

Heat transfer field synergy analysis *

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Abstract: The turbulent convective heat transfer in the finned tubes with circumferential fins is investigated numerically, and the field synergy principal is used to discuss how the velocity field and temperature field influence heat transfer. It can be found in numerical simulation that near $P/H=8$, the harmony between velocity and temperature field is the best; the harmony of field harmony becomes better with the augment of fin spacing. The results verify that the synergy principal can be applied to turbulent convection.

Keywords: heat transfer enhancement; field synergy; numerical simulation.

1. Introduction

Since the convective heat transfer gets broad application in various engineering areas, many techniques have been developed to enhance it in the past decade. Guo and his co-workers proposed a novel concept of enhancing convective heat transfer based on the parabolic fluid flow situation [1]. They pointed out that convective heat transfer not only lies on the flow characteristics and physical properties of fluids but also depends on the harmonious degree between velocity field and temperature field. Consider a steady, 2-D boundary layer flow. They transformed the convection term into the form of the dot product of velocity and temperature gradient then integrated energy equation over the thermal boundary layer. That is, the quality of heat transfer at thermal boundary layer.

$$q = \rho c_p \int_0^{\delta} (\vec{u} \cdot \text{grad} T) dy \quad (1)$$

From the formula, we can know that the convective heat transfer can be effectively enhanced by reducing the intersection angle between velocity and temperature gradient. The coordination property between velocity and temperature gradient was studied further detailed in [2] with 2-D laminar flow. It was pointed out that the convection terms is the main equivalent heat transfer that variation law decides heat transfer law at solid wall, and the heat transfer coefficient is higher where there is an excellent harmonious degree between velocity and temperature field. This concept has been extended to elliptic fluid flow and other transport phenomena in [3], and it is better to have some verification by some of

laminar examples. In ref [4], the author provides an interesting example to show that the three convention methods for enhancing single phase convective heat transfer can be unified by the field synergy principle. The reason of heat transfer of finned tube being enhanced was disclosed from the viewpoint of field synergy principle in [5].

In this paper, the turbulent convective heat transfer in the circumferential fins tube is investigated numerically. The field synergy principal is used to discuss the mechanism for enhancing heat transfer by analyzing the harmony between velocity field and temperature field. The results show that the field synergy principal can be applied to turbulent convection.

2. Models and computational methods

The geometry considered for this numerical investigation is the transverse repeated or fin, as shown in Fig .1 the fines have a height H and width W , and they are placed uniformly at a pitch P , and the resulting flow field is axisymmetric about centerline. The numerical calculation of the flow field and heat transfer is base on steady and the axisymmetric two dimensional form of the time-averaged continuity, Navier-Stokes and high Reynolds number $K-\varepsilon$ turbulent equations. The equations for the present flow configuration can be written in the general form [6]

$$\frac{1}{R} \left[\frac{\partial}{\partial X} (\bar{R} \bar{U} \phi) + \frac{\partial}{\partial R} (\bar{R} \bar{V} \phi) \right] = \frac{1}{R} \left[\frac{\partial}{\partial X} (\bar{R} \Gamma_{\text{eff}} \frac{\partial \phi}{\partial X}) + \frac{\partial}{\partial R} (\bar{R} \Gamma_{\text{eff}} \frac{\partial \phi}{\partial R}) \right] + S_{\phi} \quad (2)$$

where ϕ stands for different dependent variables. Γ_{eff}

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is effective diffusivity, “—” stand out dimensionless variables for this problem, that is [7]:

$$\bar{X} = \frac{x}{D}, \bar{R} = \frac{r}{D}, \bar{U} = \frac{u}{u_m}, \bar{V} = \frac{v}{u_m}, \bar{K} = \frac{k}{u_m^2},$$

$$\bar{E} = \frac{\varepsilon D}{u_m^3}, \bar{P} = \frac{p}{\rho u_m^2} \quad (3)$$

where u_m is mean velocity in x direction.

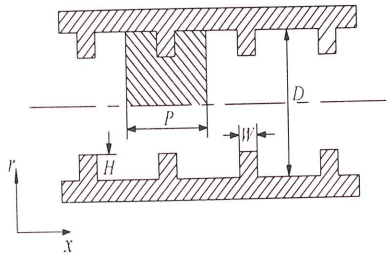


Fig.1 Geometry of tube with internal circumferential fins

The system of equations is solved under the periodicity conditions $\phi(x, r) = \phi(x + P, r)$ ($\phi = \bar{U}, \bar{V}, \bar{K}, \bar{E}, \theta$), where θ is dimensionless temperature defined by

$$\theta = \frac{T(x, r) - T_w}{T_b(x, r) - T_w} \quad (4)$$

where T_b is bulk temperature, and T_w is wall temperature.

Conditions on the symmetry axis is $\bar{v} = 0$, $\frac{\partial \phi}{\partial r} = 0$ ($\phi = \bar{U}, \bar{K}, \bar{E}, T$), and under the boundary on solid walls formulated by the wall function method.

Mean Nusselt number is defined as:

$$\overline{Nu} = \frac{\bar{h}D}{\lambda} \quad (5)$$

where λ is the thermal conductivities. $\bar{h}$ is mean heat transfer coefficient.

By vector dot product, the convection terms of 2-D convection-diffuse equation can be expressed as

$$\rho c_p (\vec{u} \cdot \text{grad} T) = \rho c_p |\vec{u}| |\text{grad} T| \cos \beta \quad (6)$$

where β is the included angle between the velocity vector and the temperature gradient. That is:

$$\cos \beta = \frac{\vec{u} \cdot \nabla T}{|\vec{u}| |\nabla T|} \quad (7)$$

Finite-difference equations are set up by the control method, and the solution algorithm is set up using the SIMPLER algorithm for the decoupling of velocity and pressure. The discretized equations are solved using line-by-line method and block-correction technique was used to accelerate the convergence rate. In ref [8], wall-function method for solid walls in flow field is

proposed, and the dimensionless distance of the node P to the wall must satisfied with $11.5 < \bar{Y}^+ < 400$. The periodic boundary conditions were implemented by mutual replacement of the field variables at inlet and outlet regions, as described by Xin and Tao[9]. In this analysis the following strict converging criterion was used $R_{\text{sum}}/q_m \leq 10^{-7}$, where R_{sum} is the total mass residual and q_m is the mean mass flux rate.

3. Results analysis and discussion

The flow characteristics in the tube with internal circumferential fins are governed by three criteria: Reynolds number, the relative height of fin H/D , the relative fin spacing P/H . Calculations are performed for $Pr=0.71$, the typical value of air. we use the notion H/D and P/H for the geometric features of internal circumferential fins, and the notion 01/10 for the fin height ratio and fin spacing ratio, where the first two digits stands for $H/D=0.01$ and the next two digits 10 stand for $P/H=10$. The relations between Nusselt Number and Reynolds Number are given in fig.2, where the geometric configurations of fins tube are 0.0625 / 18, 0.04 / 10 and $W/H=1$. The changes of Nusselt Number with respect to Reynolds Number of smooth tubes are given in fig.2. It can be found from the figure that when Reynolds Number is high enough, the ability of heat exchange of fins tubes is much better than that of smooth pipes in evidence.

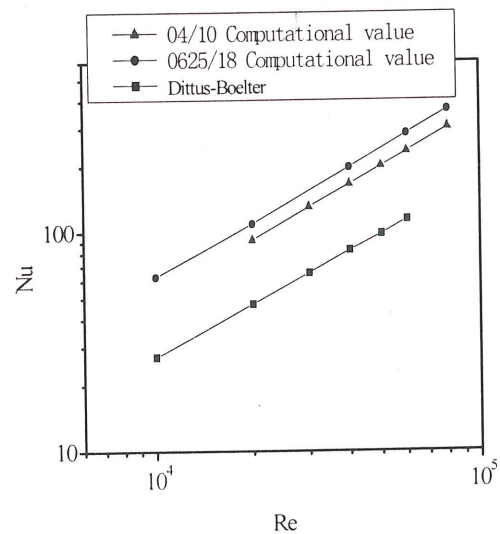
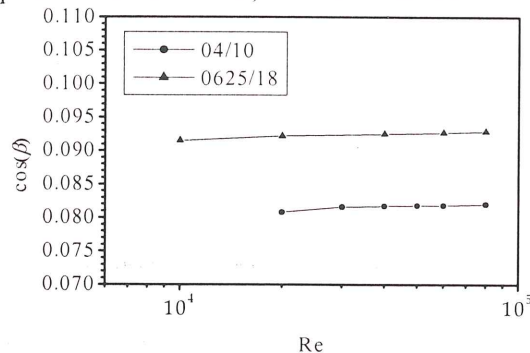


Fig.2 Relations of mean Nusselt number and Reynolds Number

According to the field synergy principal, fig.3 shows the relations between the average intersection angle velocity vector in the whole field to temperature

gradient and the product of modules of velocity vector and temperature gradient, here M denotes the product of modules of velocity vector and temperature gradient. As can be seen in fig.3 a), the average angle of the whole field almost remains unchanged with the increase of Re number, and in fig.3b), the product of modules increases with the increase of Re , namely consistent with the variation of Nusselt Number according to Re . We can see that in computational area, under the same geometric parameters conditions, with the increase of



a) Variation of mean angle with Reynolds Number

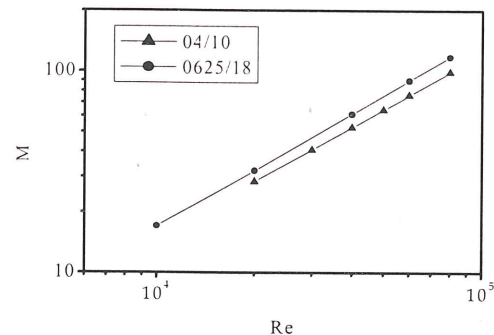
b) Variation of M with Reynolds NumberFig3 Field Synergy of variable Re

Fig. 4 shows the relations between Nusselt number and fin spacing with the same Re number, where the fin size $H/D=0.05$, the range of fin spacing is $P/H=5\sim 30$ and $Re=50000$. We can see from the figure that when fin spacing is 8, the Nusselt number reaches its maximum. When fin spacing is very small, the vortices among fins detach the main flow and wall surface, which weakens heat transfer; on the other hand, when the fin spacing is very large, the influence of fins to flow and heat transfer becomes weak too, thus it also cause the reduction of heat exchange coefficient.

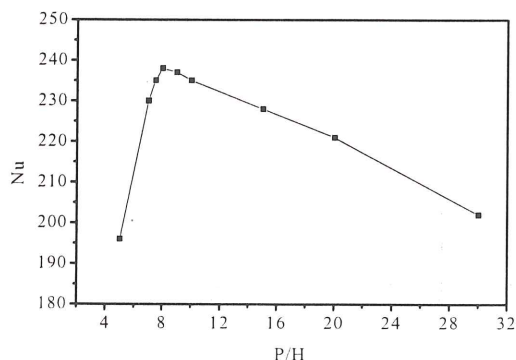
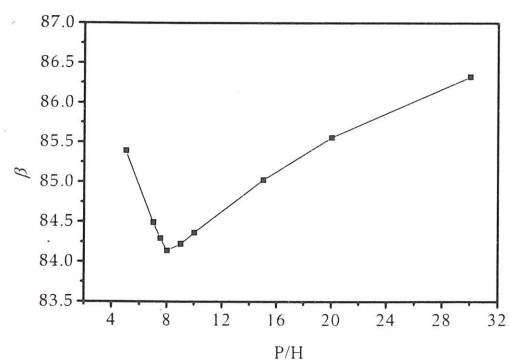
Fig4 Variation of mean Nusselt number with fin spacing, $H/D=0.05$, $Re=50000$

Fig. 5 shows the relation between fin spacing and the whole field average value of the intersection angle of velocity vector to temperature gradient. It can be seen from the figure that the fin spacing is 8, the average

Re , namely with the increase of inlet velocity, the module of velocity augments too. When module of velocity increases, heat transfer increase, that is, the increase of heat transfer mainly depends on the increase of the mass flow, but the angle between velocity vector and temperature gradient is almost invariable, it can be seen that the augment of Reynolds Number can hardly influence the harmony of field. Therefore, we can say that, the method of increase the Reynolds Number to augment heat transfer is not the best way.

value of the intersection angle reached its minimum. When the fin spacing greater or less than 8 will cause the increase of the angle, this is consistent with that mentioned above, where Nusselt number reaches the maximum at the fin spacing value of 8. When fin spacing is near the value of 8, the velocity vector and temperature gradient harmony reaches its best, and the effect of heat transfer is also the optimal.

Fig5 Variation of mean angle with fin spacing $H/D=0.05$, $Re=50000$

Fin size is the other important parameter, which influence strengthening heat transfer. Taking the fin size of tubes, $P/H=10, 20, 30$, as analytic object, Reynolds number is 50000, the range of fin size is $H/D=0.04\sim 0.12$. Fig.6 shows the relations between Nusselt number and fin size when the other conditions is unchanged. We can learn from the figure that

according to the increase of fin size, Nusselt number augments exponentially, and when fin spacing is rather large, the influence of fin size to Nusselt number will be larger in the same conditions.

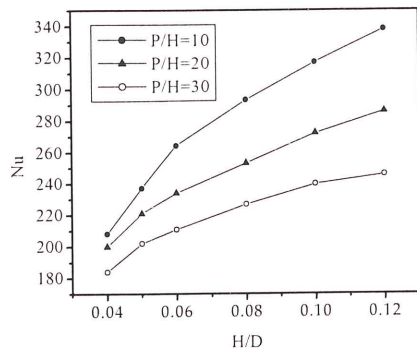


Fig6 Variation of mean angle with fin sizes, Re=50000

Further, we analyze the effect of fin size on heat transfer with the field synergy principal. Fig.7 shows the relations between fin size and the average value of velocity vector and temperature gradient in the whole field, we can see from the figure that, according to the increase of fin size, the average intersection angle between velocity field and temperature field reduces, this shows that the fields harmony better, the ability of heat transfer increases; on the contrary, the fields harmonious degree become worse, the ability of heat transfer reduces. And when fin size is pretty large, fin spacing will influence the synergy of filed obviously, this is consistent with the relations between heat transfer and fin size mentioned above. Therefore, the fields harmony becomes better, and the ability of heat transfer increases.

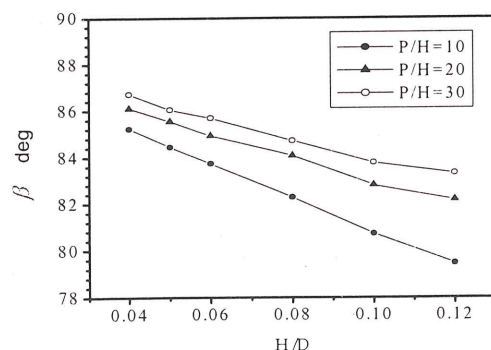


Fig7 Variation of mean angle with fin sizes, Re=50000

4. Conclusions

The following conclusions can be draw from the study of field synergy above:

1) When the geometric shape is fixed in the computational range, Nu augments obviously with the increase of Re, but the intersection angle between velocity vector and temperature gradient is almost

invariable, It shows that the synergy property of field does not change obviously when Reynolds number increases.

2) When fin spacing is fixed, Nu augments with the increase of fin size in the computational range, and when $H/D > 0.05$, the average intersection angle between velocity vector and temperature reduces with the increase of fin spacing, this shows that the synergy property of fields gradually go better become better gradually according to the increase of fin spacing.

3) When the fin size and Re are fixed, heat transfer coefficient reaches the peak when $P/H=8$. On the other hand, the intersection angle between velocity vector and temperature gradient drops to least when $P/H=8$. This shows that in the range $P/H=8$, velocity vector and temperature obtain the best harmony.

4) Using the field synergy principal, we analyze the heat transfer property of circular internal circumferential fins tube with respect to the change of Reynolds number, fin size and fin spacing on turbulence condition. It is testified that the field synergy principal can be applied to turbulence problem.

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