Numerical Study on Enhancing Heat Transfer of the Belt-type Resistance Heater in the Hypersonic Wind Tunnel

Qing Mao *, Jiufen Chen, Xiaobin Xu, Xiaohua Fan
Department of Hypervelocity Aerodynamics Institutes, China Aerodynamics Research and Development Center, Mian Yang, China

*Corresponding author e-mail: maoqing229@163.com

Abstract. Numerical studies of Heat transfer enhancement of belt-type Electric-resistance Heater is reported in this paper. The effect of different kinds of belt arrangements is studied in detail. Results show that, for changing \( m \) and \( n \), which is the spacing between adjacent belts both in vertical and horizon, the comprehensive Performance Evaluation Criterion (PEC) increases as belt spacing decreases; For the case of model adding several baffles, the PEC reaches 1.6, with \( \frac{Nu}{Nu_0} \) and \( \frac{f}{f_0} \) comes to 3.38 and 9.51; For the staggered arrangement belt geometry, the PEC attains 1.18 and the flow field uniformity improves significantly compared with the aligned arrangement one.

1. Introduction

The hypersonic wind tunnel is widely used to simulate the critical parameters of the real hypersonic flight environment as a main aerodynamic ground test equipment. Being of particular significance for the hypersonic wind tunnel, the heater is installed before the Setting Chamber to increase the airflow’s stagnant temperature in case of air condensation due to high Mach number when flowing through the nozzle. Considering its advantages of rapid heating and no impurities are introduced to airflow, belt-type Resistance Heater is adopted in the CRADC \( \Phi0.5m \) hypersonic wind tunnel. However, the heating resistors element is easily burned out at a high Mach number and the repair processes is time-consuming and expensive. But few studies have touched on this area. In contrast, shell-and-tube heat exchangers (STHEs), which are particularly similar to the heater we discussed, carried on an extensive and thorough research about how to improve efficiency in the past decades.

In general, ways to enhance heat transfer can be classified into two types: passive and active techniques. The passive method, in which heating due to convection alone and needs no additional external power, such as extended surfaces, displaced enhancement devices, is concerned.

A typical structure of STHEs is shown in figure 1[1]. Baffles are widely used in STHEs for it improves heat transfer by forcing the shell-side fluid to flow in a tortuous, zigzag manner across the tube bundle, which can enhance turbulence and increase the shell-side flow channel[2]. Muley and Manglik[3]-[6] derived formulas for calculating the heat transfer coefficient of STHEs with various types of baffles experimentally, and pointed out that the non-uniform distribution of fluid is the main factor that affect performance. The tube has two kinds of arrangement, staggered and in-line bundle. According to Zhukauskas’ work[7], compared with the in-line bundle, the heat transfer performance of heat exchanger with staggered tube bundle is 20% higher, and the friction is 40% lower. OuYang and
Xiong compared the thermal performance of aligned and staggered arrangement, and came up with the conclusion that aligned arrangement is more appropriate under condition of large flow rate or friction of fluid is limited strictly.

With the rapid development of computer science, numerical simulation become popular in study of STHEs[[9]-[11]]. Taher et al.[[12]] simulated heat exchangers with helical baffles by using FLUENT, and found that the heat transfer efficiency decreases with the increase of baffle space.

Inspired by the research above, we proposed three ways, including changing space between belts, inserting baffles and using staggered belts bundle, to strengthen the belt-type heater’s heat transfer efficiency. Numerical simulation is used to verify the effectiveness of these methods.

2. Performance evaluation criteria

The enhancement of the heat transfer and the changing of drag losses need to be considered at the same time.

The Nusselt number $Nu$ is used to characterize the strength of convective heat transfer. $f$ stands for friction factor which represents the flow resistance of airflow.

$$Nu = \frac{hl}{\lambda}$$

(1)

$$f = \frac{dp}{dx} \frac{2d_e}{\rho u^2}$$

(2)

Webb[[13]-[15]] used the ratio of equation (5) as the Performance evaluation criteria for heat transfer enhancement (The subscript 0 stands for the benchmark model). And PEC is widely adopted in the field of heat transfer enhancement, such as enhanced surface [[16]-[18]], micro channel heat transfer[[19],[20]], tubes[[21],[22]].

$$PEC = \frac{Q}{Q_0} \left( \frac{Nu}{Nu_0} \right)^{1/3} \left( \frac{f}{f_0} \right)^{1/3}$$

(3)

Consequently, the Performance Evaluation Criteria (PEC) of heat transfer enhancement is adopted in this paper.

3. Numerical modelling

3.1. Model

This research set the Ф0.5m belt-type resistance heater in CARDC as the prototype. The structure of a heating box is shown in Figure 2. When the heater is working, belt-type resistances reach a high temperature dramatically after energized, meanwhile the airstream travel through the box axially and
been heated due to the huge temperature difference. The six-layer belt-type resistances, which are evenly distributed along the axis formed a heating unit together with the shell.

![Figure 2. Sketch of a heating box in different angles](image)

To improve the computational efficiency and make it more convenient to study the different enhancement methods, a two-dimensional model is built which mainly concern of the typical flow characteristic in axial direction. The physical model is 1:1 with the heater in Φ0.5m, and due to the symmetry of the model, half of the original heater is built shown in Figure 3. The direction of airflow is along the x axis.

![Figure 3. 2D model diagram](image)

### 3.2. Numerical Method
The simulation makes assumptions as follows:

1) Heat transfer mode is the forced convection heat transfer, and the heat radiation is neglected;
2) Ignore air gravity effect;
3) The heater shell is an adiabatic wall;

RNG k-ε engineering turbulent model and SIMPLEC algorithm is applied after selection. The grid number is 82,000 for the whole computational domain. Besides, boundary conditions of mass flow inlet and pressure outlet are used here, and the surface of the resistance belt is set as heat flux wall.
### 3.3. Numerical method validation

In order to validate the numerical method, considering the symmetry, the 1/4 3D model of 1:1 is built for numerical simulation as shown in Figure 4, to be compared with the experiment results of the Φ0.5m heater. And air flows the other way along the Z axis.

![Figure 4. 3D model diagram](image)

Table 1. shows four different calculate states. After simulation, the outputs are compared with data from Φ0.5m tunnel's experiment at the same state as shown in Table 2.

| State | Ma | $P_o$(Mpa) | Q(kg/s) | $T_0$(K) | P(KW) |
|-------|----|------------|--------|---------|-------|
| 1     | 5  | 1.0        | 15.4   | 288     | 296   |
| 2     | 5  | 2.0        | 30.0   | 288     | 805   |
| 3     | 6  | 2.0        | 12.1   | 303     | 801   |
| 4     | 6  | 5.0        | 29.2   | 303     | 2050  |

| State | 1     | 2     | 3     | 4     |
|-------|-------|-------|-------|-------|
| Experiment. | 309.55 | 315.55 | 367.61 | 369.30 |
| Simulation  | 304.25 | 310.51 | 359.96 | 362.61 |
| Absolute error | 5.30  | 5.04  | 7.65  | 6.69  |
| Relative error | 1.71%  | 1.60%  | 2.90%  | 1.81% |

Seen from the table above, overall numerical results are lower than the experimental results. More specifically, the absolute error of the highest is 7.65K. The reason that caused the error may be:

1) The error caused by model simplification
2) Inside of the heater, thermocouple measurement is a single point temperature, and numerical calculation results take the average temperature of the outlet, which caused an error;
3) Heat flux released by each layer of the electric heater should be different, but the calculation is set to be equal.

On the whole, the numerical calculation result is close to the experimental result at each state, and the relative error is less than 3%. So, the numerical simulation method is considered reliable.

### 4. Analysis of different heat transfer enhancement methods

According to the following three kinds of enhanced heat transfer means, heat transfer efficiency of varied internal arranged structures of heater are investigated with the two-dimensional model.
4.1. Changing spacing between resistance belts

Here defines the distance between two adjacent layers of the resistance belt gap as $m$ and the same layer resistance as $n$, and sketch is as follows. The effect of changing $m$ and $n$ on heat transfer is discussed.

![Figure 5. The 2D computational domain that illustrates the interval between two belts](image)

**Figure 5.** The 2D computational domain that illustrates the interval between two belts

4.1.1. Changing $m$.

Variables $m$ is investigated firstly. $m$ varies from 2mm to 16mm and the interval is 2mm. However, the value of $m$ in the benchmark model is 8mm. After calculation, a series of curves is obtained as shown in Figure.6.

![Figure 6. Output curve of changing $m$](image)

**Figure 6.** Output curve of changing $m$

From the perspective of heat transfer, that is curve of $Nu/Nu_0$ versus $m$, the value of $Nu/Nu_0$ under all size of $m$ is always greater than 1, except the case of $m=6mm$, and $Nu/Nu_0$ reach maximum when $m=2mm$. From the perspective of flow resistance, that is the curve of $f/f_0$ versus $m$, with the boundary of $m=8mm$, $f/f_0$ is greater than 1 when $m>8mm$,and $f/f_0$ is lower than 1 when $m<8mm$. The ratio of resistance factor generally increases as $m$ increases. Combining the two sides, curve of PEC versus $m$ indicate that, PEC is larger than 1 when $m<12mm$, and PEC increases when $m$ drops, which achieves maximum when $m=2mm$. It means that, when $m$ is getting smaller, PEC is becoming greater, and effect of enhanced heat transfer is getting better.

4.1.2. Changing $n$.

To study the effect of the variable $n$, the range of $m$ is set from 10mm to 25mm, and the interval is 3mm. Yet inside of the benchmark model, $n$ is unequal-spaced. The result from simulation is as follows:
4. Adding baffles

Adding baffles is frequently used in heat exchangers to improve heat transfer capability, because that it can lengthen the flow channel and change the direction of air flowing through resistance belts. Wondering whether this method is applicable for heater used in the hypersonic tunnel, a two-dimensional baffled model is established for calculation seen in Figure 8. And in which the height of the baffle plate is as follows:

\[ L = \frac{2}{3} D_s \]  

(4)

A complete model is built due to the loss of structural symmetry, and the direction of the flow is from left to right.

Figure 8. The two-dimensionial computational domain of heater with baffles

The results of calculation are summarized as follows. Contour of pressure and velocity on model adding baffles are shown in Figure 9 and Figure 10.
Pressure distribution is severely unevenly distributed, and it is decreasing along the flowing direction. Specifically, there exists a blockade at the entrance when the flow field width narrows, and pressure reaches about 5Mpa at the entrance, which is 250% bigger than the initial pressure. The velocity distribution is also uneven all over the domain, particularly at the exit, and even uneven. Meanwhile, vortex of various sizes is formed at the corner of the flow-path and the resistances’ leeside.

Specifically, according to the calculation we can get:

\[ \frac{Nu}{Nu_0} = 3.38 \] \hspace{2cm} (5)

\[ \frac{f}{f_0} = 9.51 \] \hspace{2cm} (6)

\[ PEC = \frac{Nu}{Nu_0} \left( \frac{f}{f_0} \right)^{1/3} = 1.60 \] \hspace{2cm} (7)

Obviously, the heat transfer efficiency and resistant factor both increase in the model adding baffles, and the resistant factor reaches more than nine times as before, which says that, the baffles bring more loss in energy as improving the heat transfer efficiency. And the Performance Evaluation Criteria attains 1.60, because compared to the original heater, heater with baffles produces lots of vortex when working, and vortex can remarkable improves the heat transfer, but causing energy dissipation as well. Furthermore, the airflow uniformity turns worse for baffles making the flow channel narrow.
4.3. Staggered arrangement heater

Aligned and staggered arrangements are classic arrangements which are used widely in shell-and-tube heat exchangers. The Φ0.5 heaters use the aligned type and here staggered model is established shown below, to be compared with the aligned one. The displacement $S$ of resistance bands in the even row can be expressed as follows:

$$S = \frac{1}{2} n$$

(8)

\[ \text{Figure 11. The two-dimensional computational domain of heater with staggered arrangements} \]

The calculated temperature contours of aligned and staggered models are shown in Figure 12. The air flows from top to bottom. In comparison with aligned one, heater in staggered arrangements have more flow paths among resistance belts. Thus, the airflow is heated evenly and flow field uniformities of temperature improves obviously.

\[ \text{Figure 12. Comparison of temperature distribution} \]

Besides:

$$Nu / Nu_0 = 1.54$$

(9)

$$f / f_0 = 2.24$$

(10)

$$PEC = \frac{Nu / Nu_0}{(f / f_0)^{1/3}} = 1.18$$

(11)
Seen from above, both of Nu and f for the staggered arrangement are bigger than the aligned one. And the PEC reaches 1.18, namely staggered arrangement has a certain effect on enhancing heat transfer. Because the area of airflow been heated is larger in the staggered heater than in the aligned model, the disturbance of airflow is strengthened which is helpful to heat transfer enhancement.

5. Conclusion
Study found that:

1) For changing spacing m and n, the smaller the interval, the greater the PEC, the better the heat transfer enhancement effect. However, when the heater is working, the resistance belt of high temperature being too close to each other may be harmful to the heater, such as reducing the resistor’s service life and causing circuit fault.

2) For adding baffles, the flow channel becomes S type, and the long edge of belts become to windward side, which lead to plenty of vortex. As a result, PEC reaches 1.60. Meanwhile, resistance factor increases to more than nine times than the benchmark model, that is, the energy loss extremely increases. And the sudden increased pressure at the entrance of the heater is dangerous when the wind tunnel is working. Lastly, the non-uniform flow field in heater is against the wind tunnel’s overall flow field quality.

3) For staggered arrangement resistance belt, it has more flow channels, and its area of airflow been heated become larger, and the disturbance of airflow is strengthened. On the whole, staggered arrangement has a certain effect on enhancing heat transfer for PEC being 1.18. Besides, the flow field uniformities improve obviously.

Thus, future we will focus on the experiment validation of staggered arrangement.

References
[1] M Rajiv. Effectively design shell and tube heat exchanger[J]. Chemical Engineering Progress. 94 (2) (1998), 21-37.
[2] P Stehlik, J Nemcansky, Dl Kral, LW Swanson. Comparison of correction factors for Shell-and-tube Heat exchangers with segmental or helical baffles. Heat transfer engineering. 15 (1) (1994), 55-65.
[3] A Muley, RM Manglik, Experimental study of turbulent flow heat transfer and pressure drop in a plate heat exchanger with chevron plates. Journal of heat transfer.121(1) (1999), 110-117.
[4] RM Manglik, AE Bergles, Heat transfer and pressure drop correlations for the rectangular offset strip fin compact heat exchanger. Experiment Thermal and Fluid Science. 10 (2) (1995), 171-180.
[5] RM manglik, AE Bergles. Heat transfer and pressure drop correlations for twist-tape inserts in isothermal tubes: Part II--Transition and turbulent flows. Journal of heat transfer. 115 (4) (1993), 890-896.
[6] RM manglik, AE Bergles. Heat transfer and pressure drop correlations for twist-tape inserts in isothermal tubes: Part I--laminar flows. Transaction-American Society of Mechanical Engineers Journal of Heat Transfer. 115 (1993), 881-881.
[7] AA Zhukauskas, Convective transfer in heat exchangers. Nauka, Moscow,1982.
[8] XP OuYang, GP Xiong. Comparison Study of Thermal Performance of Plate Fin Type Heat Exchangers with Aligned and Staggered Arrangements. Chinese Journal of Power Engineering. 2(25)271-274, 2015.
[9] JF Zhang, YL He, WQ Tao, 3D numerical simulation on shell and tube heat exchangers with middle-overlapped helical baffles and continuous baffles-Part I: Numerical model and results of whole heat exchanger with middle-overlapped helical baffles. Int. J. Heat and Mass Transfer. 52(2009)5371-5380.
[10] JF Zhang, YL He, WQ Tao, 3D numerical simulation on shell and tube heat exchangers with middle-overlapped helical baffles and continuous baffles-Part II:Simulation results of periodic model and comparison between continuous and noncontinuous helical baffles. Int. J. Heat and
Mass Transfer. 52(2009)5381-5389.

[11] JJ Liu, ZC Liu, W Liu, 3D numerical study on shell side heat transfer and flow characteristics of rod-baffle heat exchangers with spirally corrugated tubes. Int. J. Thermal Sciences. 89 (2015) 34 - 42.

[12] FN Taher, SZ Movassag, K Razmi, RT Azar. Baffle space impact on the performance of helical baffle shell and tube heat exchangers. Applied Thermal Engineering. 44 (2012) 143 - 149.

[13] R L Webb. Principle of enhanced heat transfer, John Wiley & Sons, Inc. New York, 1994.

[14] R L Webb. Performance evaluation criteria for use of enhanced heat transfer surfaces in heat exchanger design, Int. J. Heat and Mass Transfer. 24 (4) (1981) 715 - 726.

[15] R L Webb and M J Scott, A parametric analysis of the performance of internally finned tubes for heat exchanger application, Int. J. Heat Transfer. 102 (1980), 38 - 43.

[16] V D Zimparov, N L Vulchanov. Performance evaluation criteria for enhanced heat transfer surfaces, Int. J. Heat and Mass Transfer. 37 (12) (1994) 1807 - 1816.

[17] V D Zimparov, Extended performance evaluation criteria for enhanced heat transfer surfaces: heat transfer through ducts with constant wall temperature, Int. J. Heat and Mass Transfer. 43 (17) (2000) 3137-3155.

[18] V D Zimparov, Extended performance evaluation criteria for enhanced heat transfer surfaces: heat transfer through ducts with constant heat flux, Int. J. Heat and Mass Transfer. 44 (1) (2001) 169 - 180.

[19] L Chai, G D Xia, H S Wang, Numerical study of laminar flow and heat transfer in microchannel heat sink with offset rib on sidewalls, Int. J. Applied Thermal Engineering. 92 (2016), 32 - 41.

[20] Y F Li, G D Xia, D D Ma, Y T Jia, J Wang, Characteristics of laminar flow and heat transfer in microchannel heat sink with triangular cavities and rectangular ribs, Int. J. International Journal of Heat and Mass Transfer. 98 (2016), 17-28.

[21] Z Huang, GL Yu, ZY Li, WQ Tao, Numerical study on heat transfer enhancement in a receiver tube of parabolic trough solar collector with dimples, protrusions and helical fins, Energy Procedia. 69 (2015), 1306-1316.

[22] X B Zhao, G H Tang, XW Ma, Y Jin, WQ Tao, Numerical investigation of heat transfer and erosion characteristics for H-type finned oval tube with longitudinal vortex generators and dimples. Applied energy. 127 (2014), 93 - 104.