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A Numerical Study

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Preface

Heat exchangers are equipment to realize heat exchange, and are widely used in geothermal development, waste heat recovery, battery heat dissipation, wastewater treatment, solar power generation, nuclear energy development, etc. The failure of heat transfer elements caused by flow-induced vibration is one of the most prominent problems faced in the design and application of heat exchangers. Flow-induced vibration is an unfavorable factor affecting the service life of heat exchangers, and also a positive factor for enhancing heat transfer. Elastic tube bundle (ETB) heat exchangers replace traditional rigid heat transfer elements with elastic heat transfer elements, utilizing fluid-induced internal ETBs vibration to achieve composite enhanced heat transfer, opening up new directions and ideas for the application of passive enhancement technology in heat exchangers.

However, after extensive investigation by the authors of this book and their research team, it has been found that there are still some shortcomings in the current research on flow-induced vibration, vibration-enhanced heat transfer, and vibration/heat transfer control of ETB heat exchangers. Mainly including: (a) Due to the influence of ETB structure, ETB heat exchangers have a small heat transfer area per unit volume, resulting in poor overall heat transfer performance and thus affecting its market competition. (b) Flow-induced vibration in ETB heat exchangers is a complex fluid solid interaction problem involving multi-field fluid. At present, there is a lack of systematic research on numerical analysis of flow-induced vibration of ETBs under complex flow conditions. (c) In practical engineering applications, there is a phenomenon of uneven vibration for ETBs in ETB heat exchangers. In this way, ETBs with severe vibration are prone to vibration damage, while ETBs with mild vibration have poor heat transfer efficiency, which further affects the service life and heat transfer efficiency of ETB heat exchangers. At present, there is no good solution to this problem.

In response to the above shortcomings, starts from the vibration response of a single and multi-row of ETBs induced by uniform shell-side fluid, the vibration responses of ETBs in heat exchanger under actual shell-side fluid induction are investigated. Then, by selecting appropriate vortex element and improving the branch domain channel structure, a distributed pulsating flow generator is designed to conduct numerical analysis and experimental research on the vibration responses of ETBs induced by the coupling of shell-side fluid and distributed pulsating fluid. In addition, based on the ETB structural improvement and the baffle installation, the vibration and heat transfer performances of the ETBs in heat exchangers are compared and studied. And also, the influences of the baffle structure parameters (height and curvature) on the vibration-enhanced heat transfer performance of an improved ETB heat exchanger are systematically studied under different conditions. The research work in this book has important theoretical and engineering significance for improving the heat transfer performance of ETB heat exchangers and effectively stimulating and controlling the vibration of ETBs.

The content of the book is a summary of the authors and their research team members' research work over the past decade, and is a reference book in the field of enhanced heat transfer. Among them, Chap. 1 was completed by Assoc. Prof. Jiadong Ji (Anhui University of Science and Technology) and Prof. Baojun Shi (Hebei University of Technology), Chap. 2 was completed by Assoc. Prof. Jiadong Ji (Anhui University of Science and Technology) and Prof. Haishun Deng (Anhui University of Science and Technology), Chaps. 3–7 were completed by Jiadong Ji (Anhui University of Science and Technology), Chap. 8 was completed by Assoc. Prof. Jiadong Ji (Anhui University of Science and Technology) and Prof. Baojun Shi (Hebei University of Technology), and Chap. 9 was completed by Assoc. Prof. Jiadong Ji (Anhui University of Science and Technology) and Prof. Haishun Deng (Anhui University of Science and Technology). The total number of words written by Assoc. Prof. Jiadong Ji, Prof. Baojun Shi and Prof. Haishun Deng are 210 thousand words, 40 thousand words, and 30 thousand words. This book is drafted by Assoc. Prof. Jiadong Ji.

Special thanks to Prof. Peiqi Ge (Shandong University) for his selfless guidance and assistance in the research project. During this book, Profs. Qinghua Chen (Anhui University of Science and Technology) and Ping Liu (Anhui University of Science and Technology) gave warm support and help. The postgraduate students Yuling Pan, Jingwei Zhang, Feiyang Li, Xuwang Ni, and Jinhui Zhao participated in the draft writing. The authors express their gratitude to them.

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Huainan, China Jiadong Ji
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About This Book

To solve the problems existing in the research and application of elastic tube bundle (ETB) heat exchangers, vibration and heat transfer of ETBs in heat exchangers under shell-side fluid induction are systematically studied in this book. There are nine chapters, including introduction, numerical calculation method, vibration of ETBs induced by uniform shell-side fluid, vibration and heat transfer analysis of ETBs induced by actual shell-side fluid, design of a shell-side distributed pulsating flow generator, effect of pulsating flow generator on vibration and heat transfer of ETBs, effect of baffles on vibration and heat transfer of TETBs, research on vibration-enhanced heat transfer of IETB heat exchanger, and effect of baffle structure on the performance of IETB heat exchanger.

This book can be used as a reference for researchers and engineering technicians engaged in energy recycling, enhanced heat transfer, vibration control, and other fields. This book can also be used as a reference for teaching courses such as "Advanced Engineering Fluid mechanics", "Modern Design Methods of Fluid Machinery" for graduate students of related majors in colleges and universities, and "Thermal Engineering Foundation", "Heat Transfer" for senior undergraduate students.

Contents

Nomenclature

A	Amplitude/heat transfer area
a	Acceleration
C	Damping matrix
C_d	Drag coefficient
C_l	Lift coefficient
C_p	Specific heat at constant pressure
C_μ	Turbulence model constant
$C_{\varepsilon 1}$	Turbulence model constant
$C_{\varepsilon 2}$	Turbulence model constant
D	Diameter/mark of flow direction
d	Diameter/width/hypotenuse length
E	Elastic modulus
F	Force/face/Fanning friction factor
f	Frequency
g	Displacement
H	Pitch/height/row spacing
h	Heat transfer coefficient
h^{s}	Node displacement
J	Colburn factor
K	Stiffness matrix
k	Turbulent kinetic energy equation
L	Length
l	Transverse dimension
M	Mass matrix
m	Number of nodes
n	Normal vector/number
Nu	Nusselt number
Pr	Prandtl number
p	Pressure
Q	Convection heat exchange
q	Heat flow density

R	Radius/maximum radius
Re	Reynolds number
r	Minimum radius
S	Vibration displacement/distance
St	Strouhal number
T	Temperature
t	Time
u	Flow velocity
W	Width
w	Longitudinal dimension
x, y, z	Axes

Greek Letters

α	Installation angle/included angle
β	Transition angle
γ	Direction angle
δ	Wall thickness
ε	Turbulent kinetic energy dissipation equation
ζ	Root mean square
η	Elliptic ratio/height factor
θ	Swing angle/baffle curvature
λ	Thermal conductivity
μ	Dynamic viscosity
υ	Kinematic viscosity coefficient/Poisson's ratio
ρ	Density
σ	Diffusion Prandtl number
τ	Stress
φ	Taper/position angle

Subscripts

a	Average/actuarial calculation
b	Baffle
c	Constant
f	Fluid
in	Inlet
l	Laminar fluid
n	Node
out	Outlet

pul	Pulsating flow
r	Rough calculation
s	Structural
t	Turbulent fluid
v	Vibration/velocity
w	Wall

Abbreviations

ETB	Elastic tube bundle
FFT	Fast Fourier Transform
FSI	Fluid–solid interaction
GGI	General grid interface
HB	Have baffle
IETB	Improve ETB heat exchanger
NB	No baffle
PEC	Performance evaluation criteria
RMS	Root mean square
TETB	Traditional ETB heat exchanger

Chapter 1
Introduction

Heat exchangers [1–3], as shown in Fig. 1.1, are equipment to realize heat exchange, and are widely used in geothermal development, waste heat recovery, battery heat dissipation, wastewater treatment, solar power generation, nuclear energy development, biological refrigerant storage, etc. [4, 5].

Taking mine ventilation as an example, after the fresh air from the ground is fed into the intake shaft, it supplies fresh air to the working face and also absorbs heat dissipation from the surrounding rock, mechanical equipment, coal oxidation, personnel, and other aspects. When the air is discharged from the return shaft, the temperature of the mine return air is much higher than that of the intake air. In addition, the mine return air has a large amount of low-temperature heat energy, which is not utilized and directly discharged into the atmosphere, It will cause great waste of thermal energy [6]. Using heat exchanger to recover waste heat resources and use them for mine fresh air heating, building heating and other occasions can effectively reduce energy consumption and carbon emissions, so it has outstanding social and economic benefits [7]. On the other hand, the abundant underground space created during the mining process of the deposits provides the basic conditions for the large-scale storage of renew energy such as solar energy. A novel method of realizing seasonal storage of renewable energy, such as solar energy, is the contruction of backfill heat exchangers with a heat storage/release function by inserting ground heat exchangers into backfill bodies in mines, as shown in Fig. 1.2. Therefore, heat exchanger equipment and related technologies play an important role in industrial production.

For modern chemical industry, the cost of heat exchanger equipment accounts for about 30% of the total cost. In refining equipment, the heat exchanger equipment accounts for about 40% of the total cost. In seawater desalination, the process equipment is almost all the heat exchanger equipment [2]. On the other hand, the heat exchanger energy consumption accounts for about 13–15% of the total industrial energy consumption. It can be said that the heat transfer performance and service life of the heat exchanger is directly related to the effective use of energy and the

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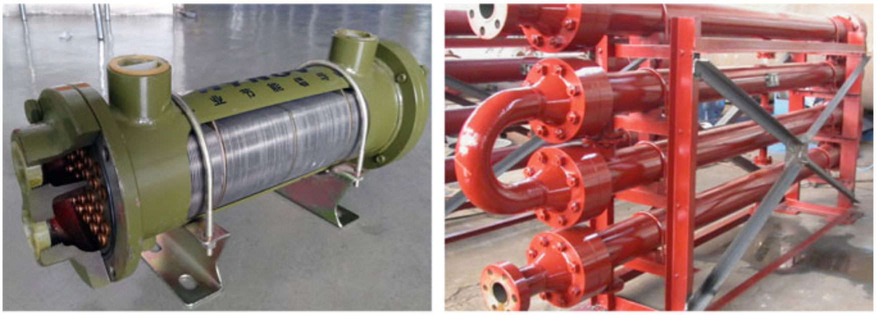

(a) Shell-and-tube heat exchanger (b) Double-tube heat exchanger

(c) Plate heat exchanger (d) Spiral wound heat exchanger

Fig. 1.1 Physical images of four types of common heat exchangers

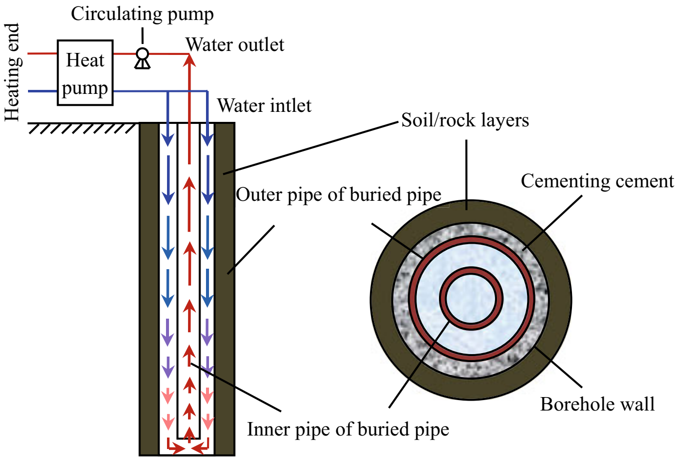

Fig. 1.2 Deep shaft heat exchange system

normal operation of equipment, and has a direct impact on the economic benefits of high energy consumption industry [8]. Therefore, it is of great significance to develop efficient and energy-saving heat transfer technology and equipment to save energy and reduce energy consumption.

The rapid development of heat exchangesr and related technology in recent decades have made a lot of fruitful progress [9–12]. At the same time, some urgent problems such as flow-induced vibration and fatigue failure of heat transfer elements have also emerged, restricting the further development of heat exchangers and related technologies [1].

It is well known that flow-induced vibration will cause fatigue damage of heat transfer elements in heat exchangers, and then affect the service life of heat exchangers [10–12]. The failure of heat transfer element caused by flow-induced vibration is one of the most prominent problems in modern heat exchanger design and practical application. There are many examples of vibration failure of heat exchangers [16]: In the early period, the tubular exchanger manufacturers association (TEMA) investigated 42 heat exchangers and found that 24 of them had vibration failure. The heat transfer research institute (HTRI) conducted a survey of 66 heat exchangers and found that 58 had suffered vibration failure. In recent years, the reports of vibration damage of heat exchangers have been numerous.

The failure of heat transfer element caused by flow-induced vibration can be alleviated or reduced to a certain extent by increasing the stiffness of heat transfer element. However, it is impossible to completely eliminate vibration in the heat exchangers, and the method of increasing the stiffness of the heat transfer elements is not very effective.

On the basis of reasonable use of vibration and taking into account heat transfer performance and fatigue life of components, heat transfer element of elastic tube bundle (ETB) [1, 4, 8, 14, 15] can enhance heat transfer by using flow-induced vibration of ETBs (as shown in Fig. 1.3). The core idea of the design of the ETB is to replace the rigid heat transfer element with the elastic heat transfer element. The vibration of the ETBs induced by the fluid flow around is used to strengthen the heat transfer, and the vibration of the ETBs is controlled to ensure that it has a certain service life [1].

Accordingly, the research on heat transfer enhancement, flow-induced vibration, vibration excitation and control has become the focus of academic circles [17–19]. The following is literature review on vibration enhanced heat transfer and vibration control, and then the main research content of this book is introduced.

1.1 Research Status of Vibration Enhanced Heat Transfer

Enhanced heat transfer technology is an advanced technology to improve the heat transfer performance of heat transfer elements. The main objectives are to reduce equipment costs, protect high-temperature components and realize rational utilization of energy by improving heat transfer efficiency [20–22].

Fig. 1.3 Manufacturing process and finished products of ETB heat exchangers

There are many ways to enhance heat transfer. Especially in recent years, with the rapid development of heat transfer technology, a large number of new, efficient and practical technologies and methods have emerged [23, 24]. Based on the research content of this book, the convection enhanced heat transfer technology is mainly discussed.

Based on the classification standard proposed by Bergles [25], heat transfer enhancement by convection can be divided into active enhancement technology, passive enhancement technology and composite enhancement technology. The introduction is as follows:

(1) Active enhancement technology refers to the technology that requires the consumption of external high-quality energy such as mechanical force and electromagnetic force to achieve enhanced heat transfer. It mainly includes: mechanical agitation [26, 27], heat transfer wall vibration or fluid pulsation [28–30], electromagnetic field [31–33], suction or jet impact [34, 35], etc.
(2) Passive enhancement technology refers to the technology of heat transfer enhancement without consuming additional high-quality energy or power. It mainly includes: surface treatment [36–39], surface roughness [40–42], surface extension [43–45], swirl element [46–49], tension structure [50] and additive [51], etc.
(3) Composite enhancement technology refers to the combination of two or more kinds of strengthening technology. It mainly includes: composite strengthening technology of helical groove tube and bond [52, 53], composite strengthening technology of helical groove tube and inlet cyclone [54], composite heat transfer enhancement of inner fin tube and bond [55], etc.

1.1.1 Active Enhancement Technology

It is well known that the heat transfer surface strengthens the disturbance of the surrounding fluid through vibration and destroys the boundary layer of the wall, thus achieving enhanced heat transfer. Early research on enhanced heat transfer by vibration mainly focused on enhanced heat transfer experiments based on forced vibration. The vibration forms mainly include: mechanical vibration or motor driven eccentric device and ultrasonic excitation vibration. With the rapid development of computer technology and numerical analysis methods, people begin to use various numerical simulation methods to study the heat transfer characteristics of heat transfer components under forced vibration conditions.

As shown in Fig. 1.4, mechanical vibration device or eccentric device is simple in structure and easy to adjust the amplitude and frequency, and the heat transfer performance of heat transfer components under different conditions can be studied in depth. Among them, Deaver [56], Lemlish and Rao [57], Penny and Jefferson [58], Hsieh and Marsters [59], Dawood et al. [60], Saxena and Laird [61], Leung et al. [62], Katinas et al. [63, 64], Takahashi and Endoh [65], Karanth et al. [66], Cheng et al. [67], Klaczak [68], Gau et al. [69], Bronfenbrener et al. [70], Fu and Tong [71], Leng et al. [72] and Lee et al. [73], based on natural and forced convection, the heat transfer performance of vibrating tubes with different structural parameters has been studied experimentally or numerically.

Tables 1.1 and 1.2 are the summaries of some studies. Where, d is the tube diameter, A is the vibration amplitude, f is the vibration frequency, and h is the heat transfer coefficient.

It can be seen from Tables 1.1 and 1.2 that the heat transfer performance of the vibrating tube varies significantly with the change of the fluid medium and its flow state. Under natural convection conditions, the heat transfer coefficient of vibrating tube is increased, with the highest increase of 1228%, and the research results of various literatures are consistent. Under forced convection conditions, the heat transfer coefficient of vibrating tube does not always increase. For example, in

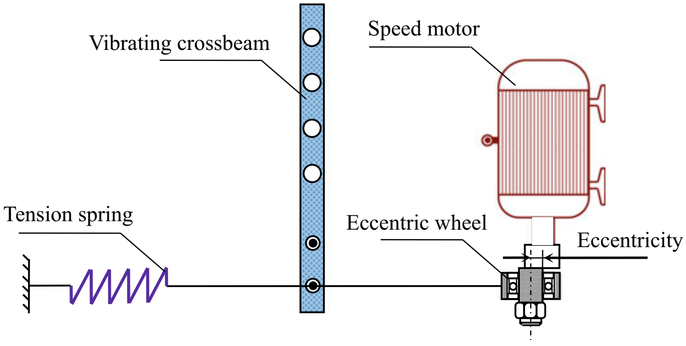

Fig. 1.4 Schematic diagram of eccentric device driven by motor

Table 1.1 Research on heat transfer performance of vibrating tube under natural convection

Researcher	Medium	d/mm	Vibration parameter		Main conclusion
			A/mm	f/Hz	
Deaver	Water	0.18	2.54–70	4.25	h increases by 4 times
Lemlish	Air	0.64, 1.00, 2.06	1.40–5.87	39–122	
Lemlish	Water and glycerin in water	1.25	0.05–2.18	17–37	h increases by 12.3 times
Penny	Water	0.2	63.5	4.5	h increases by 5 times
Penny	Ethylene glycol	0.2	63.5	4.5	h increases by 2.5 times
Hsieh	Water	10	0.16–6.35	27–51	h increased by 54%
Dawood	Air	8.50, 12.7	0–17.8	0–68	h increases by 3 times

Table 1.2 Research on heat transfer performance of vibrating tube under forced convection

Researcher	Medium	Parameters (d/mm; A/mm; f/Hz)	Main conclusion
Saxena	Water	$d = 22$, $A = 19.6–43.8$, $f = 0.4–1.2$, $Re = 3500$	The degree of heat transfer enhancement is proportional to A and f, h increases and the maximum increase is 60%
Leung	Water	$d = 38$, $A = 0.25$ and 0.5, $f = 10$ and 30, $Re = 3 \times 10^3–5 \times 10^5$	When $Re < 1.5 \times 10^3$, h increases, but the increase is smaller When $Re > 2.5 \times 10^3$, vibration suppresses heat transfer effect
Leng	Water	$d = 20$, $A = 0–2.0$, $f = 6.67–24$, Re is small	The degree of heat transfer enhancement is proportional to A and f, h increases and the maximum increase is 311%
Cheng	Air	$d = 16$, $A = 0–10.0$, $f = 0–20$, $Re = 0–4000$	The increase of Nu is proportional to A and f, and h increases by up to 30%
Klaczak	Water-vapour	$d = 608$, $A = 0.2–0.5$, $f = 20–120$; $Re = 430–2300$	h decreased with a maximum reduction of 20%

the gas–liquid heat transfer test conducted by Klaczak [68], the surface heat transfer coefficient decreased, with a maximum reduction of 20%. Under the condition of forced convection, the heat transfer enhancement of single-phase flow is proportional to amplitude and frequency, and the heat transfer effect decreases with the increase of *Re*. In addition, the properties of the medium also affect the effect of vibration in enhancing heat transfer. For example, in the research conducted by Lemlish and Rao [57], the heat transfer effect of water is better than that of glycerin in water.

Although mechanical vibration can enhance heat transfer significantly, its operation requires extra energy consumption and belongs to the category of active enhancement technology, which has no advantages in terms of energy saving. Studies have shown that the energy gained from improving heat transfer is only 5% of the energy consumed by external equipment [13]. Based on this, the application prospects of the mechanical vibration enhanced heat transfer are relatively bleak.

In view of the deficiency of active enhancement technology, it is necessary to explore a vibration mode which can not only avoid or reduce the consumption of extra energy, but also make effective use of the effect of vibration enhancement of heat transfer. Based on this, the technology of flow-induced vibration to enhance heat transfer without external energy consumption has gradually become a hot topic in academic research.

1.1.2 Flow-Induced Vibration

It is well known that flow-induced vibration of heat transfer element in heat exchanger is a universal phenomenon. This flow-induced vibration can be expressed as various vibration phenomena caused by "fluid flow around poor fluid engineering structures" [74].

In the heat exchanger, the fluid that induces the vibration of the heat transfer element can be divided into vertical flow (flow parallel to the axis of the heat transfer tube) and horizontal flow (flow perpendicular to the axis of the heat transfer tube). Generally speaking, the vibration of heat transfer element induced by vertical flow has low intensity and little harm, which can be ignored in the research process. The intensity of horizontal flow induced vibration of heat transfer element is relatively high, and it also poses great harm to the heat transfer element, which is the main factor inducing vibration of heat transfer element.

The formation mechanism of flow-induced vibration is complex. At present, the main mechanism of horizontal flow-induced vibration in heat exchangers include vertex shedding excitation, turbulent buffeting, fluid elastic instability and acoustic resonance [75]. Based on these mechanisms, researchers have carried out a lot of fruitful research, and put forward many theoretical models and empirical formulas [76–79], which have played a guiding role in the development and design of heat exchangers.

1.1.2.1 Planer ETB Heat Exchanger

In the design and manufacture of heat exchangers, the flow-induced vibration of heat transfer elements does not always lead to the failure of heat transfer elements. If the structure of the traditional shell-and-tube heat exchanger is changed, the flow-induced vibration can be used effectively to enhance heat transfer without causing damage to heat transfer elements.

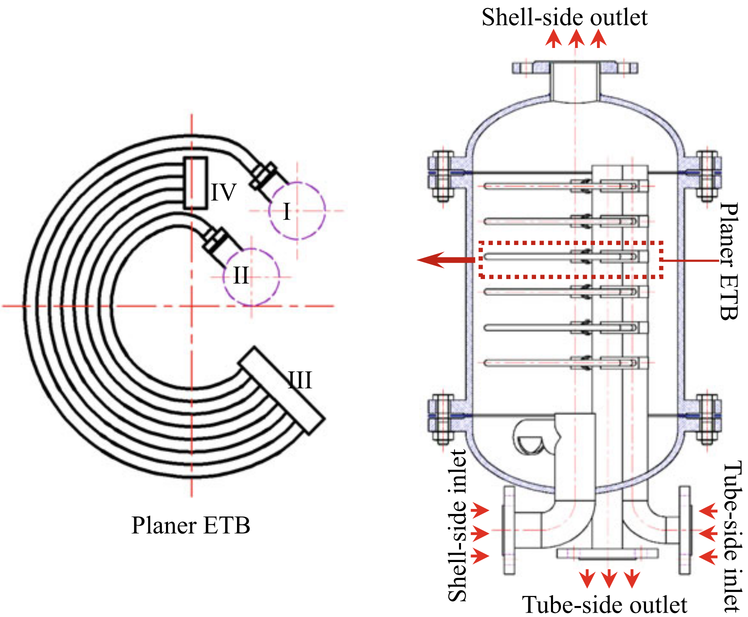

Fig. 1.5 Structure diagram of the planer ETB heat exchanger [4]

A planer ETB (also known as traditional ETB) heat exchanger, as shown in Fig. 1.5, which is different from the design idea for the traditional shell-and-tube heat exchanger, was proposed [1, 14, 80–82] based on the idea of using heat transfer element vibration to enhance heat transfer. If not specified, the "ETB" in this book refer to the "planner ETB".

As shown in Fig. 1.5, the ETB is composed of four copper bend tubes and two stainless steel connectors (III and IV), with the fixed ends at I and II. During the actual operation of the heat exchanger, the tube-side fluid enters from port I and flows through the stainless steel connectors III and IV multiple times before exiting from port II. It is found that the heat exchanger achieves passively enhance heat transfer by using the small amplitude low-frequency vibration of the ETB induced by shell-side and tube-side fluid, especially under low flow rate conditions [24, 80]. At the same time, the damage of the ETB and the noise caused by violent vibration can be avoided. In addition, the ETB has a very obvious descaling effect in the vibration process.

Zheng et al. [83] studied the modal frequency and mode shape of the ETB by using a component mode synthesis method. The results show that the natural vibration modes of the ETB are mainly divided into in-plane vibration (vibration in the plane of the ETB) and out-of-plane vibration (vibration perpendicular to the plane of the ETB). The vibration of the ETB is the combination of vibrations in different directions as a result of complex excitation in actual shell-side and tube-side fluid field.

Cheng and Tian [84] experimentally studied the heat transfer and flow resistance characteristics of a water-water ETB heat exchanger. And also, the change rule of heat transfer coefficient of the ETB is analyzed under different working conditions. In their study, by measuring the flow resistance loss of the shell-side and tube-side fluid, a series of formula are given to calculate the flow resistance in shell-side and tube-side change.

Su et al. [85, 86] experimentally studied the role of flow-induced vibration on the vibration response of a single ETB. The results show that the vibration characteristics of the ETB are strongly influenced by flow velocity, and vibration harmonics of the ETB are triggered at low fluid velocities.

Duan et al. [87–89] analyzed the effect of different structural and installation dimensions of r ETBs on vibration-enhanced heat transfer. The results show that when the tube wall thickness is smaller or the distance between tubes is larger, the effect of vibration enhancing heat transfer is stronger.

Cheng et al. [90] and Tian et al. [91] experimentally studied the heat transfer characteristics of the ETB heat exchanger under steam-water heat transfer condition. The results show that the ETB can enhance heat transfer significantly at low Reynolds number compared with fixed ETB. In addition, through systematic experimental study, the correlation formula of Nusselt number at low Reynolds number was obtained as follows [91].

For the heat exchanger with pulsating flow device:

$$Nu = 0.911 Re^{0.633} Pr_{\mathrm{f}}^{1/3} \left(\frac{Pr_{\mathrm{f}}}{Pr_{\mathrm{w}}} \right)^{0.25} \tag{1.1}$$

For the heat exchanger without pulsating flow device:

$$Nu = 0.711 Re^{0.645} Pr_{\mathrm{f}}^{1/3} \left(\frac{Pr_{\mathrm{f}}}{Pr_{\mathrm{w}}} \right)^{0.25} \tag{1.2}$$

where, Nu is the Nusselt number, Re is the Reynolds number, Pr_{f} is the Prandtl number using the average temperature of the fluid as the qualitative temperature, Pr_{w} is the Prandtl number using the wall temperature as the qualitative temperature, the subscripts “w” and “f” represent the wall and the fluid, respectively.

The applicable range of the above correlation formulas is: $100 < Re < 500$, and the error between the correlation formula and the experimental value is about $\pm 5\%$.

In response to the shortcomings of low heat transfer area per unit volume and high fixed end stress in planer ETB, Jiang [92] made certain improvements on the basis of the traditional ETB and conducted experimental research on the vibration and shell-side heat transfer characteristics of the modified ETB. The results show that the modified ETB has a lower natural frequency, and the stress at the fixed end is about 1/6 of the traditional ETB with the same mass. In addition, the heat transfer area per unit volume of the modified ETB is 24.7% higher than that of the traditional ETB.

1.1.2.2 Space Conical Helical ETB Heat Exchanger

In view of the above problems of serious stress concentration and simple secondary flow of the traditional ETB, by taking the structural optimization of the ETB as the entry point, Yan et al. [13, 17, 18, 93–96] designed a space conical helical ETB heat exchanger based on the working principle of the planer ETB heat exchanger. The structure diagram of the space conical helical ETB heat exchanger is shown in Fig. 1.6.

The space conical helical ETB is composed of two copper helical tubes and a stainless steel connector (M). The tube-side fluid flows in from port I, flows through the stainless steel connector M, and flows out from port II. The installation of multi row space conical helical ETBs in the heat exchanger adopt a nested form.

Research has found that the natural vibration modes of the space conical helical ETB include longitudinal vibration and transverse vibration, with longitudinal vibration being the main mode [93]. The multi-row space conical helical ETB has a complex mode and each mode corresponds to a frequency band. In addition, the taper and thickness-diameter ratio of the space conical helical ETB have great influence on its natural frequency, while the pitch and stainless steel mass connector have little influence on its natural frequency [94–96].

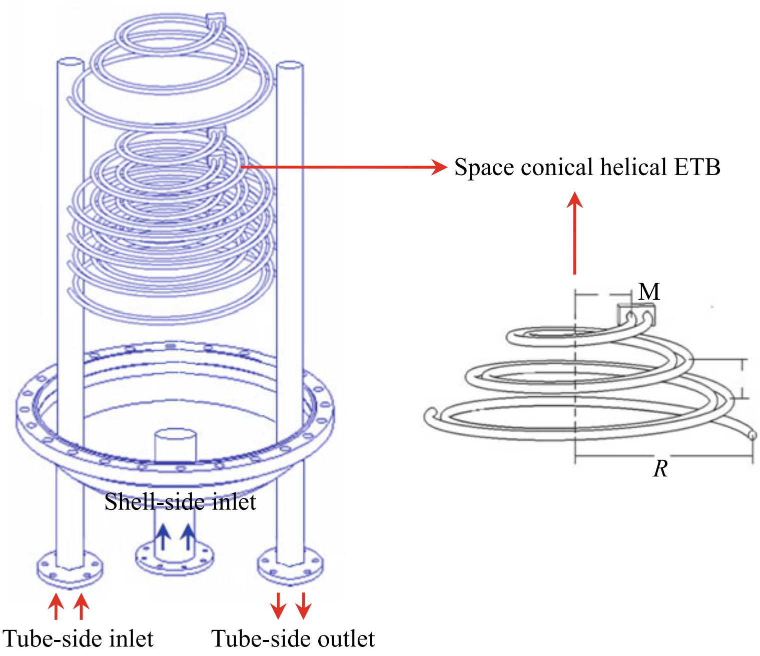

Fig. 1.6 Structure diagram of the space conical helical ETB heat exchanger [13]