



Review Heat Exchanger: Research Development of Self-rotating Inserts in Heat Exchanger Tubes

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PAPER INFO

Paper history:

Received 18 January 2014

Received in revised form 17 May 2014

Accepted 26 June 2014

Keywords:

Tube inserts

Self-rotating Heat Transfer Enhancement

Anti-scaling and Descaling

ABSTRACT

Heat exchangers are widely used in power engineering and industrial applications. Many techniques such as coiled tube, surface tension devices, rough surfaces and extended surfaces have been investigated to enhance thermal performance and minimize the cost and size of the heat exchanger equipment. One of the most important techniques is tube insert. In general, tube inserts can be classified into two broad categories: stationary inserts and self-rotating inserts. Compared with stationary inserts, the self-rotating inserts can rotate in the tube by fluid and the comprehensive performance of self-rotating inserts is improved significantly. This paper mainly focuses on reviewing the large number of experimental and numerical works taken by researchers on self-rotating inserts such as twisted tapes, miniature hydraulic turbine, turbine-type swirl generators, etc. To improve the thermal efficiency of heat exchanger and serviceable to designers implementation of passive enhancement techniques in heat exchanger are required. The authors found that self-rotating inserts can strengthen the heat transfer efficiency, meanwhile achieve on-line automatic anti-scaling and descaling effect. When the fluid velocity is more than 0.2 m/s, most of self-rotating inserts can be applied. The heat transfer performance and frictional loss have been discussed to get the optimal configuration of self-rotating inserts. The convective heat transfer correlations have also been discussed. Determining how to find the optimal self-rotating insert is the main objective of this paper.

doi: 10.5829/idosi.ije.2014.27.10a.03

1. INTRODUCTION

Heat exchanger equipments are widely used in the chemical industry, power engineering, refrigeration and air conditioning, etc. Improving the efficiency of heat exchanger equipment not only can conserve energy and protect the environment, it also can save investment and operating costs as well [1-5].

As one of the most simply improved heat transfer technology heat transfer augmentation techniques, tube inserts technology has been widely used in heat exchangers. Tube inserts technology can be divided into two categories. The first is the active technique and the other is the passive one. For the active technique, external force such as jet impingement, stirring of the fluid, fluid and surface vibration, and electric field are required. Equally, the passive technique requires special

surface geometries such as extended surface, displaced inserts, swirl flow inserts, and surface roughening. Many researchers have studied and have tried to develop the new type of inserts for increasing the thermal performance and reducing the pressure drop inside the common plain tube to be as low as possible [6-11].

Passive tube inserts can be divided into stationary and self-rotating inserts. Stationary inserts such as static mixer conical ring and so on, have the relatively fixed position in the pipe. Self-rotating inserts such as twisted tapes, miniature hydraulic turbine, and the like are defined so because they can rotate automatically while the fluid in the tube is flowing [12-14].

Stationary inserts include twisted tape, ribs, conical nozzle, which was found by Liu and Sakr [15] that significantly improved the heat transfer process; also, twisted tape inserts are widely investigated; which are

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used to enhance the heat transfer efficiency of heat exchangers.

Different techniques have their work-specific applications. Twisted tape inserts have better performance in laminar flow than turbulent flow. However, some other passive techniques such as ribs, conical nozzle, and conical ring, etc. are usually more efficient in the turbulent flow than in the laminar flow.

Self-rotating inserts can strengthen the heat transfer efficiency, meanwhile achieve on-line automatic anti-scaling and descaling effect. This is because self-rotating inserts change the direction of fluid flow, form a rotational flow, get the bulk flow and fluid at the tube surface mixed and disrupt the development of boundary layer. A variety of developed self-rotating inserts are popularly researched by many scholars both at home and abroad and widely used for heat exchangers because of the simple manufacturing process, easy installation and operation. Different self-rotating inserts have different shapes and principles of heat transfer enhancement. This paper reviews the experimental and numerical work of employing self-rotating inserts and display their findings.

2. THE CONFIGURATION DEVELOPMENT OF SELF-ROTATING INSERTS

2.1. Coiled Wire and Spiral Spring Yu et al. [16, 17] studied the developed on-line automatic rotating helical spring device in China, which is shown in Figure 1. The results show that the device not only can implement on-line continuous and automatic descaling and anti-scale function, but also can improve the tube side heat transfer coefficient by more than 30% through experimental work; the minimum speed of tube fluid flow is generally in 0.5m/s-0.7m/s. The inserts could rotate when the speed of tube fluid flow reaches the minimum value. The convective heat transfer correlations of tube with self-rotating helical spring inserted have been concluded as:

$$Nu = 0.0119 Re^{0.835} Pr^{1/3} \left(\frac{m}{m_w} \right)^{0.14} \quad (1)$$

where μ is the viscosity of cold fluid and μ_w the viscosity at the wall temperature of the water.

In order to solve the weakness of self-rotating driving force and deficiency on the capacity of resisting high temperature of plastic twisted strip, Yu et al. [18] carried out a study of the heat transfer and pressure drop characteristics of turbulent flow by using plastic coated spiral instead of traditional steel wire spiral. The results indicate that the descaling efficiency decreases slightly, but the convection heat transfer augmentation rate reaches 51.6%. Furthermore, Xing et al. [19] experimentally studied the heat transfer, flow

resistance and rotating characteristics of the different helix rotors in circular tube; the helix rotors are shown in Figure 1. The results show that heat transfer is improved by 30% and the friction factor is increased 5 times compared to those of in plain tube. The double helix rotors could continuously operate for more than half a year without any problem. The rotating speeds of the upstream rotors are higher than that of the downstream ones, while the size of single helix rotors is much smaller than the double helix.

Besides experimental investigations, numerical studies were also carried out on heat transfer enhancement technologies. Solano et al. [20] built up a computational fluid dynamics (CFD) model to investigate the effect of helical wire on the enhancement in heat transfer in pipe. The results show that laminar eddies grow downstream of the wire and spread along the next helical pitch, promoting radial mixing.

2.2. Twisted Tape Twisted tapes are usually made of aluminum or polymer plastic with some suitable techniques. The heat transfer enhancement using twisted tapes mainly depends on the twist ratios and pitches. The twist ratio is usually defined as $y=H/d$, where H is the twist pitch length and d the inside diameter of the tube. Pitch is defined as the distance between two points measured parallel to the axis of the same twisted tape [21]. The sketch map of twisted tape device is shown in Figure 3. The twisted tape which is fixed on both ends of heat exchanger tube using the rotating device can rotate around the center by itself while the fluid in the tube flows.

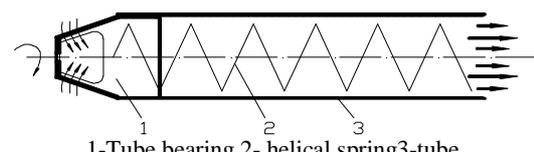


Figure 1. The sketch map of helical spring device

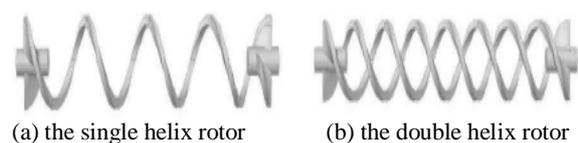


Figure 2. The sketch map of the helix rotor

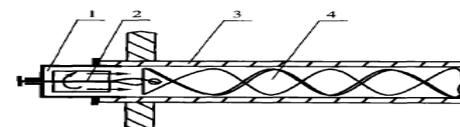
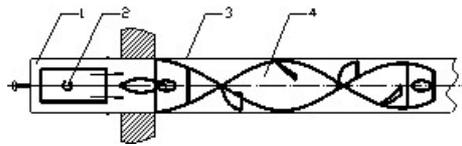
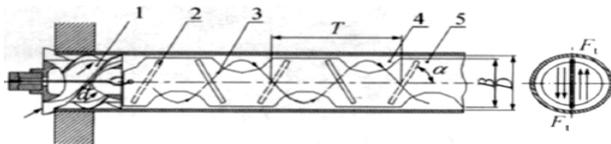


Figure 3. The sketch map of twisted tape device



1—Tube bearing 2—spindle 3—tube 4—twisted tape with oblique teeth

Figure 4. The sketch map of oblique teeth twisted tape device



1—Tube bearing 2—straight strip with elliptical teeth and broken edge 3—Spiral line 4—elliptical teeth 5—straight strip

Figure 5. The sketch map of straight strip with elliptical teeth and broken edge (serrated edges) device



Figure 6. The sketch map of miniature hydraulic turbine device

Substantial number of experimental works have been carried out to study the comprehensive performance of various twisted tapes in China. Lin et al. [22] studied the heat transfer enhancement mechanisms of heat exchanger tubes with self-rotating twisted tape inserts. The results indicate that for the heat transfer enhancement, the velocity increase effect near the tube wall area and the reduction effect of the equivalent diameter are the main factors, when $y \geq 10$, the helical flow effect is the main element when $y < 10$, and only when $y \leq 1$, the secondary recirculation becomes the main factor. Meanwhile, Lin et al. [23] experimentally investigated the self-preventing fouling technology for the self-rotating twisted tape in heat exchangers. Their results show that the average adhesive velocity of fouling in twisted tape tubes is only 54% of that in the plain tubes and the average dynamic thermal resistance of fouling is 30% smaller than that of the plain tubes.

Yu et al. [24] investigated the fouling removing and heat transfer performance at low flowing velocity by inserting twisted strip with oblique teeth into a tube, as shown in Figure 4. The principle is that there are asymmetrical oblique teeth distributed evenly on both surfaces of the strip and the heat transfer flowing fluid led by the strip has a asymmetrical reacting force on the strip over which the force moment of self-rotation is formed. The results show that this could be used to remove fouling and enhance heat transfer rate with a low flow velocity of 0.5-1.0 m/s automatically. Comparing with the smooth twisted strip, the total

moment was increased by 75%-101% and the heat transfer coefficient raised by 171%. Peng et al. [25] experimentally investigated the removing fouling and heat transfer enhancement characteristics of straight strip-insert with elliptical teeth and broken edges (serrated edges); this is shown in Figure 5. The spiral flow channels were designed in each elliptical gear backward position. The results indicate that comparing with twisted tape, straight strip-insert could work at the flow speed of 0.5 m/s in tube and make the heat transfer coefficient inside tubes increase by 171%. The flowing resistance equaled 3.25kPa/m when the flow velocity in tube was 0.625 m/s.

Researchers have carried out considerable bulk of research on twisted tapes [26, 27]. They have found that while it is obvious that the twisted tapes can improve the heat transfer rate, the performance of twisted tape inserts is better with laminar flow. It could reduce the extra pressure drop by using short length twisted tapes or multiple short length twisted tapes.

2. 3. Miniature Hydraulic Turbine

The technology of online anti-scaling and descaling in the heat exchanger using miniature hydraulic turbine was proposed by Lin et al. [28]. This device is shown in Figure 6. Miniature hydraulic turbines are made by welding a blade on a tube. In order to be easily placed in the heat exchanger tube, its diameter is smaller than the inside diameter of heat exchanger tube. The convective heat transfer correlations of tube with miniature hydraulic turbine inserted have been concluded as:

$$Nu = 0.0119 Re^{0.835} Pr^{1/3} \left(\frac{m}{m_w} \right)^{0.14} \quad (2)$$

where h is the viscosity of cold fluid and h_w the viscosity of the wall temperature of the water.

Considerable of experimental work and theoretical researcher as been conducted by Lin et al. [29-31] to study the performance of various miniature hydraulic turbines. All the results indicate that the heat transfer rate is enhanced significantly, while the pressure loss raises only slightly with the miniature hydraulic turbine. In contrast with a plain tube, the miniature hydraulic turbine can enhance heat transfer to some extent. The rotating speed is 850 rpm when the flow velocity in tube is 1 m/s. The heat transfer Nu number and friction resistance increases 1.49-1.62 and 1.13-1.16 times respectively compared with those in a plain non-fouling tube. It is found that the average dynamic fouling with miniature hydraulic turbine is 30% smaller than that of the smooth tubes by online industrial test.

2. 4. Helical Blade Rotor Helical blade rotors shown in Figure 7 are a new addition to the family of inserts for descaling and heat transfer enhancement [32]. Meanwhile, helical blade rotors have a wide range of

applications in a variety of engineering areas. Yang et al. [33] experimentally investigated the heat transfer and single phase pressure drop with rotor-assembled strands inserted tubes with the Reynolds number ranging from 2300 to 9000. The results show that the Nu number is increased by 30% to 60%. Helical blade rotors could work at the flow speed of 0.2 m/s in tube; the rotating speed of the Helical blade rotors reach 600 rpm when the fluid velocity is 1 m/s.

The convective heat transfer correlations of tube with helical blade rotor inserted have been concluded as follows:

$$Nu = 0.023 Re^{0.8} Pr^{0.4} i_1^{-0.2} (i_2 i_3 i_4)^{0.8} \quad (3)$$

where i is scale factor of the tube axial average flow velocity of the fluid in smooth tube.

Zhang et al. [34] experimentally studied the effects of rotor assembly with helical lobes and grooved helical lobes on the characteristics of flow friction and thermal performance in a circular tube. The results indicate that the Nu number with helical lobe rotor assembly and grooved helical lobe rotor assembly increased 1.06-1.26 and 1.03-1.15 times of that of the plain tube, respectively. The friction factor with helical lobe rotor assembly and grooved helical lobe rotor assembly increased 60%-68% and 36%-51% with respect to that of the plain tube, respectively. Grooved helical lobe rotor assembly has a better thermal performance characteristic. Except the research work of Zhang et al. [33], most of research works mentioned the swirl flow devices which are the fixed type swirl inserts.

Duangthongsuk et al. [35, 36] experimentally investigated the heat transfer and pressure drop characteristics of a circular tube fitted with rotating and fixed turbine-type swirl generator; this is shown in Figure 8. The data for a common smooth tube is compared with the data for fixed (FTSG) and freely rotating turbine type swirl generator (RTSG). The measured data illustrates that the heat transfer performance of the tube with RTSG inserts is 6.3% and 56% higher than that of the FTSG insert and the conventional smooth tube, respectively. The pressure drops of the tube with RTSG inserted were higher than those of the conventional plain tube by approximately 2.5 times. Compared with the FTSG inserts, the tube with RTSG inserts gives the lowest pressure drop.

2. 5. Imbalance Spiral-gear The imbalance spiral-gear inserts which are shown in Figure 9, are proposed to solve online fouling removal problem in heat transfer tubes. Peng et al. [37] experimentally studied the self-rotating and convective heat transfer performance of imbalance spiral-gear inserts. The results show that the imbalance spiral-gear connected clockwise and counterclockwise alternately can spin more easily, and the imbalance spiral-gear could rotate when the fluid flow

velocity is 0.35 m/s. When the heat transfer temperature difference is 15 °C, the overall heat transfer coefficient of the imbalance spiral-gear tube is 89% to 112% greater than that of straight plain tube, and 12% to 25% higher than that with balanced spiral-gear insert. The spiral-gears connected clockwise and counterclockwise alternately have the greatest force moment and can spin more easily.

2. 6. New Rotor New rotor inserts were proposed based on the helix rotor structures that already existed to further reduce the flow resistance, which is shown in Figure 10. Xin et al. [19, 38, 39] numerically and experimentally investigated the flow resistance, anti-fouling features and rotor rotation characteristics in a circular tube fitted with new rotor inserts. The results show that the rotating speed of the new rotor reaches 100 rpm when fluid flow velocity is 0.76 m/s, the flow resistance of circular tube with the new rotor insert has a 2 times increase compared with that of the plain tube. The flow resistance could be further reduced to 1.4 times increase by adding diversion frustum and smaller radius of the rotational sleeve. The weight of the plain tube increases 1.6g compared to that fitted with new rotor inserts after 10 days of continuous operation. Appropriately increasing the helix pitch of rotor, reducing the gap between blade and tube wall and reducing the radius of rotating shaft can lead to a better heat transfer performance.

Based on the MRF model and the moment balance method, Zhu et al. [40] used CFD simulation to study the fluid flow in circular tubes inserted with blade helical rotors and straight-line rotors. The results indicate that the flow resistance of the circular tube with straight-line rotors inserted is 3 to 4 times of that of the plain tube, half of the circular tube inserted with blade helical rotors.



Figure 7. The structures of helical blade rotors



Figure 8. Bare FTSG and RTSG

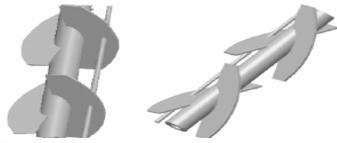


Figure 9. The sketch map of imbalance spiral-gear

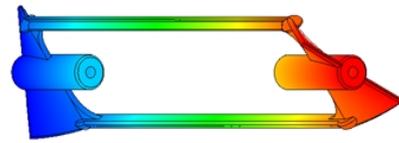


Figure 10. The sketch map of new rotor

TABLE 1. The Performance Comparisons of Self-rotating Inserts

Self-rotating Inserts	Characteristics of Rotating	Heat Transfer Enhancement(%)	Resistance Increment(times)
Coiled Wire and Spiral Spring[16-20]	The minimum speed of tube fluid flow is generally in 0.5 m/s	4.67-87.14	0.52-3.46
Twisted Tape[21-25]	The minimum speed of tube fluid flow is generally in 0.3 m/s	32-171	1.57-5.08
Miniature Hydraulic Turbine[28-31]	The rotating speed was 850r/min when the flow velocity in tube was 1 m/s	49-62	4-5
Helical Blade Rotor[32-34]	The rotating speed was 600r/min when the flow velocity in tube was 1 m/s	30-120	3-5
New Rotor[19, 38-40]	The rotating speed was 100r/min when the flow velocity in tube was 0.76 m/s	49-62	4-5
Imbalance Spiral-gear[37]	The minimum speed of tube fluid flow is generally in 0.35 m/s	89-112	4.4-8.69

3. THE PERFORMANCE COMPARISONS OF SELF-ROTATING INSERTS

The various performance comparisons of self-rotating inserts are shown in Table 1. All the performances of tube with a self-rotating insert are compared with those of a plain tube without inserts. It can be concluded that both the heat transfer rate and the pressure drop increased with the tube fitted with self-rotating inserts. The development trend of self-rotating inserts is with a smaller and streamline configuration in overall dimensions in order to reduce the resistance loss.

4. CONCLUSION

Self-rotating inserted into a conventional smooth tube is an innovative way to increase the thermal performance of the heat exchangers. The numerical simulations and experimental studies have been conducted to investigate the characteristics of heat transfer rate and friction factor of the tube fitted with self-rotating inserts. The conclusions are listed as follows:

1. Compared with the stationary inserts, both the heat transfer enhancement and the function of on-line automatic self-cleaning can be achieved with the self-rotating inserts in tube. Meanwhile, the non-fouling equipment can be operated efficiently with the self-rotating inserts in tube.

2. Most of the researchers need to decrease the extra pressure loss by using self-rotating inserts. In the selection of the self-rotating inserts, the structure of the insert is the major parameter. When the fluid velocity is more than 0.2m/s, most of self-rotating inserts can be

applied, meanwhile the convective heat transfer correlations have been discussed.

3. The heat transfer coefficient significantly increases when the fluid flows past the stationary and self-rotating inserts. However, the stationary and self-rotating inserted into the common smooth tube results in an increase of the pressure drop. The tube with self-rotating inserts gives the lowest pressure drop.

4. Along with the increase of the heat transfer rate, the pressure drop increases significantly in tube with the self-rotating inserts. The best performance of the optimal self-rotating inserts inserted in a tube has the topmost heat transfer rate and the lowest resistance loss. Determining how to find the optimal parameter is the main objective of the study for researchers.

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Self-rotating Heat Transfer Enhancement

Anti-scaling and Descaling

مبدل های حرارتی به طور گسترده ای در تولید انرژی و کاربردهای صنعتی استفاده می شود. فنون متعددی مانند لوله های مارپیچ، تجهیزات تغییر کشش سطحی، خشن سازی سطوح و سطوح گسترش یافته به منظور افزایش عملکرد حرارتی و به حداقل رساندن هزینه و اندازه تجهیزات مبدل های حرارتی بررسی شده است. یکی از فنون مهم قرار دادن قطعه اضافی درون لوله است. به طور کلی، قطعه اضافی درون لوله را می توان به دو گروه عمده طبقه بندی کرد: قطعه اضافی ثابت و قطعه اضافی خودگرد (خودچرخش). در مقایسه با قطعه اضافی ثابت، قطعه اضافی خودگرد می تواند در لوله های همراه مایع بچرخد. عملکرد قطعه اضافی خودگرد به طور قابل توجهی بهبود یافته است. در این مقاله به طور عمده تعداد زیادی از آثار تجربی و عددی انجام شده توسط محققان در قطعه اضافی خودگرد بررسی مانند نوار حلزونی، توربین هیدرولیک مینیاتور، ژنراتور چرخش توربین و غیره بررسی شده است. بهبود بهره وری حرارتی مبدل های حرارتی و شرایط تعمیر مورد علاقه طراحان اجرای فنون تقویت غیرعامل در تبادل حرارت است. آنها دریافتند که قطعه اضافی خودگرد می تواند کارایی انتقال حرارت، در عین حال رسیدن به ویژگی پوسته پوسته نشدن و پاک کنندگی رسوب به صورت خودکار هنگامی که سرعت سیال بیشتر از 0.2 sm باشد، بسیاری از قطعه اضافی خودگرد قابل استفاده اند. در عین حال همرفتی انتقال حرارت نیز مطرح شده است. برای به دست آوردن تنظیمات بهینه از قطعه اضافی خودگرد عملکرد انتقال حرارت و افت اصطکاکی نیز مورد بحث قرار گرفته است. تعیین چگونگی پیدا کردن قطعه اضافی مطلوب خودگرد هدف اصلی این مقاله است.

doi: 10.5829/idosi.ije.2014.27.10a.03