Numerical analysis of heat transfer enhancement in pulsating flow pipes

Jianfeng En¹², Ziyao Ma¹², Siran Jia¹², Jie Mu³, Zhenbang Gao¹²
¹ Shanghai Tiandi Mining Equipment Technology CO., Ltd., Shanghai, 200030;
² China coal technology and Industry Group Shanghai CO., Ltd, Shanghai, 200030;
³ Coal Research Institute, Beijing 100013, China
*Corresponding author’s e-mail: 1632214118@qq.com

Abstract. In this paper, a rectangular flow runner is used as the research object to study the influence of adding a spoiler on the wall of the flow runner on its heat transfer characteristics and flow characteristics. Using the finite element method to analyse the influence of different spoiler’s structures and parameters of the spoilers on the heat transfer characteristics and flow characteristics of the flow runner, the study found that: by the comparison of the smooth flow runner and the rectangular spoiler flow runner, the comprehensive heat exchange effect of the spoiler runner is the best when the arc is arranged in the flow runner, and the accumulation effect of impurities in the runner is the slowest.

1. Introduction
Rectangular flow runner as a commonly used enhanced heat exchange pipeline has the advantages of simple processing, high strength, and high heat exchange efficiency. It is widely used in the heat dissipation of mechanical equipment, power energy, and chemical engineering. It plays an important role on improving equipment heat dissipation efficiency, temperature control on chemical equipment, and improving equipment reliability. Scholars at China and abroad have done a lot of research on the enhancement of heat transfer technology for rectangular flow runners [1-3], but the studies on the arrangement of spoilers on the left and right walls of the rectangular flow runners are not enough. This article mainly studies the spoilers were added on the wall of the rectangular flow runner and explores the structure of the spoilers, and also studied the influence of structural parameters on the flow characteristics and heat transfer characteristics of the runner.

2. Principles of computational fluid dynamics
To study the heat transfer effects of rectangular runners under different structural parameters, it is necessary to explore the motion states of rectangular runners with different structures. The fluid follows the law of conservation of mass, law of momentum, and law of conservation of energy [4]. Through initial conditions and boundaries, the motion state of the pipeline fluid and energy conversion can be solved by simultaneous three equations can solve [5].

2.1. Conservation equation
\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v_x)}{\partial x} + \frac{\partial (\rho v_y)}{\partial y} + \frac{\partial (\rho v_z)}{\partial z} = 0
\]  (1)
Where: \( \rho \) is the density; \( v_x \) is the velocity component in the x direction; \( v_y \) is the velocity component in the direction; \( v_z \) is the velocity component in the z direction.

\[
f = \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \nabla^2 \nu = \frac{d\nu}{dt}
\]  

(2)

where: \( f \) represents mass force, N; \( p \) represents pressure; \( \nu \) represents speed.

\[
\frac{\partial (\rho T)}{\partial t} + \text{div}(\rho \nu T) = \text{div}(k \nabla T) + S_T
\]  

(3)

Where: \( C_p \) is the specific heat capacity; \( T \) is the temperature; \( k \) is the fluid heat transfer coefficient; \( ST \) is the fluid dissipation term.

2.2. Boundary conditions

1) Using the method of pressure inlet and pressure outlet;
2) The fluid wall adopts constant temperature, it is 85 °C, and using water as the fluid, the temperature is 25 °C;
3) Adopted no-slip conditions on the wall;

3. Analysis of the influence of the spoiler block on the runner

Figure 1 is a schematic diagram of the rectangular runner structure. The left picture shows the arrangement of a spoiler block in the runner. The right picture shows the arc spoiler blocks were added to the runner. Under the principle of control variable, it was studies that the influences of structure and structure parameters of the spoiler block to the flow characteristics in the runner and the law of the heat transfer characteristics. the fluid working medium is liquid water.

![Figure 1. Schematic diagram of rectangular runner](image)

(a) Rectangular spoiler runner  
(b) Arc spoiler block runner

In fluid mechanics, the Nusselt number \( Nu \) is usually used as the evaluation parameter to evaluate the flow heat transfer effect between the fluid and the wall. The larger the Nusselt number, the better the heat transfer effect of the pipe. The resistance coefficient \( f \) is usually used as the evaluation parameter to evaluate the pipeline resistance. The larger the resistance coefficient, the more serious the pressure loss when the fluid flows through the pipeline. In the theory of enhanced heat transfer, the heat dissipation efficiency of the pipe is strengthened by increasing the turbulence intensity of the fluid, and the increased turbulence intensity will cause the collision between the pipe fluid micro-clusters to cause turbulent dissipation, and the result is the resistance increased. Therefore, the comprehensive evaluation factor \( PEC \) is used for comprehensive conversion. Thermal coefficient and resistance coefficient. When \( PEC > 1 \), the comprehensive heat transfer effect is enhanced. And when \( PEC < 1 \), the comprehensive heat transfer effect is weakened. The expressions of Nusselt number, resistance coefficient and comprehensive evaluation factor \( PEC \) are as follows [6]:

\[
Nu = \frac{h d}{\lambda} = \frac{q}{(T_w - T_f) \lambda} \frac{d}{\lambda}
\]  

(4)

Where: \( h \) is the convective heat transfer coefficient; \( d \) is the characteristic length of the flow runner; \( \lambda \) is the thermal conductivity of the fluid; \( q \) is the heat flux density of the fluid; \( T_w \) is the flow runner wall temperature; \( T_f \) is the mainstream fluid temperature.

\[
f = \frac{2 \Delta P d}{L \rho v^2}
\]  

(5)
Where: $\Delta P$ is the pressure difference between the inlet and outlet of the flow runner; $\rho$ is the fluid density; $v$ is the average velocity of the flow runner section.

$$PEC = \frac{Nu / Nu_0}{(f / f_0)^{1/3}}$$  \hspace{1cm} (6)$$

Where: $Nu, Nu_0$ represent the Nusselt number of the enhanced heat exchange runner and the smooth runner; $f, f_0$ represent the resistance coefficient of the enhanced heat exchange runner and the smooth runner.

When the fluid passes through the pipe, the heat is transferred to the pipe wall through convective heat exchange with the pipe wall. The expression of the heat exchange amount $Q$ is as follows [7].

$$Q = cm\Delta t$$  \hspace{1cm} (7)$$

Where: $c$ is the specific heat capacity; $m$ is the mass; $\Delta t$ is the temperature difference between the inlet and outlet.

To avoid the influence of the size of the spoiler block on the result, the rectangular spoiler block and the semi-circular spoiler block use the same $L, R,$ and $D$. The values are 150mm, 40mm, and 7mm respectively.

![Figure 2. Schematic diagram of runner](image)

3.1. Analysis of numerical calculation results

Figure 3 shows the variation of Nusselt number with Reynolds number for three kinds of runners. It can be seen from the figure that arranging semi-circular spoilers and rectangular spoilers in smooth runners can increase the heat transfer capacity of the runners. But the rectangular spoiler has the greatest impact on the heat transfer characteristics of the runner. With the increase of Reynolds number, the Nusselt numbers of the three flow runners all increased, it indicates that the increase in flow velocity will increase the convective heat transfer effect between the fluid and the wall. The main reason is that the faster the flow velocity, the greater the turbulence intensity of the fluid in the flow runner. The more severe the boundary layer damage, the more obvious the convective heat transfer efficiency between the fluid and the wall. In the range of $3000<Re<16000$, the Nusselt number of the smooth pipeline increases, and the growth rate slows down while the flow runner of the semi-circular spoiler block and the rectangular spoiler block flow runner are in the given Reynolds number range. The growth rate of the number does not slow down with the increase of the flow velocity, it indicates that the increase of the flow velocity is positively related to the improvement of the heat transfer efficiency of the flow runner, and it will only promote the effect in a certain range, and the increase of the spoiler in the flow runner will prolong this Scope.
Figure 3. Nu variation curves of three kinds of runners

Figure 4 shows the variation of the resistance coefficient of the three runners with the Reynolds number. As the Reynolds number increases, the drag coefficients of the three runners decrease, and the decreasing speed becomes more and more gentle. According to the definition of the resistance coefficient, the resistance coefficient is directly proportional to the wall shear stress and inversely proportional to the fluid kinetic energy. The increases of the flow velocity will simultaneously cause the flow runner wall shear force and kinetic energy to increase, but the kinetic energy growth rate is higher than the shear force. As the flow rate increases, the gap between the two decreases, so the drag coefficient tends to be flat with the increase in flow rate. Under the same Reynolds number, the rectangular spoiler runner has the highest drag coefficient among the three runners. The circular spoiler runner is the second, and the smooth runner has the lowest drag coefficient. Due to the same of the Reynolds numbers and the kinetic energy of three types of runners, the rectangular spoiler has the largest influence on the runner resistance.

Figure 4. f variation curves of three kinds of runners

Figure 5 shows the change of the comprehensive evaluation factors of the three runners under different Reynolds numbers. The heat transfer performance of the runner is enhanced, and the pressure drop at the inlet and outlet of the runners will also be increased. The evaluation criteria for the enhanced heat transfer efficiency of the runners. It is to obtain good heat exchange efficiency under the condition of small pressure drop. As the Reynolds number increases, the comprehensive evaluation of the rectangular spoiler runner and the arc spoiler runner have shown a downward trend. The downward trend of the rectangular spoiler runner is more obvious. When the Reynolds number Re>10000, the PEC value is less than 1. The comprehensive heat transfer effect is weaker than that of a smooth runner, and the comprehensive evaluation factor of the arc spoiler is greater than 1 in the range of 3000<Re<16000, and its heat transfer effect is stronger than that of a smooth pipe. In the range of 3000<Re<16000, the PEC value of the arc spoiler runner is 1.04~1.08, and the PEC value of the rectangular spoiler runner in
this range is 0.98–1.07. In the summary, the arc should be disturbed. The flow block serves as the spoiler block of the flow runner.

3.2. Analysis of heat transfer and flow mechanism

In order to further explore the mechanism influence of the spoiler block on the flow characteristics and heat transfer characteristics of the runner, the numerical calculation results are displayed in the cloud diagram of the velocity field and the temperature field. The velocity cloud diagrams of flow runners with different structures shows that the flow velocity gradually increases from the wall to the central mainstream area. According to Newton’s law of internal friction, any fluid has viscosity. When the fluid flows, the velocity of the fluid which close to the wall is very small due to the effect of viscosity. The relative sliding between fluids will also be hindered due to the effect of viscosity. When the distance of the fluid from the wall is farther, the hindering effect of viscosity on the fluid becomes small and negligible compared to the effect of fluid inertia. Among the three flow runners, the flow velocity in the mainstream area of the rectangular spoiler is the highest, it is reaching 1.8m/s. Followed by the flow velocity in the mainstream area of the semi-circular spoiler being 1.4m/s, and the flow velocity in the mainstream area of the smooth rectangular flow runner is the lowest at 1.2m/s. According to the knowledge of fluid mechanics, the faster the fluid velocity, the stronger the turbulence of the fluid, and the better the convective heat transfer between fluids. In addition, the increase in velocity will aggravate the destruction of the fluid boundary layer thermal effect and strengthen the convective exchange between the fluid and the wall.
Figure 7 shows the local velocity cloud diagrams of the rectangular spoiler flow runner and the circular arc spoiler flow runner. From the velocity cloud diagram, it can be found that the fluid velocity is very small at the front and back of the rectangular spoiler, and the vortex areas of windward and leeward are large. The boundary layer at the top of the flow block is not significantly weakened. The main reason is that the cross-sectional area of the flow runner becomes smaller, and the flow velocity increases when the fluid passes through the position of the spoiler. Bernoulli’s principle shows that the outlet pressure at this position decreases. The flow rate decreases and the pressure increases when passing through the block, and there is a negative pressure zone at this position to form a vortex. When the fluid flows through the arc-shaped spoiler block, the fluid sweeps the spoiler block and washes it, only forming a small flow dead zone at the wall junction. The vortex fluid in the dead zone of the flow does not exchange mass with the mainstream fluid, and the heat exchange efficiency is low. The integrated arc spoiler block has a higher heat transfer efficiency in the runner.

![Local velocity field of rectangular spoiler block](a)

![Local velocity field of arc spoiler block](b)

Figure 7. Local velocity cloud diagram

4. Conclusion

(1) Adding spoilers to the left and right walls of the rectangular flow runner can increase the heat transfer efficiency of the flow runner, and the resistance of the flow runner will increase accordingly.

(2) By comparing the flow runner of the circular spoiler block and the flow runner of the rectangular spoiler block, the rectangular spoiler block flow runner has high heat transfer efficiency, but the pressure loss is serious, and the impurities are accumulated seriously. Compared with the arc spoiler block, the comprehensive heat exchange effect is better.

In the summary, this paper mainly proposes a method based on the principle of pulsating flow to enhance the energy efficiency of the flow runner. While the spoiler block strengthens the turbulence intensity of the fluid, the spoiler block can make the fluid in the flow runner present a pulsating flow. This method has significant guidance on the study of multi-runner enhancement of the heat dissipation efficiency in the flow runner.

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