TUBE BUNDLE VIBRATION ANALYSIS AND OPTIMIZATION DESIGN

by

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Original scientific paper
https://doi.org/10.2298/TSCI2403115Y

The shell-and-tube heat exchanger is an important equipment in various applications. However, the bundle vibration and low heat transfer efficiency are the main shortcomings. In this article, ANSYS platform was used to simulate and analyze the shell-and-tube heat exchanger, the natural frequency was calculated, and the dominant factors affecting the vibration were determined. The theory of inventive problem solving was used to design the heat exchanger for anti-vibration. The results show that the improved heat exchanger's natural frequency is much larger than the fluid excitation frequency, as a result, the resonance is avoided.

Key words: *theory of inventive problem solving, shell-and-tube heat exchanger, vibration mechanism, optimization design*

Introduction

Vibration is double-edged, it can be used for energy harvesting [1-3], but it can also cause damage. Vibration analysis becomes a useful tool for nano/micro devices, *e.g.*, nanobeam vibration [4-6], and micro-electromechanical systems pull-in instability [7-9]. In many engineering applications, anti-vibration structures [10] were designed to reduce the vibration-induced failure.

The shell-and-tube heat exchanger has seen its wide applications due to its low production cost, high reliability, easy manufacturing, simple structure, strong processing capacity, and ability to withstand high operating pressure and temperature [11-15]. Due to the need for installation and disassembly, there is a gap between the baffle and the tube in the shell-and-tube heat exchanger. In the actual use, due to thermal expansion and contraction and tube vibration, there will be relative displacement between the baffle and the tube, and the connection position between the tube and the baffle will collide due to tube vibration, causing wear and fracture of the tube. Based on the problem of vibration-induced failure, this article conducts vibration analysis of the shell-and-tube heat exchanger and uses the theory of inventive problem solving (TRIZ) [16, 17] for optimization design.

Theory of inventive problem solving

The TRIZ is an innovative method proposed by a team of Soviet inventors and scientists [16, 17], it is a systematic scientific theory method that includes invention problem

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analysis tools such as component analysis, function analysis, substance-field analysis, and resource analysis. It also includes invention problem-solving tools such as algorithm for inventive problem solving (ARIZ) algorithm, invention principles, 76 standard solutions, and a scientific effects library. Users can use the analysis process and tools provided by TRIZ to conduct innovative design, predict future product development trends using tools such as the evolution tree, and conduct scientific product layout [18, 19].

Fluid induced vibration mechanism

In recent years, in order to enhance heat transfer and improve production efficiency, heat exchangers are developing towards large-scale and integrated direction, and nanofluid technology is one of the best candidates for enhancing heat transfer through the boundary layer [20-23]. The heat exchangers with high pressure and high-flow rate are extremely welcome in enterprises, but the high pressure and high flow rate of fluids can cause serious vibration, including fluid-induced vibration, elastic excitation, turbulence-induced vibration, vortex shedding, and acoustic resonance.

Vortex shedding and turbulent excitation

According to the design and principle of heat exchanger, when the spacing between heat exchange tubes is small, the vibration of heat exchanger tube bundle is mainly caused by turbulence buffeting. When the spacing between tubes is large, the effect of vortex shedding is greater. Studies have shown that when the ratio of pipe spacing to pipe diameter is less than 1.5, vortex separation will not cause violent vibration of tube bundle due to dense bundle arrangement. In our study, the tube spacing of the heat exchange tube is 32 mm, and the outer diameter of the heat exchange tube is 25 mm, so the ratio of tube spacing to tube diameter is 1.28, which is less than 1.5. Therefore, turbulent chattering is the main exciting factor.

When the flow in the shell is turbulent, the pulsation changes in the turbulent flow act on the heat exchange tube, and the pressure field and the velocity field provide energy to the heat exchange tube and exert exciting force on the heat exchange tube. When the main frequency stimulated by the pulsation changes of the heat exchange tube is near to the natural frequency of the heat exchange tube, the heat exchange tube absorbs energy and produces vibration. The dominant frequency of turbulent buffeting is expressed by [24]:

$$f_{\mathrm{t}} = \frac{Vd_0}{lT}\left[3.05\left(l - \frac{d_0}{T}\right)20.28\right] \tag{1}$$

where f_{t} [Hz] is the turbulent buffeting frequency, l [m] – the longitudinal heat exchange tube center distance, T [m] – the transverse heat exchange tube center distance, and d_0 [m] – the diameter of heat exchange tube.

Through the heat exchanger parameters provided by the enterprise, the longitudinal heat exchange tube center distance $l = 0.0277$ m, the transverse heat exchange tube center distance $T = 0.032$ m, by eq. (1), we predict the turbulent buffeting frequency $f_{\mathrm{t}} = 54$ Hz.

Elastic excitation

For heat exchangers with a ratio of tube spacing to tube diameter less than 1.5, turbulence buffeting is the main influence, elastic vibration is also one of the reasons for the heat exchanger vibration. When any one or several heat exchange tubes in the tube bundle has an instantaneous displacement, the balance state is broken, as a result, vibration arises. When the transverse flow velocity of the fluid reaches a certain value, the work of the fluid elastic force on the tube bundle is greater than the work of the tube bundle own damping, and the heat exchange tube will produce violent vibration, the reason for this vibration is the fluid elastic excitation. The above transverse velocity is the critical cross-flow velocity [25].

The critical cross-flow velocity is related to fluid elastic parameters, the natural frequency of the heat exchange tubes, mass damping and other parameters. Cording to Chinese standard GB 151, we have:

$$V_{\mathrm{c}} = K_c f_{\mathrm{n}} d_0 \delta_s^b \tag{2}$$

$$\delta_s = \frac{m\delta}{\rho_0 d_0 2} \tag{3}$$

where V_{c} is the critical cross flow velocity, δ_s – the mass damping parameter, m [kgm^{-1}] – the per unit length mass of heat exchange tube, δ – the logarithmic decay rate of the heat exchange tube, gas is δ = 0.01~0.06, ρ_0 [kgm^{-3}] – the shell path fluid density, d_0 [m] – the outer diameter of heat exchange tube, f_{n} [Hz] – the natural frequency of the heat exchange tube, and K_c – the proportionality coefficient.

The GB-151-1999 appendix is shown in tab. 1.

Table 1. Choices in different situations

Flow angle	δ_s	K_c	b
Regular triangle	0.1~2 > 1~300	3.58 (S/d_0 – 0.9) 6.53 (S/d_0 – 0.9)	0.1 0.5
Corner triangle	0.01~1 > 1~300	2.8 2.8	0.17 0.5
Square	0.03~0.7 > 0.7~300	2.1 2.35	0.15 0.5
Corner square	0.1~300	3.54 (S/d_0 – 0.5)	0.5

In the gas environment, the logarithmic decay rate, a, of the heat exchange tube δ is 0.01~0.06, and the heat exchanger with high damping and low frequency is the maximum value. Here, δ is 0.06, the shell path fluid density ρ_0 = 36.0489 kg/m^3, and δ_s = 1.638 can be obtained by calculating according to eq. (3). By referring to tab. 1, it can be obtained that the proportional coefficient K_c is 2.8, b is 0.5, the critical cross flow velocity V_{c} = 1.55 m/s.

Acoustic resonance

Acoustic resonance occurs only when the fluid is a gas. When the flow of the gas to the tube bundle forms a vortex separation, the longitudinal wave perpendicular to the direction of gas flow and the direction of the heat exchange tube axis is generated, and it changes periodically. The longitudinal wave propagates in the shell path, thus forming an acoustic standing wave between the shell walls. When the frequency is coupled with the vortex frequency, the turbulent buffeting frequency, and the natural frequency of the tube, noise and sound resonance are produced. Acoustic vibration in tube-shell heat exchangers is caused by gas vortex separation, so acoustic vibration is not considered in this paper.

Calculation of natural frequency of heat exchange tube

Since the finite element method was first proposed in 1943, the finite element theory and its application have been developed rapidly, and have been widely used in chemical industry, aerospace, machinery and automobile fields.

The gas excited vibration of the heat exchanger tube bundle is closely related to the natural frequency of the heat exchange tube. When the gas excited frequency acting on the heat exchanger is close to or exceeds a certain value of the natural frequency of the heat exchange tube, it will cause the vibration of the heat exchanger tube bundle, resulting in the heat exchanger damage. The finite element method is used to discretize the heat exchanger model, and then the finite element model is analyzed to get the natural frequency of the heat exchanger.

The outer diameter of the heat exchange tube studied in this paper is 25 mm, the inner diameter is 23 mm, and the tube length is 5000 mm. The heat exchange tube material is S31608(06Cr17Ni12Mo2), and the baffle material is S30408 (06Cr19Ni10). The related physical parameters of the heat exchange tube and baffle plate are shown in tab. 2 [26].

Table 2. Physical parameters of each material

Digital code	New brand	Density ρ [kgdm^{-3}]	Specific heat, Cp [KJkg^{-1}K^{-1}]	Thermal conductivity λ [Wm^{-1}K^{-1}]		Coefficient of linear expansion α (10^{-6} per K)		Modulus of elasticity E [GPa]
				100 ℃	500 ℃	100 ℃	500 ℃	
S31608	06Cr17Ni12Mo2	8.00	0.50	16.3	21.5	16.0	18.5	193
S30408	06Cr19Ni10	7.93	0.50	16.3	21.5	17.2	18.4	193

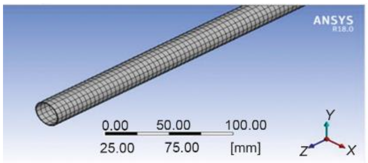

Figure 1. The ANSYS model diagram

For the modal analysis of a single heat exchange tube, the model is simplified. The connection between the heat exchange tube and the tube plate is a fixed support. Due to the problems of manufacturing process and subsequent disassembly, the baffle plate only plays a supporting role for the heat exchange tube, and there is a gap between the baffle plate and the heat exchange tube. That is, the heat exchange tube and the baffle plate are simply supported constraints, and the radial displacement of the heat exchange tube is small, but it can rotate and move axially, so the degrees of freedom in the X- and Y-directions are constrained at the baffle position. The cross section of the heat exchange tube is Ø25×2, and the length L = 5000 mm. The specific finite element model is shown in fig. 1.

In practical engineering applications, high-order modes generally have little influence on the operation of equipment. Through solving and calculating, the first eight order frequencies of a single heat exchange tube are calculated, as shown in tab. 3.

Table 3. Frequency table of each order

Vibration mode	First order	Second order	Third order	Fourth order	Fifth order	Sixth order	Seventh order	Eighth order
Frequency [Hz]	5.98	16.48	32.30	53.34	79.61	111.04	147.70	189.44

Analysis of fluid induced vibration of shell pass

In the fluid-induced vibration mentioned previously, the ratio between tube spacing and tube diameter of the heat exchange tube is less than 1.5, and the dominant factors causing heat exchange tube vibrations are turbulent buffeting and elastic excitation. The chatter vibration diagnosis [27, 28] is necessary to study the fluid-induced vibration.

According to the calculation analysis, when the fluid velocity reaches the critical cross-flow velocity, the work done by the fluid elastic force on the tube bundle of the heat exchange tube is greater than the work consumed by the damping effect of the heat exchange tube, and the response amplitude of the heat exchange tube will increase rapidly, resulting in violent vibration.

The results of solving the natural frequency of the heat exchange tube are shown in tab. 4.

Table 4. Frequency solver

Calculation method natural frequency [Hz]	Finite element analysis [Hz]	Vortex shedding [Hz]	Turbulent buffeting [Hz]	Elastic excitation [ms^{-1}]
17.301	5.98	48.6	54	1.55

According to GB151-1999 *shell and tube heat exchanger* standard, the vibration of the heat exchanger is determined by the basis, when the fluid excitation frequency conforms to any of the following, the heat exchange tube will occur vibration phenomenon:

- The vortex shedding frequency, f_v, and the lowest natural frequency of the heat exchange tube, f_n, is greater than 0.5, namely $f_v/f_n > 0.5$.
- The turbulent buffeting frequency, f_t, and the lowest natural frequency of the heat exchange tube, f_n, is greater than 0.5, namely $f_v/f_n > 0.5$.
- The cross-flow velocity in shell flow field is greater than the critical cross-flow velocity, $V > V_c$.

Based on the vibration judgment criteria, the ratio between the vortex shedding frequency, f_v, and the lowest natural frequency of the heat exchange tube, f_n, is greater than 0.5, and the fourth-order natural frequency is 53.34 Hz, which is close to the vortex shedding frequency, which will induce the vibration of the heat exchange tube. The ratio between the turbulent buffeting frequency, f_t, and the lowest natural frequency of the heat exchange tube, f_n, is greater than 0.5, and the fourth-order natural frequency is 53.34 Hz, which is close to the turbulent buffeting frequency, which will induce the vibration of the heat exchange tube.

The elastic excited flow rate of the heat exchange tube is 1.55 m/s, and the average transverse flow rate of the shell flow is about 4.5 m/s, so the elastic excited vibration is also one of the reasons for the vibration of the heat exchange tube bundle. It can be seen that turbulent buffeting is the dominant factor of heat exchanger vibration. Vortex shedding and elastic excitation can also cause tube bundle vibration, but it is not the dominant factor.

Anti-vibration design

The contradictions existing in the system are shown in tab. 5, with the physical contradiction expressed as the need for both fixation and gaps between the baffles and the heat exchange tubes. Fixation between the baffle plate and the heat exchange tubes is necessary to increase the natural frequency and reduce heat exchange tube vibration, to avoid wear and tear. A gap is also required between the baffle and the heat exchange tube to facilitate the installation and removal of the heat exchange tube. There are different needs at different times, there needs to be gaps in manufacturing, disassembly and cleaning, and fixed in the work. According to resource analysis, the shell path has vibration and belongs to high temperature environment. Among the invention principles applicable to time separation, we choose invention Principle 1-segmentation, 15-dynamic characteristics, and invention Principle 37-thermal expansion. According to the suggestion of principles 1, 15, and 37 of the invention, the baffle plate is divided into two parts, the part of the baffle close to the heat exchange tube becomes smaller in inner diameter when working, and is in close contact with the heat exchange tube to change the natural frequency and eliminate wear.

Table 5. Contradiction description table

If	There is a gap between the baffle and the heat exchange tube	The baffle plate is fixed between the heat exchange tube
So	Easy to install and disassemble	Eliminate wear and resonance
But	Produce wear, resonance	Installation and disassembly are difficult

Optimization design and feasibility analysis

According to the tips of innovative principles in the contradiction analysis, the design scheme is proposed as shown in fig. 2, where the shaded portion of the baffle plate close to the heat exchange tube is replaced with a material with a higher coefficient of thermal expansion, while the rest of the baffle uses a material with a smaller coefficient of thermal expansion. When working, high temperature gas heating baffle plate, because the inner ring of the baffle plate is larger than the outer ring deformation, the inner ring is constrained by the outer ring, and close contact with the heat exchange tube, so as to change the natural frequency, avoid resonance, reduce wear. The diameter of the shell in the paper is 450 mm, the effective heat exchange length of the heat exchanger is 4833 mm. The baffle plate tube hole spacing is 32 mm, the baffle plate material is S30408 (06Cr19Ni10), the thickness is 5 mm, the heat exchanger is provided with 22 baffle, on both sides of the equal spacing distribution. The outside diameter of the shaded part is 29 mm and the thickness is 5 mm.

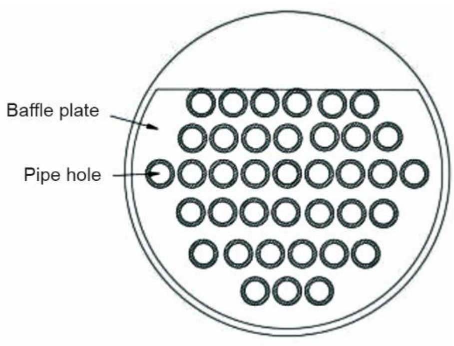

Figure 2. Baffle structure diagram

Scheme verification

– Single tube finite element analysis

The optimized heat exchange tube was solved, and the first 8 order frequencies of a single heat exchange tube were calculated, as shown in tab. 6.

The known vortex shedding frequency, f_v, is 48.6 Hz, and the turbulent buffeting frequency, f_t, is 54 H_Z. After optimization, the minimum natural frequency of the heat exchange tube is far greater than the vortex shedding frequency and turbulent buffeting frequency. According to GB151-1999 *shell and heat tube exchanger* standard, the heat exchange tube does not have violent vibration.

Table 6. Frequency table of each order

Vibration mode	First order	Second order	Third order	Fourth order	Fifth order	Sixth order	Seventh order	Eighth order
Frequency [Hz]	468.36	471.31	472.55	496	501.56	505.59	506.12	523.04

– Integral finite element analysis

The heat exchanger analyzed in this paper is a large shell-and-tube heat exchanger with a large number of heat exchange tubes. Due to the limitation of the simulation experimental conditions, the heat exchanger is simplified:
- The heat exchanger shell, tube head and inlet and outlet are deleted
- The heat exchange tube and baffle are fixed to match, no gap
- Reserve part of the heat exchange tube.

The simplified heat exchanger model is shown in fig. 3.

Modal analysis of the heat exchanger as a whole, the heat exchange tube and baffle material unchanged, fixed constraints on both ends of the tube plate, the baffle arc side fixed constraints, other Settings unchanged. The first eight orders of natural frequency of heat exchanger are shown in tab. 7.

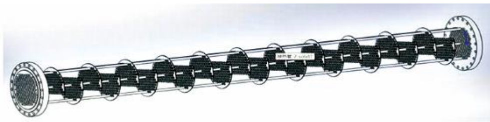

Figure 3. Finite element model of heat exchanger

Table 7. Frequency table of each order

Vibration mode	First order	Second order	Third order	Fourth order	Fifth order	Sixth order	Seventh order	Eighth order
Frequency [Hz]	291.15	406.73	452.47	469.05	478.64	481.92	485.97	488.13

The first-order mode shape of the overall modal analysis is shown in fig. 4. The minimum natural frequency of the heat exchanger is 291.15 Hz, the maximum deformation occurs in the center of the intermediate heat exchange tube, and the maximum deformation is 16.9 mm. The minimum natural frequency is much higher than the fluid excitation frequency, so the optimized heat exchanger will not have violent vibration.

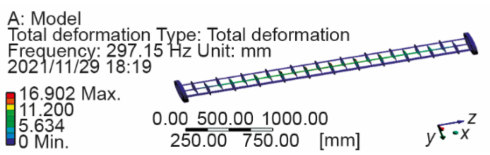

Figure 4. First-order vibration shape diagram of heat exchanger

Conclusions

This paper analyzes the vibration mechanism of shell-and-tube heat exchanger is analyzed, conducts simulation analysis, and applies TRIZ tools for optimization design. The main conclusions are as follows.

- In response to heat exchanger tube bundle vibration, simulation analysis and optimization design were performed. Based on the analysis of the heat exchanger tube bundle fracture failure phenomenon and failure model, the shell path fluid excitation frequency was calculated to analyze the fluid excitation mechanism of the heat exchange tube. By using the natural frequency formula and finite element method, it is calculated that the ratio between the fluid vibration frequency and the natural frequency of the tube bundle is greater than 0.5. And the heat exchanger tube has vibration phenomenon, which is mainly due to turbulent buffeting vibration and elastic excited vibration. Based on the principle of the invention, the vibration of the heat exchange tube is optimized, and it is concluded that the vibration can be reduced by dividing the baffle and replacing the hole part of the heat exchange tube with the material with high coefficient of thermal expansion.

- Finite element numerical simulations were conducted on the heat exchanger before and after structural improvement. The 3-D models of the heat exchanger before and after optimization were constructed, and finite element simulations were conducted using the ANSYS platform to perform modal analysis on the heat exchanger. The results show that before optimization, the vortex shedding frequency, f_v, is 48.6 Hz, the turbulent buffeting frequency, f_t, is 54 Hz. The optimized heat exchanger minimum natural frequency is 291.15 Hz, the minimum natural frequency is much higher than the fluid excitation frequency, the optimized heat exchanger will not produce resonance.

References

[1] He, C. H., *et al.*, Controlling the Kinematics of a Spring-Pendulum System Using an Energy Harvesting Device, *Journal of Low Frequency Noise, Vibration & Active Control, 41* (2022), 3, pp. 1234-1257
[2] He, C. H., *et al.*, Hybrid Rayleigh -Van der Pol-Duffing Oscillator (HRVD): Stability Analysis and Controller, *Journal of Low Frequency Noise, Vibration & Active Control, 41* (2022), 1, pp. 244-268
[3] He, C. H., El-Dib, Y. O., A Heuristic Review on the Homotopy Perturbation Method for Non-conservative Oscillators, *Journal of Low Frequency Noise Vibration and Active Control*, *41* (2022), 2, pp. 572-603
[4] Jankowski, P., Detection of Non-local Calibration Parameters and Range Interaction for Dynamics of FGM Porous Nanobeams Under Electro-Mechanical Loads, *Facta Universitatis Series: Mechanical Engineering, 20* (2022), 3, pp. 457-478
[5] Faghidian, S. A., Tounsi, A., Dynamic Characteristics of Mixture Unified Gradient Elastic Nanobeams, *Facta Universitatis Series: Mechanical Engineering, 20* (2022), 3, pp. 539-552
[6] Limkatanyu, S., *et al.*, Bending, Bucking and Free Vibration Analyses of Nanobeam-Substrate Medium Systems, *Facta Universitatis Series: Mechanical Engineering*, *20* (2022), 3, pp. 561-587
[7] Tian, D., He, C. H., A Fractal Micro-Electromechanical System and Its Pull-in Stability, *Journal of Low Frequency Noise Vibration and Active Control, 40* (2021), 3, pp. 1380-1386
[8] He, C. H., A Variational Principle for a Fractal Nano/Microelectromechanical (N/MEMS) System, *International Journal of Numerical Methods for Heat & Fluid Flow, 33* (2023), 1, pp. 351-359
[9] He, J. H., Fast Identification of the Pull-in Voltage of a Nano/Micro-Electromechanical System, *Journal of Low Frequency Noise Vibration and Active Control*, *41* (2022), 2, pp. 566-571
[10] Ling, X. J., *et al.*, A Novel Bio-Inspired Anti-Vibration Structure for Operating Hand-Held Jackhammers, *Mechanical Systems and Signal Processing, 118* (2019), Mar., pp. 317-339
[11] Emilio, D. B., *et al.*, Modeling and Prediction of Shell-Side Fouling in Shell-and-Tube Heat Exchangers, *Heat Transfer Engineering, 40* (2019), 11, pp. 845-861
[12] Bozorgan, N., *et al.*, Design and Thermal-hydraulic Optimization of a Shell and Tube Heat Exchanger Using Bees Algorithm, *Thermal Science*, *26* (2022), 1B, pp. 693-703
[13] Aydin, A., *et al.*, Optimization and CFD Analysis of a Shell-and-Tube Heat Exchanger with a Multi Segmental Baffle, *Thermal Science*, *26* (2022), 1A, pp. 1-12
[14] Sajjad, M., *et al.* Thermal-Hydraulic Analysis of Water Based ZrO_2 Nanofluids in Segmental Baffled Shell and Tube Heat Exchangers, *Thermal Science*, *24* (2020), 2B, pp. 1195-1205
[15] Kucuk, H., The Effect of Minichannels on the Overall Heat Transfer Coefficient and Pressure Drop of a Shell and Tube Heat Exchanger: Experimental Performance Comparison, *International Journal of Thermal Sciences*, *188* (2023), 108217
[16] Akay, D., *et al.*, Collaborative Tool for Solving Human Factors Problems in the Manufacturing Environment: the Theory of Inventive Problem Solving Technique (TRIZ) method, *International Journal of Production Research, 46* (2008), 11, pp. 2913-2925

[17] Ben-Moussa, F. Z., *et al.*, Reviewing the Use of the Theory of Inventive Problem Solving (TRIZ) in Green Supply Chain Problems, *Journal of Cleaner Production, 142* (2017), Jan., pp. 2677-2692
[18] Xu, B., Tan, R. H., *Failure Analysis of Mechanical System Based on TRIZ* (in Chinese), Higher Education Press, Beijing, 2016, pp. 1-12
[19] Zhao, M., *et al., TRIZ Introduction and Practice* (in Chinese), Science Press, Beijing, 2009, pp. 10-200
[20] Kumar, K., *et al.*, Irreversibility Analysis in Al_2O_3-Water Nanofluid Flow with Variable Property, *Facta Univ.-Ser. Mech., 20* (2022), 3, pp. 503-518
[21] He J., *et al.,* Efficacy of A Modulated Viscosity-Dependent Temperature/Nanoparticles Concentration Parameter on a Non-linear Radiative Electromagneto-Nanofluid Flow Along an Elongated Stretching Sheet, *J. Appl. Computat. Mech.*, *9* (2023), 3, pp.848-860
[22] He, J. H., Abd-Elazem, N. Y. The Carbon Nanotube-Embedded Boundary Layer Theory for Energy Harvesting, *Facta Univ.-Ser. Mech., 20* (2022), 2, pp. 211-235
[23] Kou S. J., *et al.*, Fractal Boundary Layer and Its Basic Properties, *Fractals, 30* (2022), 9, 22501729
[24] Bo, H. L., *et al.*, Fluid Elastic Instability of Spiral Tube Bundles (in Chinese), *Chinese Journal of Nuclear Science and Engineering, 15* (1995), 1, pp. 33-38
[25] Miao, Q., Study on Fluid Induced Vibration of Tube Bundle in Heat Exchanger (in Chinese), Ph. D. thesis, Dalian University of Technology, Liaoning, China, 2016
[26] Zeng, Z. M., *Practical Metal Materials Selection Manual* (in Chinese), Beijing: China Machine Press, 2012, pp. 191-193
[27] Kuo, P. H., *et al.*, Novel Fractional-Order Convolutional Neural Network Based Chatter Diagnosis Approach in Turning Process with Chaos Error Mapping, *Non-linear Dynamics, 111* (2023), 8, pp. 7547-7564
[28] Kuo, P. H., *et al.*, Machine Tool Chattering Monitoring by Chen-Lee Chaotic System-Based Deep Convolutional Generative Adversarial Nets, *Structural Health Monitoring, 22* (2023), 6

Paper submitted: May 5, 2023
Paper revised: August 1, 2023
Paper accepted: August 7, 2023