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Optimization and experimental study of thermal coring parameters for detecting lunar water ice



Yinchao Wang^{1,*}, Junnan Han¹, Feng Wang², Zonghao Pan¹, Tianqi Wang¹, Weiwei Zhang², Guanghong Tao¹ and Chunying Jiang¹

¹ School of Aerospace Engineering, Shenyang Aerospace University, Shenyang, China

² School of Mechanical and Electrical Engineering, Harbin Institute of Technology, Harbin, China

* Correspondence author; E-mail: wangyinchao2008@126.com.

Abstract: To address the challenges of in-situ lunar water-ice extraction—including limited extraction range, low efficiency, and high energy consumption—this study proposes a thermal drill-based water-ice extraction method utilizing induction heating. Using the Box-Behnken design, response surface methodology, and a multiphysics coupled model, the influences of four key parameters—drill needle diameter, current frequency, coil turn number, and rated input power—are systematically analyzed. The NSGA-II multi-objective optimization algorithm was adopted to obtain the Pareto optimal solution set. This research presents an innovative, parameterized design methodology for the efficient, low-energy extraction of lunar water ice.

Keywords: Lunar water ice; induction heating; multi-objective optimization; response surface methodology; heat transfer characteristics

1. Introduction

The water ice resources contained in the permanent shadow region of the lunar polar region are an important material basis for the construction of future lunar research stations [1–3]. However, the low temperature and high vacuum environment of the lunar polar regions, in conjunction with the low thermal conductivity of the lunar soil, result in the inefficiency and high energy consumption of conventional thermal extraction methods. Consequently, there is an urgent need to develop new extraction technologies. Induction heating has demonstrated significant potential for application due to its advantageous characteristics, including non-contact, high efficiency, and ease of control.

A plethora of water ice extraction schemes have been proposed worldwide [4]. Duke *et al.* [5] first proposed a solar-powered microwave heating scheme for lunar polar ice extraction. Sowers and Dreyer [6] conceptualized the framework of thermal mining for lunar permanently shadowed regions. On this basis, Zacny *et al.* from Honeybee Robotics [7–8] developed a series of engineering prototypes for in-situ water ice prospecting and extraction. Brisset *et al.* [9] established a 3D numerical model (Figure 1) for thermal extraction of lunar water ice and proposed a long drill-needle heating extraction scheme. However, the above



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methods still have obvious limitations in terms of effective extraction range, heating efficiency, and system energy consumption under the extreme lunar environment.

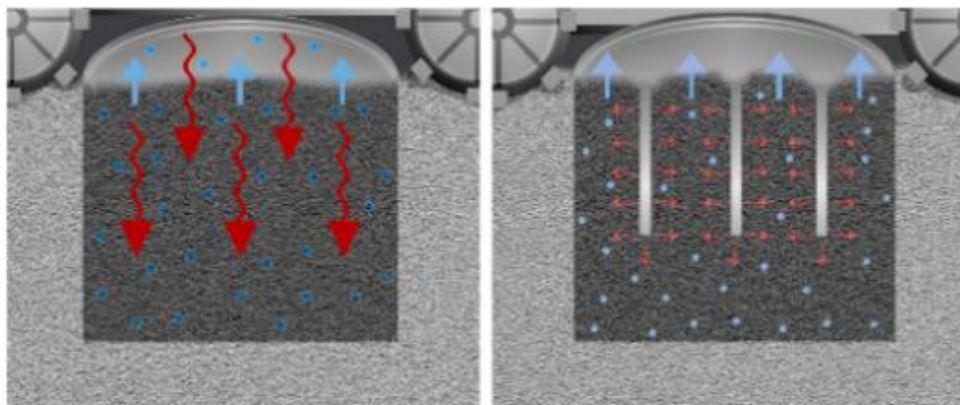


Figure 1. Illustration of the water ice extraction scheme proposed by Brisset's team.

To overcome these limitations, an induction-heating-based extraction approach offers a promising pathway, given its non-contact operation, high energy conversion efficiency, and precise controllability in vacuum environments. This paper therefore proposes a novel group-needle induction heating extraction method. The research object is a single drill needle. The response surface method and Non-dominated Sorting Genetic Algorithm II (NSGA-II) multi-objective optimization algorithm are used to systematically optimize the four key parameters of the drill needle: diameter, current frequency, coil turn number, and pin. The paper reveals the coupling influence law of these parameters on the volume, power consumption, temperature uniformity, and heating rate. The objective is to provide a design basis for the efficient and low-consumption extraction of lunar water ice.

2. Design of extraction scheme for lunar water ice resources

The group-needle in-situ thermal extraction scheme proposed in this paper (Figure 2) adopts the integrated design concept of "drilling-thermal conductivity-sealing-trapping," and realizes the efficient and controllable mining of lunar soil water ice through the coordinated operation of array fine-diameter drill needles. The single needle constitutes the core terminal that reacts with lunar soil water ice, and its performance directly determines the overall efficiency and energy consumption of the system. In this paper, the focus is on a single drill needle as the research object. The objective is to ensure the structural strength while pursuing the multi-objective collaborative optimization with the largest affected volume, the lowest power consumption, the most uniform temperature distribution, and the fastest heating rate. This approach provides a theoretical basis for the parameter configuration of the group needle system.

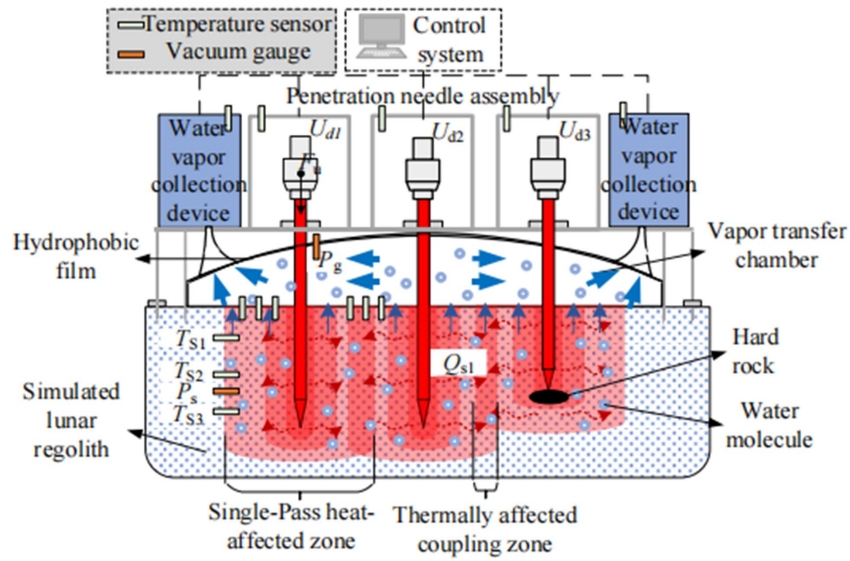


Figure 2. Schematic diagram of the multi-needle in-situ thermal extraction scheme.

3. Study on the efficiency of single-needle induction heating

3.1. Theoretical model of transient heat transfer in hot drilling

The research object of this model is a single drill needle. The needle is modeled as a slender cylindrical rod with uniform cross-section, and heat transfer is considered only along the axial direction (x-axis), reducing the problem to one dimension. This simplification is valid because the needle's diameter (6–8 mm) is much smaller than its length (400 mm), and the radial temperature gradient within the needle is negligible compared to the axial gradient. Heat is generated internally by electromagnetic induction and dissipated from the outer surface to the surrounding lunar vacuum environment via thermal radiation, as convective heat transfer is absent in the near-vacuum lunar polar conditions (pressure below 10^{-10} Pa). The establishment of a one-dimensional axial heat transfer control equation is predicated on the principle of energy conservation:

$$\rho c \frac{\partial T(x, t)}{\partial t} = \lambda \frac{\partial^2 T(x, t)}{\partial x^2} + q_v(x, t) - \frac{2}{r_0} \varepsilon \sigma [T(x, t)^4 - T_\infty^4] \quad (1)$$

Where:

ρ : Density of the drill needle material, unit: kg/m^3 ;

c : Specific heat capacity of the drill needle material, unit: $\text{J}/(\text{kg} \cdot \text{K})$;

$T(x, t)$: Absolute temperature of the drill needle at axial position x and time t , unit: K ;

x : Axial coordinate along the drill needle, unit: m ;

t : Heating time, unit: s ;

λ : Thermal conductivity of the drill needle material, unit: $\text{W}/(\text{m} \cdot \text{K})$;

$q_v(x, t)$: Volumetric heat generation rate of the drill needle induced by induction heating at position x and time t , unit: W/m^3 ;

r_0 : Outer radius of the drill needle, unit: m ;

ε : Surface emissivity of the drill needle;

σ : Stefan-Boltzmann constant, taken as $5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$;

T_∞ : Absolute ambient temperature of the lunar vacuum environment, unit: K.

Using the explicit finite difference method to solve the discrete solution, the node temperature update formula is:

$$T_i^{n+1} = T_i^n + \frac{\lambda \Delta t}{\rho c \Delta x^2} (T_{i-1}^n - 2T_i^n + T_{i+1}^n) + \frac{\Delta t}{\rho c} q_v(x_i, t^n) - \frac{2\Delta t}{r_0 \rho c} \varepsilon \sigma (T_i^n)^4 - T_\infty^4 \quad (2)$$

where:

T_i^n : Absolute temperature of the i -th spatial node at the n -th time step, unit: K.

Δx : Spatial step size of the finite difference discretization, unit: m;

Δt : Time step size of the finite difference discretization, unit: s;

x_i : Axial coordinate of the i -th spatial node, unit: m;

t_n : Time corresponding to the n -th time step, unit: s.

The model parameters are as follows: drill needle length 400 mm, diameter 7 mm, material 45 steel (thermal conductivity 50 W/(m·K), specific heat capacity 500 J/(kg·K), density 7850 kg/m³), ambient temperature 299.15 K (corresponding to 26 °C), surface emissivity 0.5.

3.2. Simulation model construction

A thermal-electromagnetic-thermal multiphysics coupling model, as demonstrated in Figure 3, is established based on COMSOL Multiphysics (COMSOL). The drill needle is simplified to a cylinder without a chip tank, and the thermal physical properties of the lunar soil are set as a function of temperature. The brown area indicates the lunar soil, the blue area indicates the vacuum environment, the red area indicates the induction heating coil, the gray area indicates the drill needle, and the black dot indicates the position of the temperature control point. The parameters used in the simulation are shown in Table 1. The temperature-dependent thermal conductivity λ_y and specific heat capacity C_y of lunar soil with 5 wt% water ice content are derived from dry lunar regolith parameters using the volumetric mixing model, following the methodology of Wasilewski *et al.* [10]



Figure 3. Schematic of the simulation model built in COMSOL.

Table 1. Main parameters of the simulation model.

Parameter Type	Symbol	Values and units	Description
Geometry parameters	R	1000 mm	Lunar soil simulation domain radius
	H	400 mm	Lunar soil height
Material parameters	λ_y	$6.65 \times 10^{-6} T + 0.11 \text{ W/(m}\cdot\text{K)}$	Thermal conductivity of lunar soil
	C_y	$2.402T + 76.31 \text{ J/(kg}\cdot\text{K)}$	The specific heat capacity of the lunar soil
	ρ_y	1850 kg/m ³	Lunar soil density
Induction heating parameters	f	50 kHz	Current frequency
	N	10	Number of turns of the coil
	P _{in}	15 W	Induction coil power

3.3. Response surface analysis that affects volume

Factor levels were determined based on physical constraints and preliminary experiments: frequency 30–70 kHz (skin effect range), turns 5–15 (balance between compactness and inductance), diameter 6–8 mm (trade-off between strength and thermal inertia), and power 10–20 W (considering energy consumption and heating requirements). A Box-Behnken design was adopted to construct a four-factor, three-level response surface model. The simulation was performed in COMSOL Multiphysics using a thermal-electromagnetic-thermal multiphysics coupling model, with lunar soil thermophysical properties defined as temperature-dependent and boundary conditions consistent with the theoretical model. Two power parameters are defined to avoid symbol confusion: (1) Rated coil input power P_{in} (independent variable, 10–20 W), the instantaneous P_{in} of the induction coil; (2) Cycle-averaged power consumption P_{avg} (optimization response), the system’s average power over a full temperature-controlled cycle, which is lower than P_{in} due to intermittent power-off during temperature holding.

Based on quadratic regression fitting of the experimental data, the ANOVA results for the four response indicators are summarized in Table 2. All models were highly significant ($p < 0.0001$) with non-significant lack-of-fit, indicating good predictive capability within the experimental range. The R² values were 0.997, 0.645, 0.952, and 0.983, respectively; all models except the P_{avg} model explained over 95% of the response variation. The lower R² (0.645) of the P_{avg} model arises from nonlinear interference of the closed-loop temperature control, which is not fully covered by the quadratic regression. The model remains highly significant ($p < 0.0001$) and can reliably characterize parameter influence trends for subsequent optimization.

Table 2. ANOVA summary of response surface models

Response	Model p -value	R ²	Significant Main Effects	Significant Interactions
Affected volume	< 0.0001	0.997	A, B, C, D	AC, BD
Cycle-averaged power consumption P _{avg}	< 0.0001	0.645	A, B, C	None
Axial temperature extreme difference	< 0.0001	0.952	B, C, D	BC, BD, CD
Heating rate	< 0.0001	0.983	A, B, C, D	BC, BD, CD

The regression equation for the four response indicators (with only salient terms retained) is as follows:

Affected volume: $V = 1.683 \times 10^7 - 6.547 \times 10^5 A - 2.101 \times 10^6 B - 4.630 \times 10^5 C + 2.877 \times 10^6 D - 2.878 \times 10^5 AC - 3.755 \times 10^5 BD + 3.255 \times 10^5 B^2 - 4.700 \times 10^5 D^2$

Cycle-averaged power consumption: $P_{avg} = 9.89 - 0.663A - 1.70B + 1.16C$

Temperature range: $\Delta T = 281.11 + 9.12B - 8.31C + 12.04D + 4.19BC - 6.85BD + 8.13CD + 6.32D^2$

Heatingrate: $R = 0.212 + 0.045A + 0.138B - 0.112C + 0.180D - 0.055BC + 0.091BD - 0.060CD$

The above regression equations are established based on coded values of independent variables, where -1 , 0 and 1 represent the low, center and high levels of each parameter, respectively. The equation coefficients can directly reflect the influence degree of each factor on the response indicators.

3.4. Analysis of parameter influence law

Based on the regression model coefficient and significance, the influence of the four parameters on each performance index is summarized as follows:

Affected volume: Coil power (D) is the most significant positive factor (coefficient $+ 2.88 \times 10^6$); increasing power directly expands the heat-affected zone. The number of coil turns (B) is the strongest negative factor (coefficient $- 2.10 \times 10^6$), because more turns increase inductance, reducing the working current under power excitation and thus weakening the heating effect. The BD interaction (coefficient $- 3.76 \times 10^5$) indicates that combining high power with many turns diminishes the positive effect. Optimization direction: use low turns (5–8), low frequency (30 kHz), and small diameter (6 mm).

Power consumption: Coil turns (B) is the most effective means of reducing P_{avg} (coefficient $- 1.70$), diameter (C) significantly increases it (coefficient $+ 1.16$), and frequency (A) offers slight energy savings (coefficient $- 0.66$). Optimization direction: prioritize increasing turns (10–15) while moderately increasing frequency and reducing diameter.

Temperature uniformity: Power (D) is the primary factor worsening temperature unevenness (coefficient $+ 12.04$), whereas diameter (C) effectively improves uniformity (coefficient $- 8.31$). The key BD interaction (coefficient $- 6.85$) indicates that increasing turns at high power can partially offset the negative effect. Optimization direction: prioritize reducing power and increasing diameter; when using high power, simultaneously increase turns.

Heating rate: Power (D) and turns (B) both significantly promote heating (coefficients $+ 0.180$ and $+ 0.138$), with a positive synergistic effect (BD interaction coefficient $+ 0.091$)—the combined effect far exceeds the sum of individual effects. Diameter (C) significantly reduces the heating rate (coefficient $- 0.112$). Optimization direction: increase both power and turns (e.g., 20 W + 15 turns) while using a small diameter.

The optimization objectives are set as: maximize the affected volume and heating rate, and minimize the cycle-averaged power consumption P_{avg} and axial temperature extreme difference. The NSGA-II algorithm is employed to address the problem of conflicting objectives, which include affected volume, power consumption, temperature extreme difference, and heating rate. The population size is 200, and 500 iterations are completed. Four regression equations are utilized as objective functions. The Pareto optimal solutions, a total of 200, are obtained through optimization, and the frontier projection is illustrated in Figure 4. The affected volume demonstrates a positive correlation with P_{avg} (Figure A), a conflict with temperature uniformity (Figure B), and a strong positive correlation with the heating rate (Figure C).

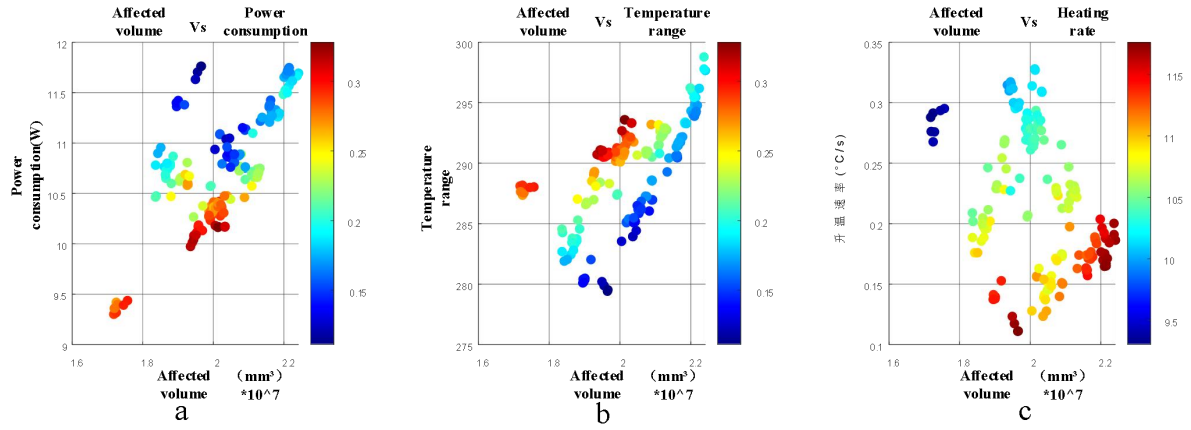


Figure 4. Scatter plot of the Pareto front for multi-objective optimization.

As illustrated in Figure 5, the distribution of decision space indicates that the optimal solution is concentrated in the region characterized by higher coil power and a lower number of turns.

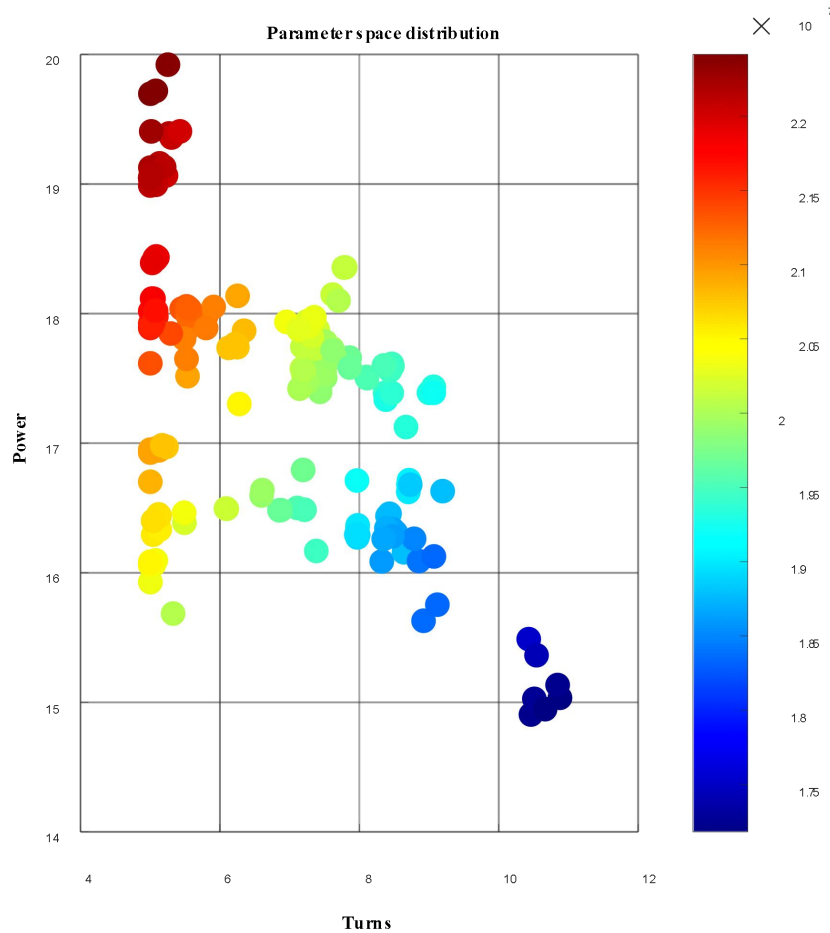


Figure 5. Two-dimensional projection of the Pareto front.

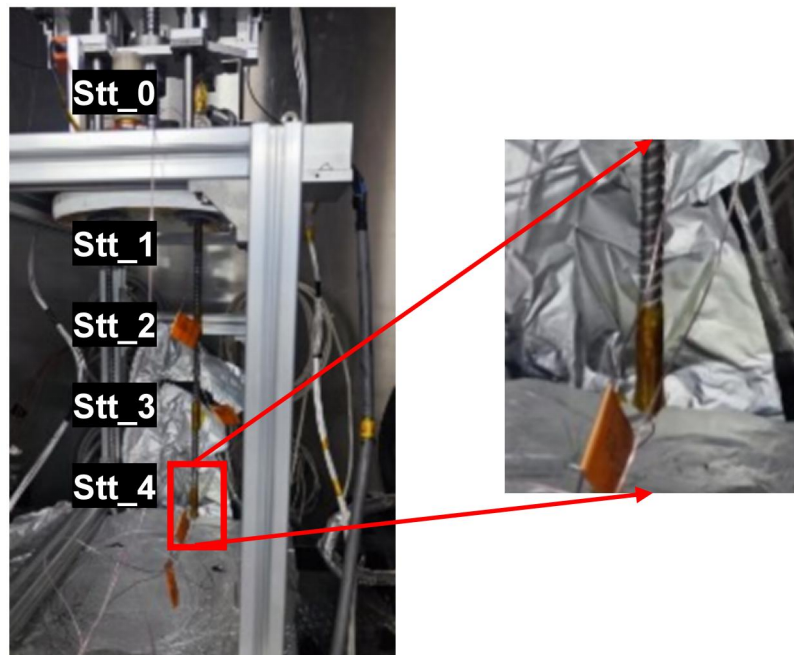
Four representative schemes are selected from the solution set (Table 3), which can be selected directly according to the task requirements.

Table 3. Representative Pareto optimal solutions.

Number	Parameter Combination	Affected Volume (mm ³)	Pavg (W)	Temperature Difference (°C)	Heating Rate (°C/s)	Characteristic Description
P1	A = 30, B = 5, C = 6, D = 20	2.25 E + 07	12.5	285.0	0.30	Mass extraction
P2	A = 70, B = 15, C = 8, D = 10	1.45 E + 07	6.8	260.5	0.05	Low power consumption
P3	A = 50, B = 10, C = 7, D = 15	1.85 E + 07	9.5	275.2	0.20	Balanced type
P4	A = 30, B = 15, C = 6, D = 20	1.70 E + 07	7.2	282.5	0.85	Speed type

4. Induction heating efficiency test

The laboratory prototype was utilized to conduct the vacuum (1 Pa) empty needle induction heating test, with an ambient temperature of 26 °C and a controlled temperature of 200 °C for a duration of 1.5 hours. The measurement of temperature is facilitated by five temperature measurement points that are arranged on the drill needle (Figure 6). A comparison between the experimental data and simulation results shows that the maximum relative error is less than 8%, and the average root mean square error is 7.07 °C (accounting for 3.5% of the controlled temperature value). This finding verifies the reliability of the theoretical model and simulation method.

**Figure 6.** Schematic diagram of the induction heating experimental setup.

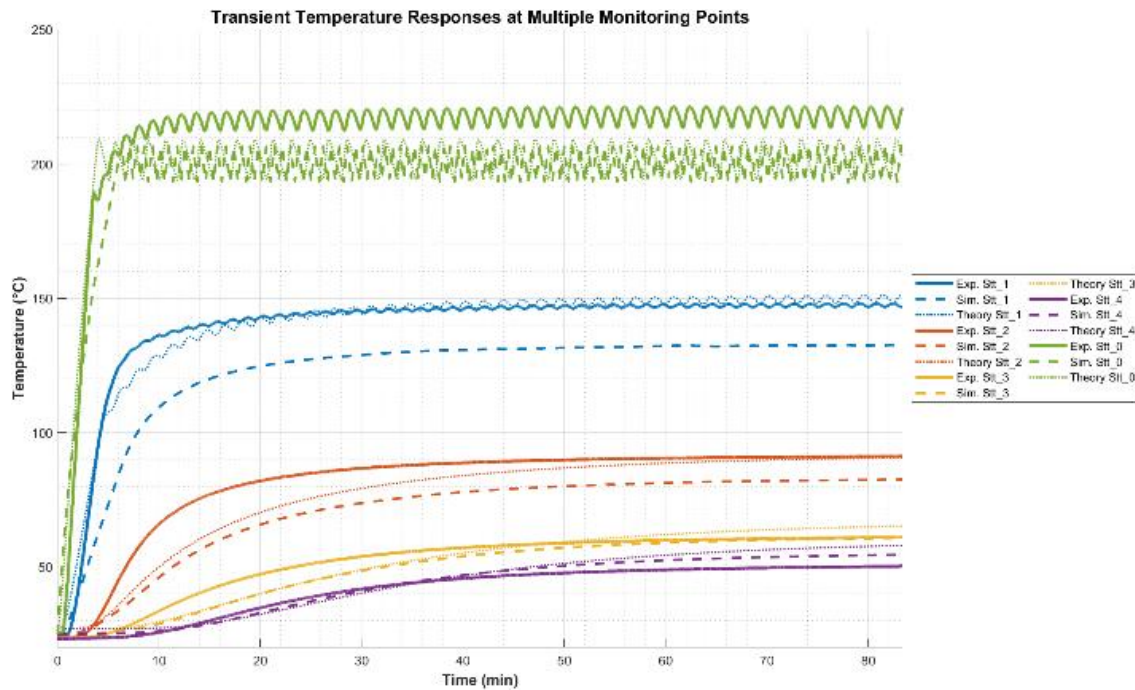


Figure 7. Comparison of temperature curves at monitoring points under 200 °C control.

5. Conclusions and prospects

The proposed group needle induction heating extraction scheme is examined, and its feasibility is validated through a combination of theoretical analyses, simulations, and experimental trials.

The response surface method was employed to ascertain the coupling influence law of drill needle diameter, current frequency, coil turn number, and power on the affected volume, power consumption, temperature uniformity, and heating rate. Consequently, a high-precision prediction model was established.

The Pareto optimal solution set is obtained based on the NSGA-II algorithm, providing a directly selectable parameter configuration scheme for different task requirements (e.g., sampling priority, long-term observation, rapid detection, *etc.*).

Declaration of Generative AI and AI-assisted Technologies

In preparing this manuscript, the author employed generative AI tools exclusively to refine the paper's language, grammar, spelling, and readability. These tools were not utilised to generate the research content, data analysis, experimental results, or academic viewpoints. The research design, experimental procedures, analysis of results, and final content of this paper were all independently completed by the author, who assumes full responsibility for the paper's integrity, originality, and accuracy.

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Authors' contribution

Conceptualization, Y.W.; Methodology, Y.W.; Writing-Original Draft, J.H.; Data Curation, F.W.; Visualization, Z.P. and T.W.; Software, J.H.; Supervision, W.Z.; Resources, W.Z. and G.T.; Writing-Review & Editing, Y.W.; Investigation, C.J.; Validation, W.Z. All authors have read and agreed to the published version of the manuscript.

Conflicts of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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