was used for studying the new technology of crude oil pipeline, and the thermal impact of the pipeline on the crude oil temperature was investigated [1]. A mathematical model was constructed for a buried hot crude oil pipeline during shutdown; the unstructured and polar coordinate grids were applied to generate grids for the soil region; and three layers in the pipe and the variations in temperatures of the soil were studied [2]. A quasi three-dimensional (3D) computational model was developed to predict the oil temperature along the pipeline, and it was verified by analytic solutions of the minimum oil temperatures along the route [3]. The thermodynamics of wax formation in crude oils is examined, and additional insights were obtained on the problem. A correlation of cloud point, or wax appearance temperature was obtained for pure-substance waxes, which could be extended to mixtures of hydrocarbons, thereby generalizing the usefulness of the correlation [4]. A physical model is proposed to study the heat transfer and oil flow of a buried hot oil pipeline under normal operation, and numerical simulation in a wide range of operating conditions is conducted. A good agreement between numerical simulations and field measurement suggests that the proposed numerical scheme is a suitable method to simulate the heat transfer and oil flow of the buried hot crude oil pipelines [5]. An efficient numerical algorithm employing methods, such as the finite volume, finite difference, Monte Carlo, and proper orthogonal decomposition (POD), was proposed to simulate the stochastic fluctuation of oil temperatures. The effects of outlet oil temperature, flow rate, pressure, buried depth, soil temperature; soil thermal conductivity, oil viscosity, and oil density on the stochastic fluctuation of oil temperatures were investigated [6].

Finite element method is an effective method for temperature field analysis, and it has been widely applied in many fields. An innovative simulation technique known as element birth and death was applied in modeling the 3D temperature field in multiple layers in a powder bed.. The temperature field during laser melting of metal powders in additive layer manufacturing was analyzed [7]. 3D finite-element thermal simulation of GaN HEMT structures was carried out, and HEMTs differing by geometry, substrate material, and cooling strategy were simulated and compared [8]. A 3D finite element temperature field model was proposed to be developed based on global model and submodel patterns to describe the thermal dynamics behavior in direct laser fabrication, and the global model exhibited the heat conduction characteristics of parts in the whole thermal history according to scanning path planning [9].

Normally, the traditional finite element method uses polynomial interpolation in some steps of the calculations. In order to improve the resolution of traditional finite element method, the curvelet transform can be combined with it. Curvelet transform is a new multiscale pyramid representation with many directions and positions at each length scale and needle-shaped elements at fine scale. Curvelet can offer a natural mechanism for decomposing the solution into a set of coefficients, and curvelet has better ability of direction identification for the added direction parameter relative to traditional wavelet transform. Since the Curvelet transform theory was put forward by Donoho et al. in 1999, the corresponding studies have attracted the attention of many scientists; many achievements based on curvelet have been presented. The application of digital curvelet transform in conjunction with different dimensionality reduction tools was introduced, and its application on the problem of facial feature extraction from 2D images was studied in depth, and the results showed that curvelet indeed has the potential to supersede wavelet [10]. A novel scheme for image compression, by means of the second-generation curvelet transform and support vector machine (SVM) regression and compression, was achieved using SVM regression to approximate curvelet coefficients with the predefined error. The results showed that this method gained much improvement and worked well for declining block effect at high compression ratios [11]. A new recognition and novelty detection approach for indicator diagram of reciprocating compressor was presented, and this method was a combination of curvelet transforms, nonlinear PCA, and SVM, results of which showed that this method was better than the traditional wavelet-based approach [12]. A review on the curvelet transform, including its history beginning from wavelets, its logical relationship to other multi-resolution multidirectional methods like contourlets and shearlets, its basic theory and discrete algorithm, was presented, and recent applications in image processing, seismic exploration, fluid mechanics, simulation of partial different equations, and compressed sensing were considered.

The curvelet transform is a very promising potential technology in traditional application fields for wavelet-like ideas, such as data analysis, and scientific computing. The objective of this research is to apply the finite element method and curvelet transform to analyze the temperature field of the crude oil in the seabed pipeline. The scaling functions of the interpolating wavelets are chosen here because the scaling functions in multiscale curvelet analysis have excellent computing abilities.

The basic property of the curvelet transforms

In 2D space R^2, x is a position parameter, ω is a spatial frequency parameter, r and θ are polar coordinates in frequency domain.

Radial window $W(r)$ and angle window $V(r)$ with smoothing, non-negative and real properties are assumed to satisfy the following admissible conditions [10]:

$$\sum_{j=-\infty}^{\infty} W^2(2^j r) = 1, \quad r \in \left(\frac{3}{4}, \frac{3}{2}\right) \tag{1}$$

$$\sum_{l=-\infty}^{\infty} V^2(t-l) = 1, \quad t \in \left(-\frac{1}{2}, \frac{1}{2}\right) \tag{2}$$

For all scales $j \geq j_0$, frequency domain window of Fourier can be defined by:

$$U_j(r,\theta) = 2^{-\frac{3j}{4}} W\left(2^{-j} r\right) V\left(\frac{2^{\left[\frac{j}{2}\right]}\theta}{2\pi}\right) \tag{3}$$

where $[\frac{j}{2}]$ denotes the integer part of $\frac{j}{2}$. U_j is a kind of wedge window in polar coordinates, which can be obtained by the product of radial window $W(r)$ and angle window $V(r)$.

The mother curvelet is defined by $\varphi_j(x)$, and its Fourier transform is expressed as $\hat{\varphi}_j(\omega) = U_j(\omega)$, and all curvelets in the scale 2^{-j} can be obtained through the rotation and translation of $\varphi_j(x)$. The rotational angle series with the same interval and displacement parameter series are introduced. The rotational angle series can be expressed as follows [14]:

$$\theta_l = 2\pi \cdot 2^{-\left[\frac{j}{2}\right]} \cdot l, \quad l = 0,\ 1,\ 2, \ldots \tag{4}$$

where $0 < \theta_l < 2\pi$, and l is a parameter.

The displacement parameter series can be expressed as follows:

$$k = (k_1, k_2) \in Z^2 \tag{5}$$

where k_1 and k_2 are the components of the displacement parameter vector.

The curvelet with the scale 2^{-j}, the azimuth θ_l, the location $x_k^{i,j} = R_{0l}^{-1}\left(k_1 \cdot 2^{-j}, k_2 \cdot 2^{-\frac{j}{2}}\right)$ can be expressed as follows:

$$\varphi_{i,j,l}(x) = \varphi_j(R_{0l}(x - x_k^{j,l})) \tag{6}$$

where R_0 denotes the rotation by θ radians, which can be expressed as follows:

$$R_0 = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{7}$$

A curvelet coefficient is simply the inner product between an element $f \in L^2(R^2)$ and a curvelet $\varphi_{j,l,k}$:

$$c(j,i,k) = \langle f, \varphi_{j,l,k} \rangle = \int_{R^2} \overline{f(x)\hat{\varphi}_{j,l,k}(x)}\mathrm{d}x \tag{8}$$

The curvelet transforms in frequency domain can be defined as follows [12]:

$$\begin{aligned} c(j,i,k) &= \frac{1}{(2\pi)^2}\int \hat{f}(\omega)\overline{\hat{\varphi}_{j,l,k}(x)}\mathrm{d}\omega \\ &= \frac{1}{(2\pi)^2}\int \hat{f}(\omega)U_j(R_{\theta l}(\omega))\mathrm{e}^{j\langle x_k^{(j,l)},\omega\rangle}\mathrm{d}\omega \end{aligned} \tag{9}$$

The finite element model of the crude oil in the seabed pipeline based on curvelet transform

Curvelet functions $\varphi_{j,l,k}^1(\varepsilon)$ and $\varphi_{m,n,q}^2(\eta)$ can form multi resolution sub-spaces $\{V_j^1\}$ and $\{V_j^2\}$ respectively, the tensor product of the two sub-spaces formed higher-level subspaces:

$$V_j = V_j^1 \otimes V_j^2 \tag{10}$$

$\{V_j\}$ forms a multi-resolution of the Hilbert space $L^2(R)$, which is expressed as follows:

$$\vec{\varphi}_{j,k,l}^1 = \{\varphi_{j,k,l}^1(\varepsilon), \varphi_{j,k,l}^1(\varepsilon+1), \ldots, \varphi_{j,k,l}^1(\varepsilon+(N-2))\} \tag{11}$$

$$\vec{\varphi}_{m,n,q}^2 = \{\varphi_{m,n,q}^2(\eta), \varphi_{m,n,q}^2(\eta+1), \ldots, \varphi_{m,n,q}^2(\eta+(N-2))\} \tag{12}$$

where j, k, l, m, n, and q are the parameters.

The corresponding scale function in space $\{V_j\}$ can be expressed as follows:

$$\vec{\varphi} = \vec{\varphi}_{j,k,l}^1 \otimes \vec{\varphi}_{m,n,q}^2 \tag{13}$$

The temperature field calculation of the crude oil in the seabed pipeline can be simplified as 2D plane problem, and the solution region of temperature field can be discretized by a great deal of finite elements, and the temperature of each node of the finite element combining with curvelet transform can be formed by using curvelet function as interpolating function [1, 2].The temperature function $T(\varepsilon,\eta)$ can be expressed as follows [3]:

$$T(\varepsilon,\eta) = \vec{\varphi}\vec{a}^e = \sum_{i,j,k,m,n,q=0}^{N-2} \varphi_{j,k,l}^1\varphi_{m,n,q}^2\vec{a}^e \tag{14}$$

where $\vec{a}^e = [a_0, a_1, \ldots, a_{-(N-2)}]^T$ is the coverlet filter coefficients.

During the stoppage of the transportation process of the crude oil in the seabed pipeline, the heat transfer mainly depended on the thermal conduction of sea water–heat insulation–fluid media. The mathematical model of the crude oil energy in seabed pipeline can be constructed based on energy conservation equation, which is expressed as follows:

$$\frac{\partial(\rho_T T)}{\partial t} + \frac{\partial(\rho_T T)}{\partial x} + \frac{\partial(\rho_T T)}{\partial y} = \frac{\partial}{\partial y}\left(\frac{k_T}{c_T}\frac{\partial T}{\partial y}\right) + Q_T \tag{15}$$

where T is temperature, K; t is time, s; c_T is the specific heat of the crude oil, J/(K kg); k_T is the thermal expansion coefficient, W/(m K); ρ_T is the density of the crude oil, kg/m^3; Q_T is the inner heat source of the crude oil and that part of the mechanical energy which is converted to the heat energy due to the viscosity of the crude oil.

The corresponding functional equation can be expressed as follows [4]:

$$\Pi(T) = \int_S \left[\rho_T\left(\frac{\partial T}{\partial T} + \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y}\right) - \frac{k_T}{c_T}\frac{\partial^2 T}{\partial y^2} - Q_T\right]\mathrm{d}x\mathrm{d}y \tag{16}$$

where S denotes the area of the crude oil.

In order to coordinate the curvelet finite element with a^e, the distribution of the nodes of the quadrilateral element is established. The temperature of the node (i, j) is defined by $T_{i,j}$, and the relationship between the global coordinate (x, y) and the local coordinate (ε,η) satisfies the following conditions [5]:

$$\varepsilon = \frac{x - x_1}{x_2 - x_1} \tag{17}$$

$$\eta = \frac{y - y_1}{y_2 - y_1} \tag{18}$$

where x_1, x_2, y_1, and y_2 are the minimum and maximum coordinates of the quadrilateral finite elements in x direction and y directions.

The corresponding functional equation can be expressed as follows:

$$\Pi^e(T) = \int\limits_{Se} \left[\rho_\mathrm{T}\left(\frac{\partial T}{\partial t} + \frac{\partial T}{\partial \varepsilon} + \frac{\partial T}{\partial \eta}\right) - \frac{k_\mathrm{T}}{c_\mathrm{T}}\frac{\partial^2 T}{\partial \eta^2} - Q_\mathrm{T}\right]\mathrm{d}\varepsilon\mathrm{d}\eta \tag{19}$$

where e is the finite element combining with curvelet transform.

The differential equation of 2D steady-state heat transfer can be acquired from the condition $\delta\Pi^e(\theta) = 0$ of the functional equation.

$$\int\limits_{Se} \left[\rho_\mathrm{T}\left(\frac{\partial W}{\partial t}\frac{\partial T}{\partial t} + \frac{\partial W}{\partial \varepsilon}\frac{\partial T}{\partial \varepsilon} + \frac{\partial W}{\partial \eta}\frac{\partial T}{\partial \eta}\right) - \frac{k_\mathrm{T}}{c_\mathrm{T}}\frac{\partial^2 W}{\partial \eta^2}\frac{\partial^2 T}{\partial \eta^2} - Q_\mathrm{T}\right] \mathrm{d}\varepsilon\mathrm{d}\eta = 0 \tag{20}$$

where W is the weight function, which can be expressed as follows [6]:

$$W_{r,s} = \varphi^1_{j,k,l}(\varepsilon)\varphi^2_{m,n,q}(\eta) = \Phi_{r,s} \tag{21}$$

The formula (14) and (21) are inserted into formula (20), and the following equation is obtained:

$$\vec{C}^e\vec{a}^e + \vec{E}^e\vec{a}^e = \vec{L}^e \tag{22}$$

where $\vec{C}^e$ is the heat capacity matrix of curvelet finite element, $\vec{E}^e$ is the heat exchange matrix of curvelet finite element, $\vec{L}^e$ is the heat load matrix of curvelet finite element, $\vec{C}^e$,$\vec{E}^e$ and $\vec{L}^e$ can be expressed as follows [7]:

$$\vec{C}^e_{r,s,u,v} = \int_0^1\int_0^1 \left(\rho_\mathrm{T}\Phi_{r,s}\Phi_{u,v} - \frac{k_\mathrm{T}}{c_\mathrm{T}}\Phi_{u,v}\right)\mathrm{d}\varepsilon\mathrm{d}\eta \tag{23}$$

$$\vec{E}^e_{r,s,u,v} = \int_0^1\int_0^1 \left[\rho_T\left(\frac{\partial\Phi_{r,s}}{\partial t}\frac{\partial\Phi_{u,v}}{\partial t} + \frac{\partial\Phi_{r,s}}{\partial \varepsilon}\frac{\partial\Phi_{u,v}}{\partial \varepsilon} + \frac{\partial\Phi_{r,s}}{\partial \eta}\frac{\partial\Phi_{u,v}}{\partial \eta}\right) - \frac{k_T}{c_T}\frac{\partial\Phi_{u,v}}{\partial\eta^2}\right]\mathrm{d}\varepsilon\mathrm{d}\eta \tag{24}$$

$$\vec{L}^e = \int_0^1 (\rho_T\Phi_{r,s}\Phi_{u,v} - \Phi_{r,s}Q_T)\mathrm{d}\Gamma \tag{25}$$

where r, s, u, and v are the parameters.

The entire differential equation of the heat conduction of the crude oil in the seabed pipeline can be constructed through superimposing the finite element matrix combining with curvelet transform and dealing with the boundary conditions.

$$\vec{C}\vec{a} + \vec{E}\vec{a} = \vec{L} \tag{26}$$

The Crank-Nicolson format can be applied in the difference in time, and the corresponding equation will be expressed as follows [8, 9]:

$$\frac{1}{2}\left[\frac{\partial T}{\partial t}\bigg|_t + \frac{\partial T}{\partial t}\bigg|_{t-\Delta t}\right] = \frac{(T_t - T_{t-\Delta t})}{\Delta t} + O(\Delta t^2) \tag{27}$$

where Δt is the time step, and $O(\Delta t^2)$ is a truncation error, and the simultaneous equation of the formulas (27) and (26) in t and $t-\Delta t$ will be described as follows:

$$(\vec{E} + 2\vec{C}/\Delta t)\vec{T}_t = (\vec{L}_t + \vec{L}_{t-\Delta t}) + (2\vec{C}/\Delta t - \vec{E})\vec{T}_{t-\Delta t} \tag{28}$$

The computing model of the crude oil in the seabed pipeline

The physical parameters of the computing model

The inner diameter of the seabed pipeline is 1200 mm, and the foam insulation is used outside the pipe wall of the seabed pipeline. The 2D model of the cross section of the seabed pipeline with the crude oil is shown in Fig. 1. The crude oil in the pipeline belongs to the fluid zone, and the insulation layer and the pipe wall of the seabed pipeline belong to the solid zone, and the thermal parameters of different zones are different, and the corresponding parameters will be set in the process of constructing model [13].

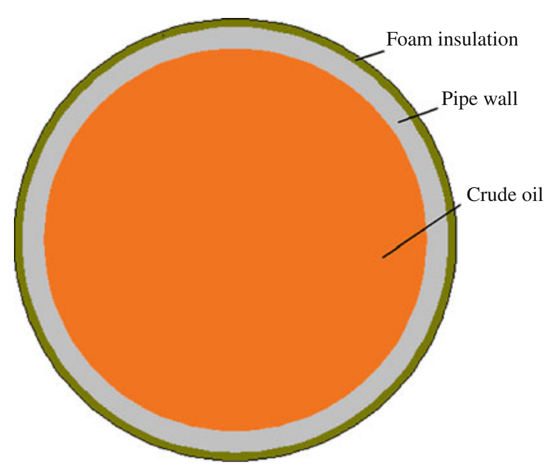

Fig. 1 The 2D model of the cross section of the seabed pipeline with the crude oil

The corresponding thermal computing parameters of the crude oil in the seabed pipeline are listed as follows:

The transportation temperature of the crude oil in the seabed pipeline is 40 °C, and the solidifying point of the crude oil is 30 °C, and the ambient temperature of the sea water near the seabed outside the pipeline is 0 °C.

The density of the crude oil can be expressed as follows:

$$\rho_{\mathrm{T}} = 780 - 1.6T + 0.0016T^2 \tag{29}$$

The heat conductivity of the crude oil satisfies the following condition equations:

$$k_{\mathrm{T}} = 0.15e^{-0.00092(T-273.15)}, \quad T > 303\,\mathrm{K} \tag{30}$$

$$k_{\mathrm{T}} = 0.6 - 0.012(T - 273.15), \quad 303\,\mathrm{K} \le T < 311\,\mathrm{K} \tag{31}$$

$$k_{\mathrm{T}} = 0.6 - 0.012(T - 273.15), \quad T \ge 311\,\mathrm{K} \tag{32}$$

The physical parameters of the steel pipeline are listed as follows:

The density of the pipe wall is $8030\ \mathrm{kg/m^3}$, the specific heat of the pipe wall is $502.5\ \mathrm{J/K\,kg}$, and the heat conductivity of the pipe wall is $16.3\ \mathrm{W/(m\,K)}$.

The physical parameters of the insulation layer are listed as follows:

The density of the insulation layer is $60\ \mathrm{kg/m^3}$, the specific heat of the insulation layer is $700\ \mathrm{J/K\,kg}$, and the heat conductivity of the insulation layer is $0.04\ \mathrm{W/(m\,K)}$.

The curvelet finite element model

In order to verify the effective of the finite element model combining with curvelet transform, the solutions obtained by ANSYS software are compared to the solutions obtained by curvelet finite element method. When combining with curvelet transform, the crude oil is meshed by 800 finite elements, the insulation layer by 500 finite elements, and the pipe wall of the seabed pipeline by 400 finite elements. However, In ANSYS software, the crude oil is meshed by 5645 traditional finite elements and 11436 nodes, and the insulation layer by 3045 finite elements and 9846 nodes, and the pipe wall of the seabed pipeline by 2453 finite elements and 8543 nodes [14].

The study on temperature change rule of the crude oil in the seabed pipeline

The crude oil in the seabed pipeline is divided into three regions to analyze the temperature change of crude oil in the seabed pipeline, the radius centering about the central point of the cross-sectional area of the pipe is used to divide different regions of the crude oil in the seabed pipeline; the temperature computing regions of the crude oil is shown in Fig. 2.

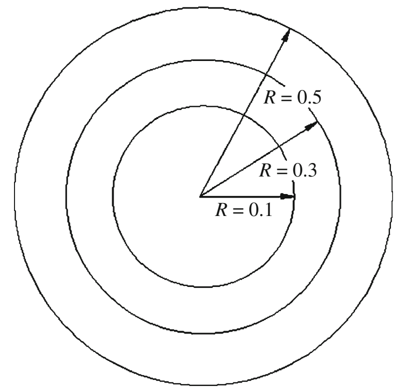

Fig. 2 The temperature region of the crude oil in the seabed pipeline

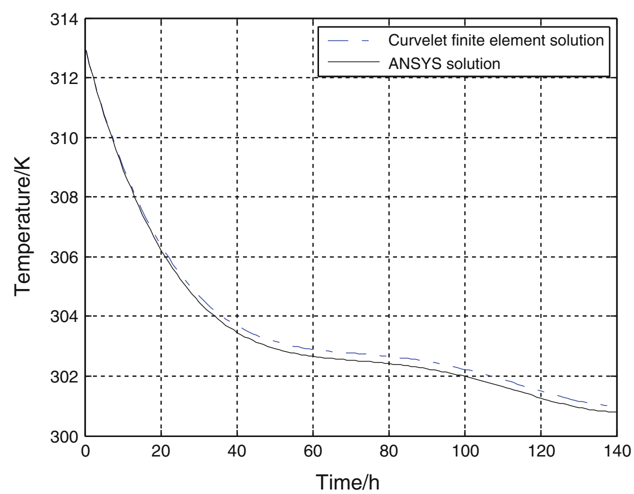

Fig. 3 The temperature changing rule curve of the crude oil at $R = 0.5$

The temperature changing process of the crude oil in the pipeline over time is analyzed by finite element method combing with curvelet transform and ANSYS software, respectively, and the computed results are shown in Figs. 3, 4, 5.

It can be seen from the Figs. 3, 4, 5 that the temperature of the crude oil in the pipeline decreases for different computing regions with the increase in the time for stoppage of the transportation. The nearer the crude oil in the pipeline to the pipe wall, the faster the rate of decrease of temperature of the crude oil in the pipeline is. Figure 3 shows the temperature changing rule curve of the crude oil at $R = 0.5$; the temperature of the crude oil in this region is lower than the critical temperature at 95 h after stoppage of the transportation, and the solidifying process occurs; Fig. 4 shows the temperature changing rule curve of the crude oil at $R = 0.3$: the temperature of the crude oil in this region is lower than the critical temperature; the crude oil begins to solidify at 115 h after stoppage of the transportation; the solidifying volume of the crude oil reaches

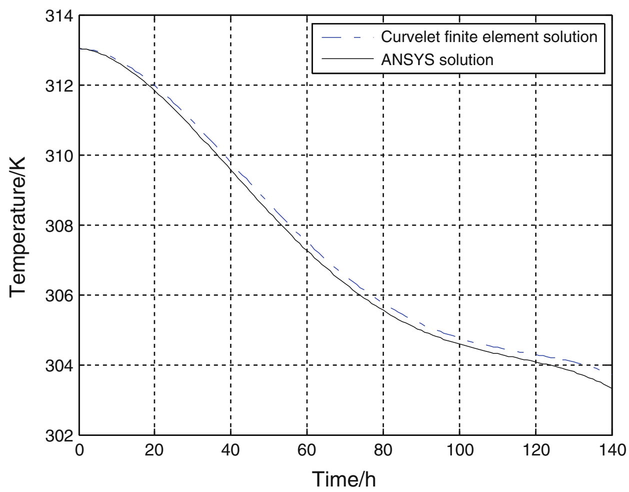

Fig. 4 The temperature changing rule curve of the crude oil at $R = 0.3$

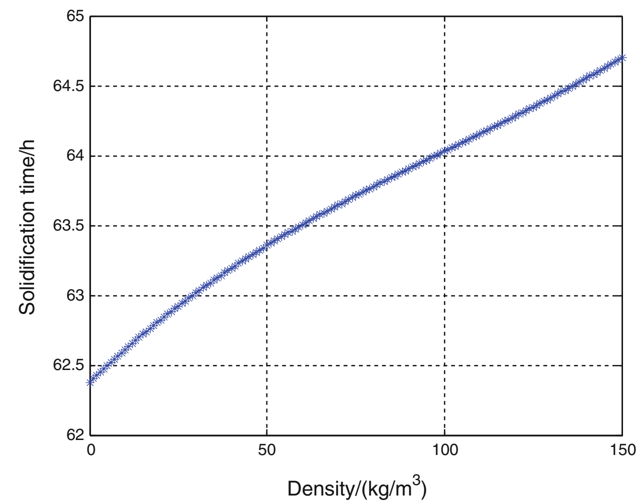

Fig. 6 The solidification time changing curve of the crude oil with the changing of the density of the insulation material

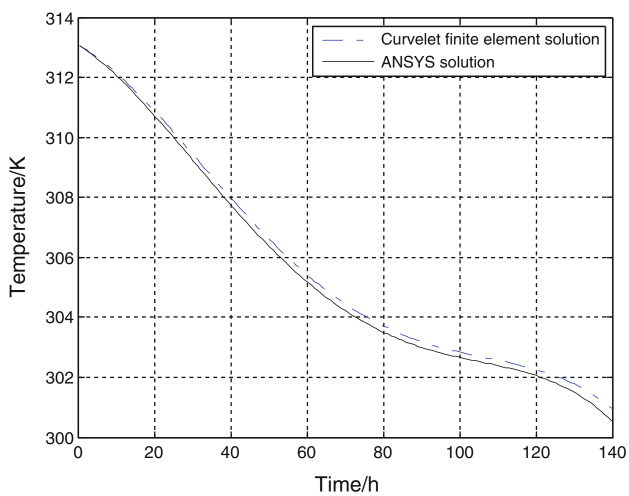

Fig. 5 The temperature changing rule curve of the crude oil at $R = 0.1$

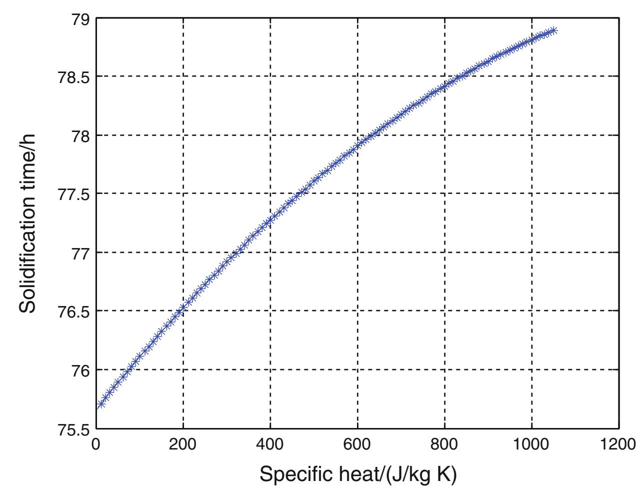

Fig. 7 The solidification time changing curve of the crude oil with the changing of the specific heat of the insulation material

14/25; and the solidification of more than half of the crude oil happens. Figure 5 shows the temperature changing rule curve of the crude oil at $R = 0.5$: the solidifying volume of the crude oil in this region reaches 22/25 at 125 h after stoppage of the transportation, and nearly the entire crude oil solidifies.

As seen from Fig. 3, 4, 5, the finite element solutions combining with curvelet transform are closer to ANSYS solution—while the finite element method combining with curvelet transform uses less finite elements combining with curvelet transform than the traditional finite elements used in ANSYS software. Therefore, the finite element method combining with curvelet transform can improve the computing efficiencyof temperature field of the crude oil in the seabed pipeline.

Study on the effect of the insulation layer on the solidification time

The characteristic parameters of the insulation layer such as density, specific heat, and heat conductivity of the insulation material relate the temperature changing speed of the crude oil; then the relationship between the characteristic parameters of the insulation layer and the solidification time of the crude oil is analyzed by curvelet finite element method, and the computed results are shown in Figs. 6, 7, 8.

As seen from Figs. 6, 7, 8, the solidification rate of the crude oil increases slightly when the density and specific heat of the insulation material increase; therefore, the effects of the density and specific heat of the insulation

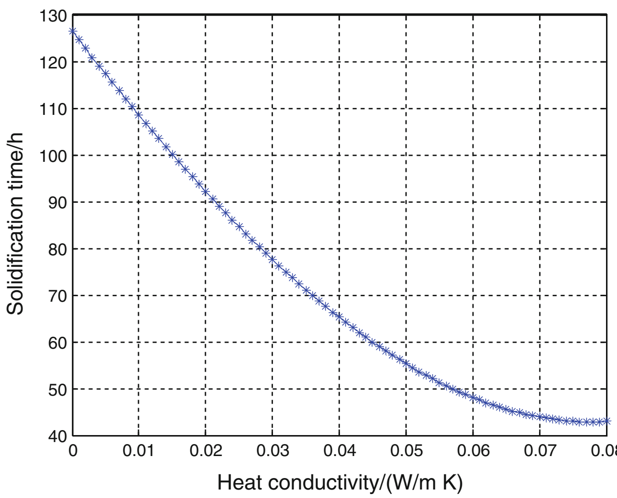

Fig. 8 The solidification time changing curve of the crude oil with the changing of the heat conductivity of the insulation material

material on the solidification speed of the crude oil are very less. The solidification rate of the crude oil decreases obviously when the heat conductivity increases, and the heat conductivity has a greater influence on the solidification rate of the crude oil in the seabed pipeline.

Conclusions

The temperature finite element is established by combining traditional finite element method and curvelet transform, and the curvelet function is used as interpolation function of nodes of the temperature finite element. The temperature changing rules of the crude oil in the seabed pipeline is analyzed by method of combining traditional finite element method with curvelet transform and ANSYS software, and the temperature changing rules and the solidification times of the crude oil in different regions of pipe are obtained.

Results showed that the combined method of the traditional finite element method and curvelet transform is more efficient than traditional finite element in ANSYS software. The advantages of Curvelet transform are applied in the new algorithm, such as sparser representation, multi-resolution multi-directional performance, and thus the accuracy of the computation results is improved.

Through studying the relationship between the characteristic parameters of the insulation layer on the solidification speed of the crude oil based on curvelet finite element method, results show that the effects of the density and specific heat of the insulation material on the solidification speed of the crude oil are very less, while the heat conductivity has a greater influence on the solidification speed of the crude oil in the seabed pipeline.

Acknowledgements This research was supported by the Liaoning education department's scientific and technical research project (L2010244).

References

1. Ling X, Wang Y, Yu B, Zhang JJ, Da X, Zhang ZW. Thermal analysis of the new technology of crude oil pipeline and products pipeline laid in one ditch. Eng Sci. 2008;10:30–6.
2. Cheng X, Bo Y, Zhang ZW, Zhang JJ, Wei JJ, Sun SY. Numerical simulation of a buried hot crude oil pipeline during shutdown. Pet Sci. 2010;7:73–82.
3. Li GY, Sheng Y, Jin HJ, Ma W, Qi JL, Wen Z, Zhang B, Mu YH, Bi GQ. Forecasting the oil temperatures along the proposed China–Russia crude oil pipeline using quasi 3-D transient heat conduction model. Cold Reg Sci Technol. 2010;64:235–42.
4. Ball R, Jones JC. Thermodynamics of the deposition of complex waxes and asphaltenes in crude oil. Open Thermodyn J. 2009;3:34–7.
5. Yu B, Li C, Zhang ZW, Liu X, Zhang JJ, Wei JJ, Sun SY, Huang JP. Numerical simulation of a buried hot crude oil pipeline under normal operation. Appl Therm Eng. 2010;30:2670–9.
6. Zhang WK, Zhang JJ, Yu B. Stochastic numerical simulation on oil temperature fluctuations of hot crude pipelines and sensitivity analysis to related factors. J China Univ Pet (Ed. Nat Sci). 2011;35:141–6.
7. Roberts IA, Wang CJ, Esterlein R, Stanford M, Mynors DJ. A three-dimensional finite element analysis of the temperature field during laser melting of metal powders in additive layer manufacturing. Int J Mach Tools Manuf. 2009;49:916–23.
8. Bertoluzza F, Delmonte N, Menozzi R. Three-dimensional finite-element thermal simulation of GaN-based HEMTs. Microelectron Reliab. 2009;49:468–73.
9. Yang J, Wang FD. 3D finite element temperature field modeling for direct laser fabrication. Int J Adv Manuf Technol. 2009;43:1060–8.
10. Mandal T, Jonathan QM, Wu YY. Curvelet based face recognition via dimension reduction. Signal Process. 2009;89:2345–53.
11. Li YC, Yang Q, Jiao RH. Image compression scheme based on curvelet transform and support vector machine. Expert Syst with Appl. 2010;37:3063–9.
12. Ma JW, Plonka G. The curvelet transform. Signal Process Mag. IEEE. 2010;7:118–33.
13. Geißler R, Saraji-Bozorgzad M, Streibel T, Kaisersberger E, Denner T, et al. Investigation of different crude oils applying thermal analysis/mass spectrometry with soft photoionisation. J Therm Anal Calorim. 2009;96:813–20.
14. Pernach Monika, Środa Marcin, Pietrzyk Maciej. Finite-element simulation of temperature-dependent three-point bending process of glass. J Therm Anal Calorim. 2011;101:651–6.