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Experimental Investigation of Heat Transfer Characteristics on the Exterior Surface of a Vertical 3-D Finned Tube under Natural Convection Conditions

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The vertical three-dimensional finned tube is one kind of strengthened tubes that effectively enhance heat transfer. In this paper, the characteristics of heat transfer on the exterior enhanced surface of a vertical 3-D finned tube were studied under natural convection conditions. The effects of varied fin height, fin width, axial fin pitch and circular fin pitch on Nusselt (Nu) number were presented. The results showed that the natural convective heat transfer performance of vertical 3-D finned tube was much better than that of a smooth tube. Under the study range, Nu number of the vertical 3-D finned tube was 2.83-2.97 times greater than that of the smooth tube. With the increase of fin height and the decrease of axial fin pitch, Nu number is increased, but the change of fin width and circular fin pitch has a little influence on the Nu number. Finally, the empirical correlation of air side free convection heat transfer was proposed for vertical 3-D finned tube, the predicted values of Nu number in agreement with the experimental values within the error of ± 11.3 %.

1. Introduction

Due to natural convection heat transfer has the advantages of safety, reliability, noiselessness and cost-effectiveness (Zilic and Darren, 2018). Natural convection heat transfer plays an important role in industrial applications, such as self-cooling transformer, electronic equipment and passive cooling unite for nuclear power plant. With the development of large-scale industrial equipment, the demands of heat dissipation from these systems increase rapidly. However, the heat transfer rate of natural convection is still low (Senapati et al., 2017). In order to overcome the biggest drawback of natural convection system, a number of studies have been directed to the issue of natural convection heat transfer intensification.

The passive methods such as extended surfaces with different geometries like perforated fins, branched fins, plate cubic pin-fins and triangular fins considered an effective technique for h and A enhancement (Zaidan et al., 2018). Jha and Bhaumik (2019) studied the heat transfer performance of a heat sink with helical fins and circular fins, and the results indicated that heat dissipation of the helically finned heat sink was 4 times greater than that of the circular fin heat sink with same fin heat transfer surface area. Park et al. (2014) experimentally investigated natural convection from vertical cylinders with branched plate fins, and found that cylinders with branched fins exhibited thermal resistances up to 36 % lower than those of cylinders with plate fins. Haghighi et al. (2018) experimentally studied the influence of fin spacing and fin numbers on natural convection heat transfer from plate fins and plate cubic pin-fins heat sinks. They found that the plate cubic pin-fins heat sinks had better heat transfer performance compared to plate fins heat sinks. Lee et al. (2016) experimentally studied natural convection heat transfer of vertical cylinders with triangular fins under various fin heights, fin numbers and base temperatures, and presented a correlation for estimating the Nusselt number. By reviewing the literature, it is clear that the finned surfaces have better thermal performances compared to the bare surfaces under natural convection conditions. However, most of these finned surfaces need to be welded, Which presents not only a high cost, but a high contact thermal resistance. The research object of this paper is a kind of 3-D finned tube, which was made by cutting and turning on the surface of the smooth tube with a special lathe, and an integral structure without contact thermal resistance obtained (Chen et al., 2019).

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Zhang et al. (2019) experimentally studied forced convection heat transfer of horizontal 3-D finned tube, and proposed heat transfer and friction factor correlations for estimating the thermal performance. Gu et al. (2019) studied the condensation heat transfer characteristic of moist air on the exterior surface of 3-D finned tubes, and found that 3-D finned tube can achieve 2 times heat transfer coefficient compared with smooth tube. However, there are few research work on heat transfer characteristics on the exterior surface of a vertical 3-D finned tube under natural convection conditions. In this paper, experiments were designed and carried out to examine the effects of different fin geometric parameters of a vertical 3-D finned tube on the heat transfer performance. A predictive correlation of Nusselt number was proposed, and expect that the results could provide a theoretical reference for the engineering applications of vertical 3-D finned tube heat exchangers.

2. Experimental setup and data processing

2.1 Experimental setup

The experimental system was set up in an airtight room. The test bench consists of four parts: theoperational mode regulation unit, the support frame, the experimental section and the computer data acquisition system, As shown in Figure 1. The operational mode regulation unit includes an AC voltage stabilizer, an AC voltage regulator and a cartridge heater. The AC voltage stabilizer is used to keep the current and voltage stable so that the power of the cartridge heater does not fluctuate with time. The support frame is used to fix vertical experimental section. Two unribbed segments for 5 cm were left for fixation at both ends of the vertical 3-D finned tube. In order to reduce the heat loss from the top and bottom sides of the vertical 3-D finned tube, the aluminosilicate wool insulation plug was inserted into the inner hole of the vertical 3-D finned tube.

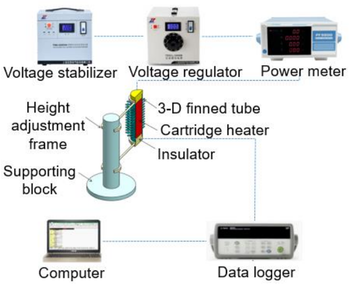

Figure 1: Schematic of the experimental system

In order to measure the mean wall temperature of the vertical 3-D finned tube, eight t-type thermocouples are arranged at equal intervals along the circumference and axis of the tube as shown in Figure 2. The ambient temperature was measured using two identical thermocouples. After a certain stable power is obtained, the data including heating power, environment temperature and 3-D finned tube wall temperature were recorded. During the experiments, the temperature fluctuation is less than 0.5 °C, and recorded continuously not less than 5 min.

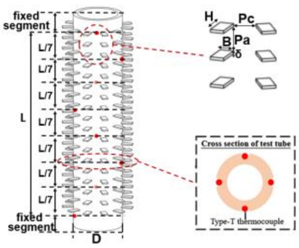

Figure 2: Schematic of finned tube structure and temperature measuring point arrangement

2.2 Experimental tube

The experimental tube is manufactured from low-carbon steel ($20^{\#}$ steel). In order to obtain the relationship between the heat transfer peformance and geometric parameters of vertical 3-D finned tube, the 3-D tubes with different geometric parameters were designed and processed. The main geometric parameters are shown in Table 1. The influence of structural parameters on heat transfer performance was obtained from the natural convection heat transfer experiment of finned tube No. 1 - 13 in Table 1. No. 14 is a smooth tube, which is used as a control group to compare the enhanced heat transfer performance of the vertical 3-D finned tubes in natural convection heat transfer.

Table 1: Main structural parameters of vertical three-dimensional finned tube

Geometry no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
H (mm)	1	3	5	7	5	5	5	5	5	5	5	5	5	/
B (mm)	2	2	2	2	1	3	4	2	2	2	2	2	2	/
Pa (mm)	3	3	3	3	3	3	3	2	4	5	3	3	3	/
Pc (mm)	3	3	3	3	3	3	3	3	3	3	2	4	5	/
L (mm)	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100
D (mm)	18	18	18	18	18	18	18	18	18	18	18	18	18	18

2.3 Data processing

There is heat loss through radiation between the vertical 3-D finned tube and the environment, so the heat dissipation by natural convection is calculated as shown in Eq(1) (He et al., 2003).

$$Q_c = Q - Q_r = VI - \varepsilon A\sigma(T_{wall}^{ave\,4} - T_{air}^{ave\,4}) \tag{1}$$

Where Q is the power of the cartridge heater, Q_r is the radiation heat loss. V is the voltage and I is the current, ε is the surface emissivity. A represents the unfinned base tubes area, σ is Stefan-Boltzmann constant. $T_{\mathrm{wall}}^{\mathrm{ave}}$ and $T_{\mathrm{air}}^{\mathrm{ave}}$ represent the average wall temperature of the tube and ambient temperature.
In the study, the average heat transfer coefficient is defined as shown in Eq(2).

$$h = \frac{Q_c}{A\Delta T} \tag{2}$$

Where ΔT represents the heat transfer temperature difference between the tube wall and the environment. The Rayleigh (*Ra*) number represents the state of air flow under natural convection. *Nu* is used to reflect the heat transfer performance of experimental tubes with different structures. The *Ra* and *Nu* are calculated from Eq(3) and Eq(4).

$$Ra = \frac{g\alpha_v \Delta T L^3}{av} \tag{3}$$

$$Nu = \frac{hL}{\lambda} \tag{4}$$

Where g denotes the local acceleration of gravity, α_v is the volume expansion coefficient of air, L represents the active length of an experimental tube, α is the thermal diffusion rate, v is the kinematic viscosity, and λ is the thermal conductivity of air.

3. Results and discussions

3.1 Comparison of the vertical 3-D finned tube and smooth tube

In this section, natural convection heat transfer performance of a smooth tube was contrasted with that of 3-D finned tube. The variation of *Nu* with the changes of *Ra* are shown in Figure 3.

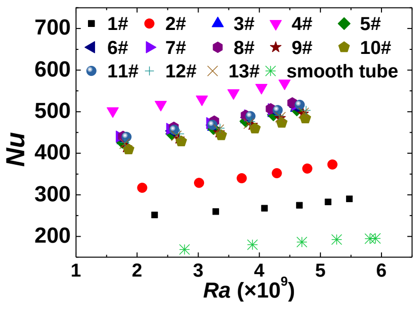

Figure 3: Variation of Nu with respect to Ra for the smooth tube, Vertical 3-D finned tubes

As shown in Figure 3, both the *Nu* of 3-D finned tubes and the *Nu* of the smooth tube increase gradually with the increasing of *Ra*. The reason is that the bigger *Ra* corresponds to a greater buoyancy force and higher airflow velocity, and the flow of air is improved enhancing the natural convection heat transfer performance. The results for the comparison of the smooth tube and 3-D finned tube in Figure 3 indicate that the *Nu* of 3-D finned tube exceeds that of the smooth tube at same *Ra*. The *Nu* number of the No.4 vertical 3-D finned tube was 2.83-2.97 times greater than that of the smooth tube.

3.2 Influence of geometric parameters

In order to obtain the effects of geometric parameters on the heat transfer performance of vertical 3-D finned tube, thirteen vertical 3-D finned tubes with different fin heights, fin widths, axial fin pitches and circular fin pitches were tested in this section.

3.2.1 Effect of fin height

Effect of fin height (*H*) was studied. Fin width, axial fin pitches and circular fin pitches were kept constant, and *H* was ranging from 1 mm to 7 mm. The variation of *Nu* with the changes of *Ra and H* are shown in Figure 4(a). It can be seen that *Nu* increases monotonically as the *Ra* increases. The *Nu* increases with the increases of *H* under the condition of constant *Ra*. This behaviour is similar to Figure 3. Figure 4(b) depicts the variation of temperature difference with *Q* and *H*. When the fin height is constant, the heat exchange temperature difference increases with the increases of *Q*. However, the T_{wall}^{ave}-T_{air}^{ave} between the tube wall and environment decrease as *H* increases. This is because the increase of the fin height results in a larger heat transfer surface area and a smaller heat dissipation resistance.

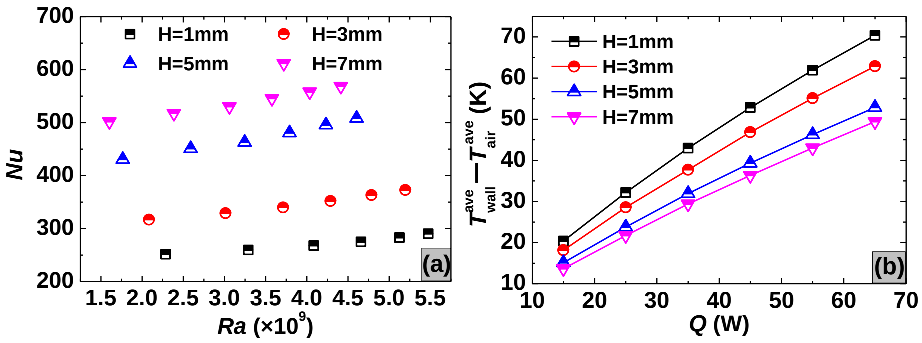

Figure 4: Effect of H on the air side heat transfer performance. (a) Nu, (b) T_{wall}^{ave}-T_{air}^{ave}

3.2.2 Effect of fin width

In this section, natural convection heat transfer performance of four vertical 3-D finned tubes with different fin width, which varied from 1 mm to 4 mm, are contrasted in detail. As can be seen in Figure 5(a), the *Nu* increases with increasing *Ra*. Figure 5(c) is a partial enlarged detail of Figure 5(b), and the heat input ranges from 35 W to 45 W. It can be seen from Figure 5 that the heat transfer performance was enhanced slightly with increasing fin width. The change of T_{wall}^{ave}-T_{air}^{ave} with *B* was more pronounced at a higher *Q*. The reason is that fin width is perpendicular to the air flow direction, the bigger fin width can destroy the boundary of air flow and the disturbance of air is significantly enhanced at the higher *Q*.

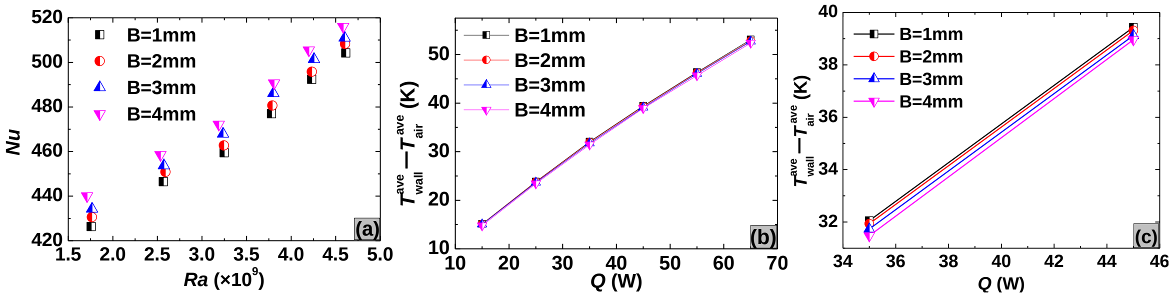

Figure 5: Effect of B on the air side heat transfer performance. (a) Nu, (b) T_{wall}^{ave}-T_{air}^{ave}, (c) Partial enlargement of b

3.2.3 Effect of axial fin pitch

In order to examine the effect of axial fin pitch on the heat transfer of vertical 3-D finned tube, four 3-D finned tubes with different axial fin pitches which are varied from 2 mm to 5 mm are tested in this section. As shown in Figure 6(a), the *Nu* increases as *Ra* increases. The change of *Nu* with *Ra* is consistent with Figure 3 and Figure 4. The *Nu* decreases as axial fin pitch increases at the same *Ra*. It is because the heat transfer surface will decrease as axial fin pitch increases, and the decrease rate of heat transfer surface is greater than that of the thermal boundary layer growing on fins. The result from Figure 6(b) also validates this conclusion, videlicet, the T_{wall}^{ave}-T_{air}^{ave} increases as *Pa* increases at the same *Q*.

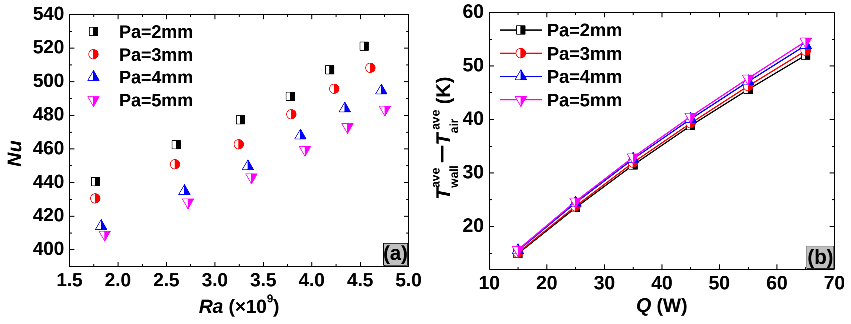

Figure 6: Effect of Pa on the air side heat transfer performance. (a) Nu, (b) T_{wall}^{ave}-T_{air}^{ave}

3.2.4 Effect of circular fin pitch

In this section, the effect of circular fin pitch was studied. Four vertical 3-D finned tube with different *Pc* which are varied from 2 mm to 5 mm were tested. As shown Figure 7(a), the *Nu* increases when *Ra* gets larger. The *Nu* decreases as *Pc* increases. The variation in the trend of the *Nu* is similar to Figure 6(a). And the effect of *Pa* on heat transfer is more pronounced than *Pc*. This is because the *Pa* has a greater effect on the heat transfer area. Figure 7(c) is a partial enlarged detail of Figure 7(b), and the heat input ranges from 35 W to 45 W. As can be seen from Figure 7(b), the *Pc* has a little influence on the T_{wall}^{ave}-T_{air}^{ave}. In the case of natural convection, the T_{wall}^{ave}-T_{air}^{ave} determines the buoyancy and the air velocity. The four vertical 3-D finned tube with different *Pc* have similar heat transfer properties.

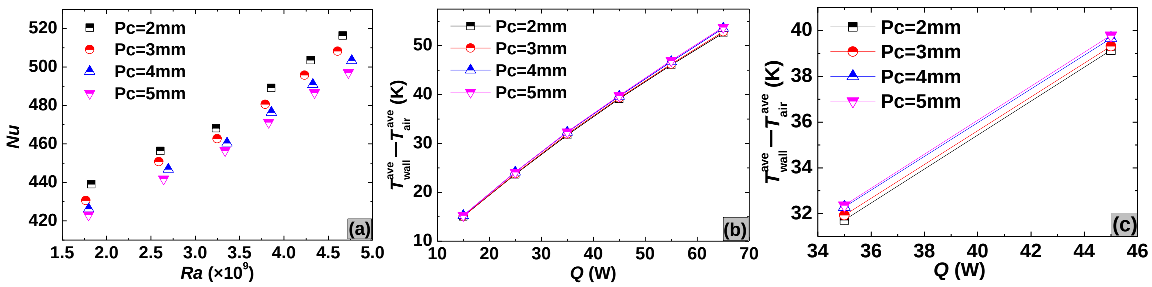

Figure 7: Effect of Pc on the air side heat transfer performance. (a) Nu, (b) T_{wall}^{ave}-T_{air}^{ave}, (c) Partial enlargement of b

3.3 Correlations and comparisons

A correlation for predicting the *Nu* of vertical 3-D finned tube was derived as a function of the geometric parameters investigated in the previous section. The *Nu* correlation (5) was obtained by multiple linear regression analysis of experimental data as follows:

$$Nu = 12.916 Ra^{0.1638} \left(\frac{H}{D}\right)^{0.4151} \left(\frac{B}{D}\right)^{0.0237} \left(\frac{Pa}{L}\right)^{-0.0886} \left(\frac{Pc}{D}\right)^{-0.0356} \quad (5)$$

The validated range for Eq (5) is *Ra* = 1.60×10^9-5.47×10^9, *H/D* = 0.0556-0.3889, *B/D* = 0.0556-0.2223, *Pa/L* = 0.0018-0.0046, *Pc/D* = 0.1111 - 0.2778. The experimental results and predicted values were compared, as shown in Figure 8. The predicted values of *Nu* number are in agreement with the experimental values within the error of ± 11.3 %. This indicates that the empirical correlation are sufficiently accurate.

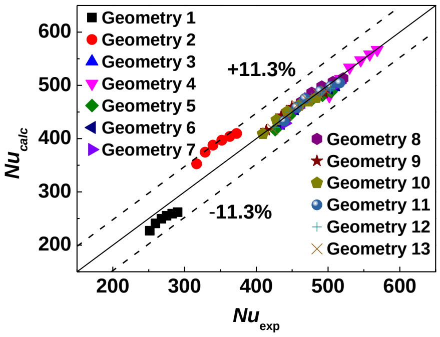

Figure 8: Comparison between the experimental date and correlated results of Nu

4. Conclusions

The vertical 3-D finned tube has the advantage of higher natural convective heat transfer performance than vertical smooth tube. The heat transfer characteristics of vertical 3-D finned tube with various fin height, fin width, axial fin pitch and circular fin pitch at different *Ra* were investigated. The results showed that heat transfer performance increases with the increase of *H*, *B* and the decrease of *Pa*, *Pc*. Specifically, the *Nu* of fin height with *H*=7 mm increases by 95.8 % – 99.5 % compared with the condition of *H*=1 mm. The *Nu* decreases by 6.9 % - 8.0 % when the axial fin pitch increases from 2 mm to 5 mm. The influence is limited with the change of fin width and circular fin pitch. The *Nu* increases by approximately 2.7 % and decreases by approximately 3.2 % when the fin width increases from 1 mm to 4 mm, and the circular fin pitch increases from 2 mm to 5 mm. Finally, a Nusselt number correlation that best predicts the heat transfer performance was proposed, and the consequences will be valuable for the industrial design of vertical 3-D aligned-finned tube heat exchangers.

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