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Sensitivity Analysis of Design Parameters in Transverse Flux Induction Heating Device

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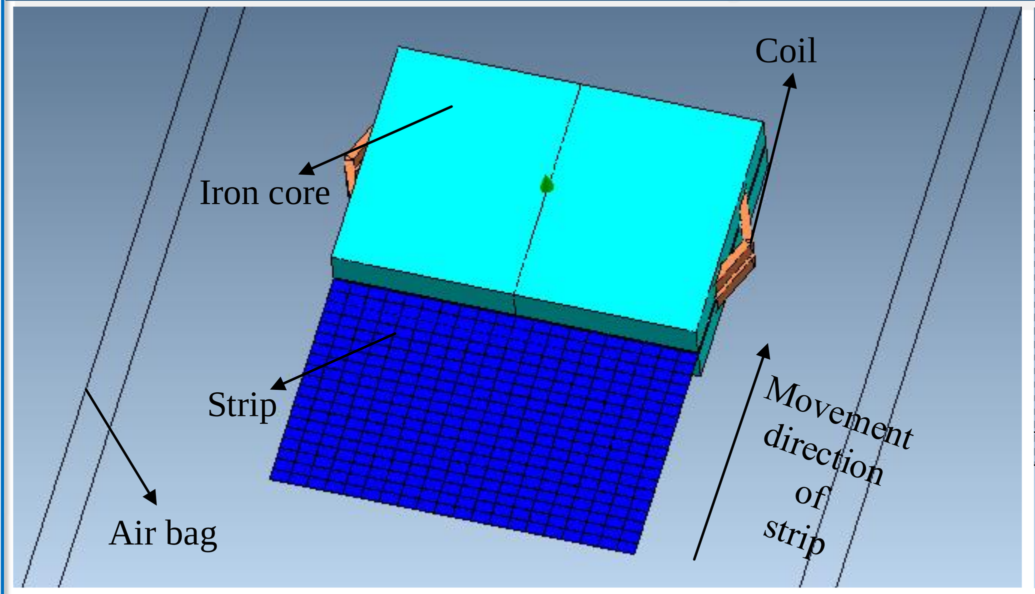
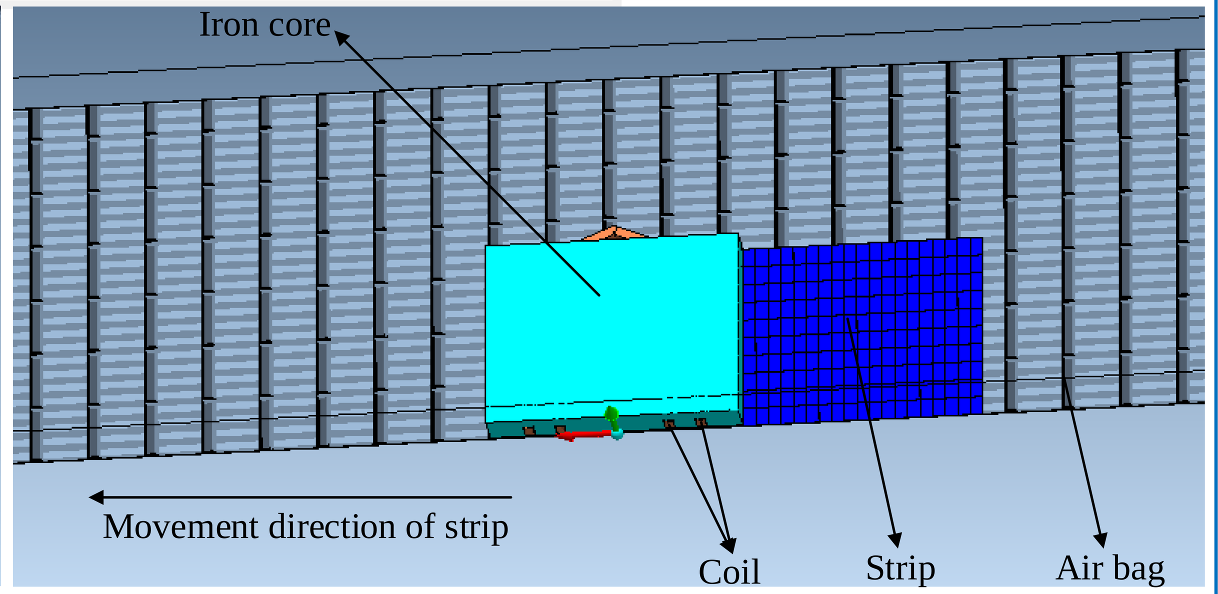
1. Introduction

- In the heating strip (e.g. steel) industry, the transverse flux induction heating (TFIH) technology is widely used. However, TFIH still have problems of uneven temperature distribution on the strip surface at the outlet of heater and the heating efficiency is lower, which need to be solved.
- For solving above problems, the design parameters of TFIH device need to be optimized or changed. But when the non-significant design parameters are selected or the number of design parameters is large, the optimization time will be very long.
- In this paper, Morris method of qualitative global sensitivity analysis (GSA) is used to rank the sensitivity values between the four design parameters (the effective value of the exciting current (I_E), the frequency of the exciting current (f_E), the moving speed of the strip (V_s), the length of the coil (L_c)) and the three objective functions (the relative non-uniformity (T_{rel}), the average temperature (T_{av}), the heating efficiency (η)) of TFIH device. It provides an optimal priority for the optimization or change of the design parameters of TFIH device, and thus the optimization time can be reduced greatly.

2. Simulation model of TFIH device



(a)



(b)

Fig. 1. Simulation model of TFIH device, (a) the full model, and (b) the 1/4 model

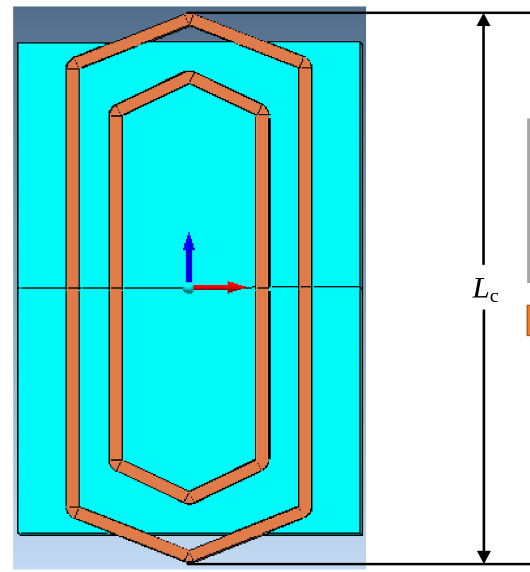


Fig. 2. Double-layer hexagonal coil structure

Temperature distribution is quit uniform at heater outlet with the utilization of this kind of coil structure

heater outlet

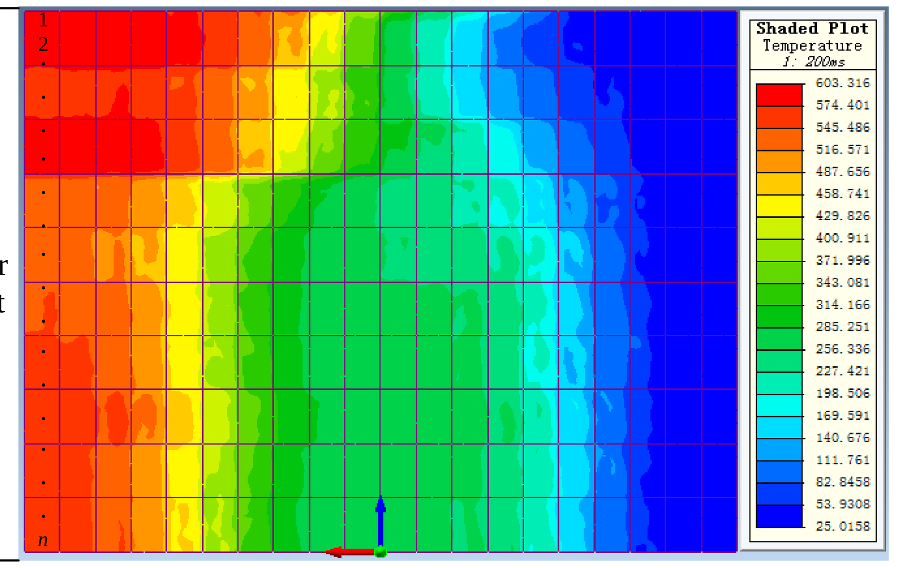


Fig. 3. The nephogram of temperature distribution

3. Objective functions of TFIH device

For TFIH device, the average temperature T_{av}, the relative non-uniformity T_{rel} and heating efficiency η are very important which are regarded as the objectives.

- T_{av} can be represented by

$$T_{av} = \frac{\sum_{i=1}^{n} T[i]}{n} \tag{1}$$

where $T[i]$ is the temperature value of the i sampling point and n is the sample number.

- T_{rel} can be calculated by

$$T_{rel} = \frac{\sum_{i=1}^{n} |T[i] - T_{av}|}{n T_{av}} \times 100\% \tag{2}$$

- η is calculated by

$$\eta = \frac{Q}{W} \times 100\% \tag{3}$$

where Q is the eddy current loss on the surface of the strip in time t, W is the input excitation in the same time.

4. Morris method and its application in TFIH

When there are y design parameters, the matrix $\mathbf{A}$ of $(y+1)\times y$ is constituted as the input matrix of the device or system researched by selecting $y+1$ group of vectors as follows

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ 1 & 0 & 0 & \dots & 0 \\ 1 & 1 & 0 & \dots & 0 \\ 1 & 1 & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 1 & 1 & 1 & \dots & 1 \end{bmatrix} \begin{matrix} \rightarrow \mathbf{x}_0 \\ \rightarrow \mathbf{x}_1 \\ \rightarrow \mathbf{x}_2 \\ \rightarrow \mathbf{x}_3 \\ \rightarrow \dots \\ \rightarrow \mathbf{x}_y \end{matrix} \quad (\text{columns } x_1\ x_2\ x_3\ \dots\ x_y) \tag{4}$$

In the input matrix $\mathbf{A}$, 0 means the initial value of each design parameter, and 1 means the values of each design parameter after change.

- Formula for calculating individual sensitivity (select the design parameters from two adjacent rows)

$$S_{x_{i+1}} = \frac{F(\mathbf{x}_{i+1}) - F(\mathbf{x}_i)}{\Delta x_{i+1}} \tag{5}$$

- Formula for calculating combined sensitivity (the performance of the design parameters from two non-adjacent rows needs to be calculated)

$$S_{x_{j+1} \dots x_k} = \frac{F(\mathbf{x}_k) - F(\mathbf{x}_j)}{|\mathbf{x}_k - \mathbf{x}_j|} \tag{6}$$

- Different design parameters have different units, to make the sensitivity values of different design parameters are comparable, thus the sensitivity needs to be normalized by

$$S = \frac{\Delta F(\mathbf{x})}{F(\mathbf{x})} \times \frac{1}{\delta} \tag{7}$$

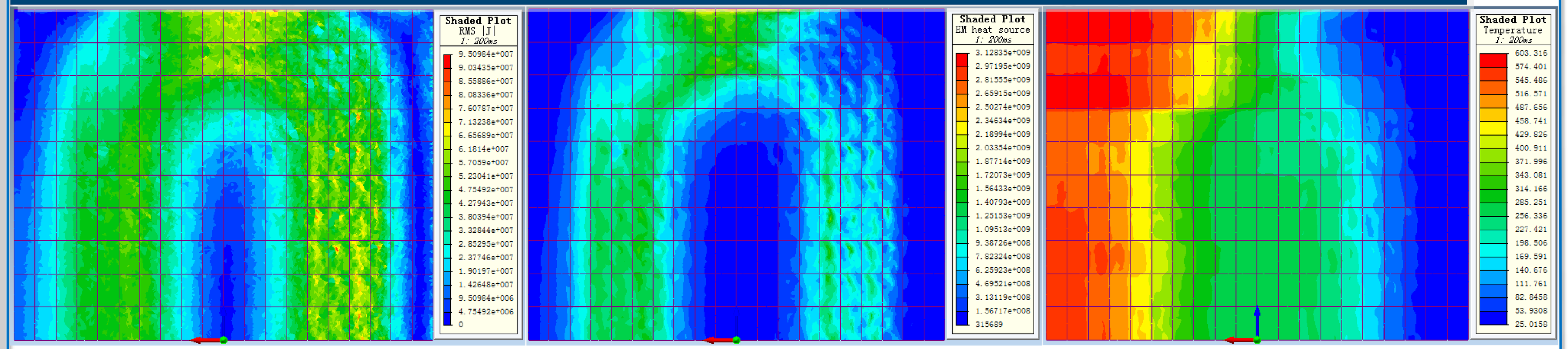
According to the above principle, for TFIH device, Tab. 1 tabulates the required samples of four design parameters.

Tab. 1. The required samples of Morris method

Design parameters	Amplitude variations of parameter (δ)				
	-20%	-10%	0	10%	20%
I_E (A)	800	900	1000	1100	1200
f_E (Hz)	400	450	500	550	600
V_s (m/s)	0.08	0.09	0.1	0.11	0.12
L_c (mm)	536	603	670	737	804

5. Computational results and conclusion

5.1. Heating results under the setting of initial design parameters



(a) (b) (c)

Fig. 4. Distribution nephogram of the strip surface, (a) the eddy current distribution, (b) the heat source distribution, and (c) the temperature distribution

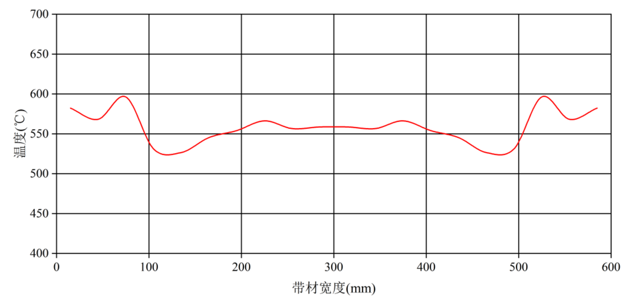


Fig. 5. Temperature distribution curve at heater outlet

Tab. 2. The heating data of the strip

Sample group	T_{av} (℃)	T_{rel} (%)	η (%)
Initial design parameters	558.5	2.83	55.1

Based on the above calculation results, it can be seen that the temperature distribution is still uneven and η is not so high under the setting of initial design parameters. Therefore, it is necessary to analyze the sensitivities between design parameters and objective functions.

5.2. Results of sensitivities calculation and analysis

Individual sensitivities

Tab. 3. The individual sensitivities between the four design parameters and T_{av}

Design parameters	Amplitude variations of parameter (δ)					Individual sensitivity
	-20%	-10%	0	10%	20%	
I_E	1.9463	2.0591	0	2.1146	2.1146	2.0587
f_E	0.4852	0.4780	0	0.5055	0.7569	0.5564
V_s	-1.2890	-1.1224	0	-0.8652	-0.9355	1.0530
L_c	0.3085	0.1341	0	0.1648	0.0242	0.1579

conclusion 1:

$|I_E|>|V_s|>|f_E|>|L_c|$

Tab. 4. The individual sensitivities between the four design parameters and T_{rel}

Design parameters	Amplitude variations of parameter (δ)					Individual sensitivity
	-20%	-10%	0	10%	20%	
I_E	-2.4205	-3.3922	0	-2.7915	-1.0424	2.4117
f_E	0.7143	1.2401	0	0.4902	0.1339	0.6446
V_s	0.5972	0.5723	0	2.3832	0.4348	0.9969
L_c	-41.2145	-33.2907	0	38.3396	32.1600	36.2512

$|L_c|>|I_E|>|V_s|>|f_E|$

Tab. 5. The individual sensitivities between the four design parameters and η

Design parameters	Amplitude variations of parameter (δ)					Individual sensitivity
	-20%	-10%	0	10%	20%	
I_E	0.8621	1.0345	0	1.6878	0.5626	1.0368
f_E	-0.1206	-0.0405	0	0.6211	-1.2643	0.5116
V_s	-0.1927	-0.2823	0	-0.9503	3.3406	1.1915
L_c	-0.7113	-1.0000	0	-0.9693	-1.0733	0.9385

$|V_s|>|I_E|>|L_c|>|f_E|$

Combined sensitivities

Tab. 6. The combined sensitivities between the four design parameters and T_{av}

Design parameters	Amplitude variations of parameter (δ)					Combined sensitivity
	-20%	-10%	0	10%	20%	
I_E	1.9463	2.0591	0	2.1146	2.1146	2.0587
f_E	2.2426	2.4387	0	2.7269	3.1916	2.6500
V_s	1.5318	1.5900	0	1.6258	1.6589	1.6016
L_c	1.7457	1.7028	0	1.8174	1.6911	1.7393

Tab. 7. The combined sensitivities between the four design parameters and T_{rel}

Design parameters	Amplitude variations of parameter (δ)					Combined sensitivity
	-20%	-10%	0	10%	20%	
I_E	-2.4205	-3.3922	0	-2.7915	-1.0424	2.4117
f_E	-1.3604	-1.7314	0	-2.4382	-0.9364	1.6166
V_s	-0.6007	-1.0601	0	-0.6360	-0.5830	0.7200
L_c	-46.7668	-37.8799	0	35.2650	27.8269	36.9347

conclusion 2:

For these three objective functions, there are certain correlations between the design parameters, but the correlations are not strong.

Tab. 8. The combined sensitivities between the four design parameters and η

Design parameters	Amplitude variations of parameter (δ)					Combined sensitivity
	-20%	-10%	0	10%	20%	
I_E	0.8621	1.0345	0	1.6878	0.5626	1.0368
f_E	0.7623	0.9982	0	2.4138	-0.8439	1.2546
V_s	0.5989	0.7441	0	1.2341	1.9328	1.1275
L_c	-0.0272	-0.1815	0	0.1452	0.4446	0.1996

6. References

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