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Interpretation of Taichi from the Perspective of Heat Exchanger

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Keywords：Heat exchanger; Taichi; Synergy; Friction coefficient

ABSTRACT

The paper proposes the use of Taichi principle by detecting the emergence of distinct Yin-Yang diagram for optimal heat exchanger design with the verification of the field synergy principle. By rotating the outer annular shell of the system and locating a pair of heat source and heat sink at both fish eyes, the heat can be transmitted from the hot eye to the cold eye. As the flow field of air is under the Reynolds number of 47.2, a well-distributed Yin-Yang diagram of distinct Taichi totem is emerged from the temperature contours of this heat exchanger, and that happens to be of the synergy optimization of both heat and flow fields with a minimal friction loss. Thus, it has been confirmed that the harmonious Yin-Yang diagram of Taichi totem can be used as a design criterion for the best performance of circular saucer shell type convective heat exchangers.

1. INTRODUCTION

The Book of Changes stated that "Taichi has two appearances; two appearances create four images; four images generate eight trigramme." Taichi is known to play a very important role in Taoist's culture, as a symbol of the universe in its most primitive chaotic state, represented by a rotating cyclic circle (see Fig. 1). The Taichi totem is constructed by drawing two circles in half the diameter of the Taichi circle. The two circles, each combined with the adjacent areas, are the so-called "Yin and Yang Fishes", colored as black and white, respectively. The center position of the one-eighth of concentric circle diameter is the eye of Fish. The two appearances of Taichi diagram, also known as Taichi Yin-Yang diagram, represent a cycle of Yin and Yang in endless loop.

The development and application of Taichi (i.e. primal chaos) along with the evolution of Chinese culture had several thousand years of history. Besides in religious belief and divination, the most well-known movement of it is the Taichi exercise stressing on leveraging the power sector to hit the rival immediately before being attacked and using his strength as a return. The routines of firmness and flexibility is consistent with the harmonic concept of Ying (feminine) and Yang (masculine) in primal chaos and mutual promotion of restless concept of eternal life. It is generally believed that the Taichi exercise can help to improve on both physical and mental states. Many studies have been conducted to better understanding and application of this exercise to improve on body disease curing, higher sleep quality and other aspects in past decades (Wei et al., 2013, Wang et al., 2013, Du et al., 2015). For the high-performance lithium battery, Zhang et al. (Zhang et al., 2014) had successfully applied Taichi concept in the manufacturing of rigid-flexible coupling cellulose-supported solid polymer electrolyte. Besides, the Yin Yang perspective is also applicable to management concepts (Law et al., 2014).

All these existing applications of the Taichi totem are mainly focused on the extension of Yin-Yang concept, such as asthenia and sthenia, hardness and softness, and other associated dual characteristics, and definitely is not direct applications on the Taichi totem. In this paper, the Yin-Yang diagram is interpreted from the perspective of heat exchanger by using the computational fluid dynamics (CFD) method. The upper and lower fisheyes in Fig. 1 are realized as a pair of heat source and sink at constant temperature, and the outer cylindrical annulus shell is set to be adiabatic. When the Taichi circle is filled with working fluids, the energy can be transferred from the heat source to the heat sink through the heat conduction of fluids. The region with the average temperature of heat source and heat sink is located at the middle line between the fisheyes (see Fig. 2A). If an S-shaped artificial boundary with the average temperature like the Yin-Yang interface in Fig. 1 is introduced between the two fisheyes, the isotherms of the heat exchanger are also similar to the Taichi totem, as shown in Fig. 2B. It is found that the thermal boundary layers on the walls of fisheyes become thinned, i.e. the heat transfer rate is increased. Actually, the heat flux of the source in this case is 1.7 times that of the case in Fig. 2A.

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The s-shaped interface is easy to be realized by simply rotating the outer cylindrical annular shell, which causes forced convection in the heat exchanger. The movement of fluids will take away the energy from the heat source at the hot fisheye, flowing toward the heat sink and transferring heat to warm up the neighboring area near the cold fish eye. In the same way, the movement of fluids in the heat sink at the cold fish eye will also bring the cold flow to the neighboring area near the hot fisheye and thus the cooling effect is produced. As the rotating speed of the annulus shell wall comes to a specific value, the temperature distribution of the flow field will resemble the distinct Yin-Yang diagram of Taichi totem, as shown in Fig. 2C. In this case, the rotation Reynolds number is small, and the heat flux of the source is 1.93 times that in the case of Fig. 2A. The value is higher than that of the case in Fig. 2B.

It is well known that the Taichi totem represents "Yang in Yin" and equally "Yin in Yang" simultaneously. The Yin and Yang fisheyes have colors opposite to those of the fishes (see Fig. 1). The main implication is that things must exist accompanying with its opposites. From the perspective of energy conservation, in this Yin-Yang heat exchanger, the event that heat energy is produced and taken away from the heat source implies that the total energy of heat source is reduced simultaneously in some forms, e.g. chemical energy. Similarly, when the heat sink adsorbs energy, its total energy must increase in some forms, such as electrical or mechanical energy.

In the Yin-Yang convective heat exchanger, the flow field, which has significant influence on heat transfer phenomena, is mainly affected by the rotating speed of the outer cylindrical annular shell. The temperature distribution of the flow field can resemble the distinct Taichi totem only at a critical rotational speed. More or less to this critical speed the temperature distribution will present no or vague primal chaos totem. Therefore, it is interesting for the onset juncture for this type of heat exchangers having temperature distribution of Taichi totem. In the meanwhile, the critical rotating speed of the outer cylindrical annular shell and the optimal heat transfer efficiency between the heat source and heat sink at both fish eyes are investigated as well.

Figure 1. Taichi totem of the Yin-Yang diagram.

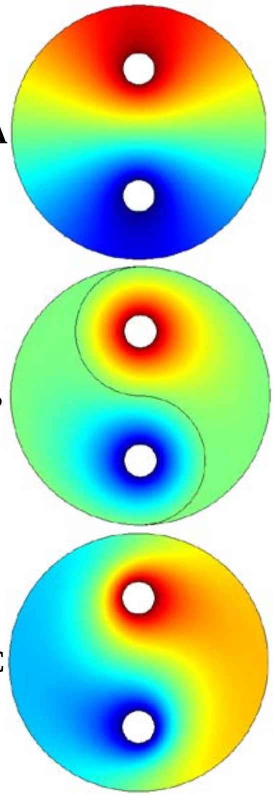

Figure 2. Normalized isotherms of the Yin-Yang-inspired heat exchanger. (A) The results in pure conduction mode. (B) An S-shaped artificial boundary condition analogous to the Yin-Yang interface (Fig. 1) is introduced in the heat exchanger under pure conduction mode. The temperature of this boundary is set to the averaged value of heat source and heat sink. The isotherms show a similar pattern to the Taichi totem. (C) The analogous Taichi diagram is observed as well by clockwise rotating the outer circle with a given specific speed.

2. Methods

This study use the computational fluid dynamics (CFD) method to solve for the governing equations, and results are subsequently used to compute the flow field distribution of velocity and temperature in the convective heat exchanger. The diameter of the outer wall, D, and the tangential velocity of the rotating outer cylindrical annular shell, U, are chosen as the characteristic length and velocity. For steady state incompressible flow without internal heat source, the governing equations for the conservation of mass, momentum, and energy are given as

$$\nabla^* \cdot \vec{V}^* = 0 \tag{1}$$

$$(\vec{V}^* \cdot \nabla^*)\vec{V}^* = -\nabla^* P^* + \frac{1}{\mathrm{Re}}\nabla^{*2}\vec{V}^* \tag{2}$$

$$\mathrm{Re}\,\mathrm{Pr}\,\vec{V}^* \cdot \nabla^* T^* = \nabla^{*2} T^* \tag{3}$$

Re and Pr stand for the Reynolds and Prandtl numbers, and are both defined as

$$\mathrm{Re} = \frac{UD}{\nu} = \frac{2R^2\omega}{\nu} \tag{4}$$

$$\mathrm{Pr} = \frac{\nu}{\alpha} \tag{5}$$

where $R = D/2$ is the radius of the outer cylindrical annual shell, ω is the rotational angular velocity, and $\alpha = k/(\rho C_p)$ is the thermal diffusivity. The normalized temperature T^* is defined as

$$T^* = \frac{T - T_c}{T_h - T_c} \tag{6}$$

where T_h and T_c are the wall temperatures of heat source and heat sink, respectively.

The energy equation (3) is integrated over the complete flow field to obtain the convective term of $\mathrm{Re}\,\mathrm{Pr}\int_{\Omega}\left(\vec{V}^* \cdot \nabla^* T^*\right) dx^* dy^*$ on the left hand side. Therefore, key factors that can affect the convective heat transfer efficiency, in addition to Re and Pr, the most important one is the dimensionless value of the integral, Int that can be expressed as (*6-10*)

$$Int = \int_{\Omega}\left(\vec{V}^* \cdot \nabla^* T^*\right) dx^* dy^* \tag{7}$$

where the inner product of both vector fields of flow velocity and temperature gradient can be expressed as

$$\vec{V}^* \cdot \nabla^* T^* = \left|\vec{V}^*\right| \left|\nabla^* T^*\right| \cos\theta \tag{8}$$

Namely, the maximal efficiency of the convective heat transfer can be effectively achieved with respect to the optimized synergy between both vector fields of flow velocity and temperature gradient under some specific conditions of Re and Pr. Therefore, in addition to the magnitude contribution of $\left|\vec{V}^*\right|$ and $\left|\nabla^* T^*\right|$, the average field synergy angle (θ) between vector fields of the flow velocity and the temperature gradient should also be as small as possible for $\theta < 90^\circ$, or as large as possible for $\theta > 90^\circ$ so that the flow field can thus have sufficient synergy contribution to the field of heat transfer.

In order to estimate the heat transfer capability of a given flow field, the Nusselt number near the heat source is adopted as a reference index, which is defined as

$$Nu = \frac{hD}{k} \tag{9}$$

Since the outer cylindrical annular shell is rotated to drive the inner air to move around, this will thus increase the wall friction resistance on both the cold and hot pipes. The skin friction drag coefficient is used here to represent the friction loss in a rotating process, which can be expressed as

$$C_f = \frac{\tau_w}{\rho U^2/2} \tag{10}$$

3. Results

To illustrate the working principle, the dimensionless model is used for discussions. The Reynolds number (Re) is defined as , in which , and are the tangential velocity of the rotating annular shell, the diameter of the outer wall and the kinematic viscosity of the working fluid (air in this study) respectively. Figure 2c is the case at Re=47.2. In order to estimate the heat transfer capability of a given flow field, the Nusselt number (Nu) near the heat source is adopted as a reference index. Since the outer cylindrical annular shell is rotated to drive the inner air to move around, this will thus increase the wall friction resistance on both the cold and hot pipes. The skin friction drag coefficient (Cf) is used here to represent the friction loss in a rotating process.

Since the Reynolds number is one of the key parameters in flow and temperature fields of a convective heat exchanger, the range of is adopted to characterize the process of heat transfer. As shown in Fig. 3, it is found that the increase of Reynolds numbers will enhance the heat dissipation in terms of Nusselt number, and in the meanwhile reduce the friction resistance in the neighborhood of heat source and sink at fisheyes. As the flow Reynolds number approaches 1000, the value of becomes very low, nearly close to zero. This is because the movement of high speed air flow is mainly concentrated in the boundary layer near the rotating outer annular cylindrical shell. In the concentric circle shaped structure, the flow speeds near the surface center of both the heat source and sink at fisheyes are not very high (see Fig. 4A). Therefore, decreases as the flow Reynolds number increases. As the rotating flow Reynolds number increases, the upper and lower symmetric patterns of temperature contours are shaped into each associated fish areas (see Fig. 4B). And at Re=47.2, the distinct Yin-Yang diagram is emerged in the Taichi totem.

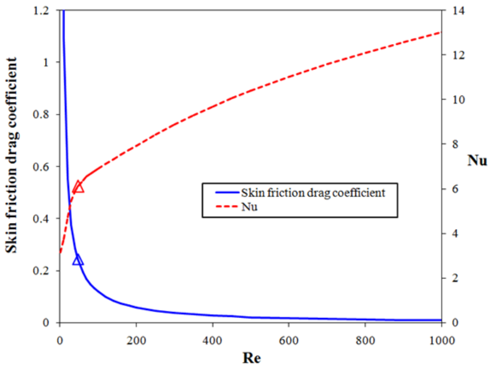

Figure 3. The Nusselt number and skin friction drag coefficient at different Reynolds numbers. The triangle marks here stands for the case of Fig. 2C at Re=47.2, which performs isotherms analogous to the Taichi diagram.

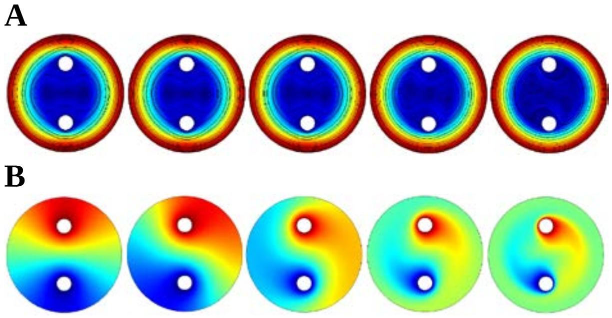

Figure 4. (A) Streamlines, normalized velocity contours and (B) isotherms of the flows. The Reynolds numbers are 1, 10, 47.2, 200 and 1000 from left to right, respectively.

4. Discussion

It can be found from Fig. 3 that the rate of change in Nu decreases with the increase of Re, namely, the increment of heat transfer efficiency is gradually decreased as Re increases. To fully understand the mechanism behind, the field synergy principle (Guo et al., 1998, Tao et al., 2002, Tao et al., 2004, Guo et al., 2005, Chen et al., 2013,) is employed in this study to characterize the heat transfer efficiency of the heat and flow fields. By examining the coordination of both the velocity and the temperature gradient fields, the research was attempted to understand the mechanism of the heat and flow fields as a whole in the convective heat exchanger of this sort, and use the findings to enhance the existing heat exchange systems, as well as to optimally redesign for new heat exchange devices.

The concept of heat flow field synergy can be understood through the vector diagram of both the flow and temperature gradient fields. It is observed that at Re=47.2 (see Fig. 5), the flows on the right hand side gradually move the heat away from the heat source of the hot fisheye; while on the left hand side the flows bring the cold flow toward the heat source into the hot fisheye. Thus, the fluid flow effectively enhances the efficiency of the convective heat transfer. In this study, the influence of Reynolds number on both the average angle of field synergy and Int is also evaluated in the range of (Fig. 6). It is found that the average angle of field synergy is small at low Reynolds numbers, which indicates that the structure of the air flow is helpful for heat transfer, and therefore the value of Int is large at low Reynolds numbers. As the flow Reynolds number increases, both the average angle of field synergy and Int are both gradually deteriorated. At Re=400, the average angle of field synergy is already higher than 70°. And for flows at higher Reynolds number, the average angle of field synergy approaches 90°, which implies that the contribution of air flow to heat transfer is already very small.

The field synergy for low Re is in good condition which can be realized from both walls on the left and the right, as shown in Fig. 7. The flow velocities are nearly in parallel to the vectors of temperature gradient. As the Reynolds number of the flow field increases, the whole synergy angle of both the flow and temperature gradient fields becomes worse, and the value of Int becomes smaller. Only two small areas near both the heat source and sink at fisheyes remain relatively high Int values. However, it is shown that at Re=47.2, larger Int is remained in the regions near the Yin-Yang fisheyes and fishtails, and therefore, the heat exchange behaviors between the heat source and sink are found very effective.

As the Reynolds number is increased to 1000, in most areas of the heat exchanger, the direction of the temperature gradient field is almost perpendicular to the velocity field (see Fig.8),which causes high field synergy angle and low Int values. The results indicate that to operate at high rotational speed of such a flow system, the enhancement on heat transfer effect is already very limited. This is why even Nu increases with the increase of Re, the rate of increase is gradually decreased (as shown in Fig. 3), and therefore do not meet the requirement for high energy exchange efficiency. Therefore, as presented in the calculation results, the temperature field distribution with a distinct Yin-Yang diagram of Taichi totem is the optimal design condition for convective heat exchanger by considering both the characteristics of heat transfer and flow resistance. Fig. 9 shows the critical Reynolds numbers in the range between 40 and 60 for the s-shaped curve in the Yin-Yang diagram of Taichi totem, which can be easily applied as an optimal design criteria for convective heat exchangers at any given specific rotating cylindrical wall velocity.

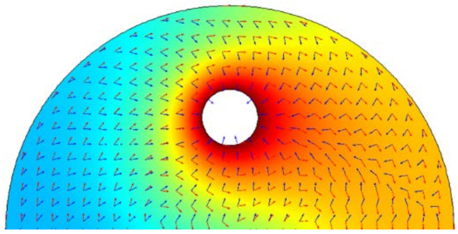

Figure 5. Vector diagram of the velocity field (red) and temperature gradient field (blue) at Re=47.2. The vector sizes are also normalized here for clarity. The estimated average synergy angle is 52.4°.

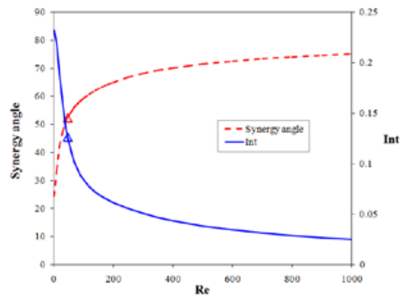

Figure 6. Average synergy angle and dimensionless integral (Int) at different Reynolds numbers. The triangle marks here stands for the case of Fig. 2C at Re=47.2, which performs isotherms analogous to the Taichi diagram.

This paper presents a new interpretation of Taichi from the perspective of optimal convective heat exchanger design. The field synergy principle is used to estimate the performance of the heat exchanger. When considering the optimal conditions for both the heat transfer and frictional flow resistance at the same time, it is found that the best outcome is presented at a Reynolds number that the distinct Yin-Yang diagram of Taichi totem is emerged in the isotherms of the heat exchanger. As the outer cylindrical annular shell is powered to rotate and a pair of internal heat source and sink are located at fisheyes, the system performance of the heat exchanger can be fully controlled to reach the highest efficiency at an estimated critical Reynolds number for any given specific rotating cylindrical wall velocity.

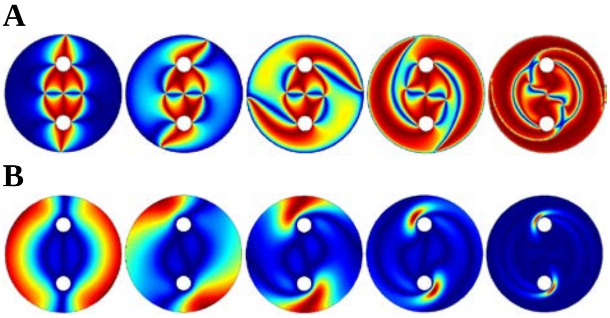

Figure 7. (**A**) Normalized field synergy angle and (**B**) Int of the flows. The Reynolds numbers are 1, 10, 47.2, 200 and 1000 from left to right, respectively.

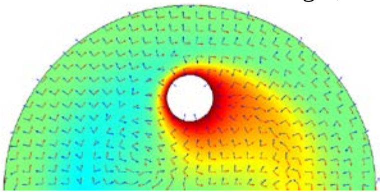

Figure 8. Vector diagram of the velocity field (red) and temperature gradient field (blue) at Re=1000. The vector sizes are also normalized here for clarity. The estimated average synergy angle is 75.1°.

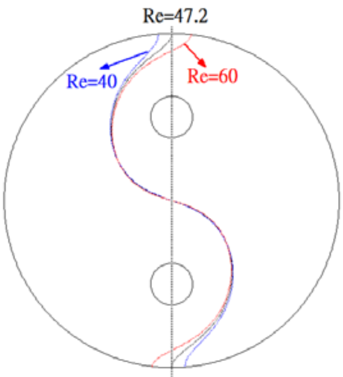

Figure 9. The S-shaped curve for Re=40, 47.2, and 60 in Yin-Yang diagram of Taichi totem.

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太極之對流換熱解析

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摘 要

本文透過使用場協同原理驗證熱交換器設計時，其結果出現獨特陰陽圖形，因此提出太極原理的應用情境。 通過旋轉系統的外環形殼體並在兩個定位點定義一對熱源和散熱器，熱量可以從熱區傳遞到冷區。 從結果可以發現，空氣流場的雷諾數為47.2，而這個熱交換器的溫度曲線出現了一個分佈均勻的陰陽圖的分佈良好的陰陽圖，這恰好是熱量和熱量的協同最優化狀態，為最小摩擦損失的流場。因此，證實太極圖騰的和諧陰陽圖可以作為圓形殼式對流熱交換器之最佳性能的設計標準。