



答辯題目：飛行器中熱電結構的設計與實驗研究

指導教師：于佳 副教授

答辯人：王娇然 2015028121 (252班)



## 研究背景



## 热电原理介绍



## 主要研究内容



## 总结



## 主要参考文献

- ◆ 热电耦合数值模拟
- ◆ 热电性能实验
- ◆ 直升机喷管热电模块设计

## 第一部分

# 研究背景与意义



图1-武装直升机(左：陆航米171型；右上：中-直10；右下：  
可调节战斗机尾喷管)

温差发电应用：  
武装直升机**红外隐身**；  
喷管**废热回收处理**。

## ● 研究背景与意义 |

碲化铋(Bi<sub>2</sub>Te<sub>3</sub>)基热电材料

工作温度： $\Delta T = 150^\circ\text{C}$

优点：**无噪音、功率重量比大**

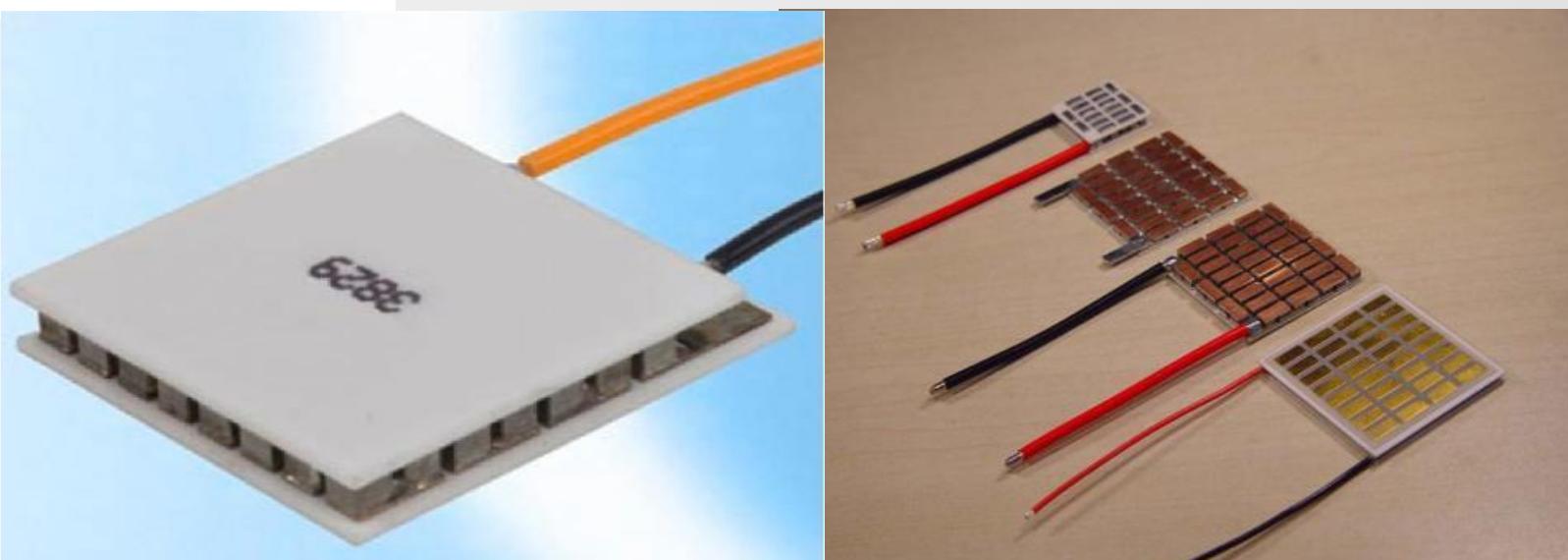


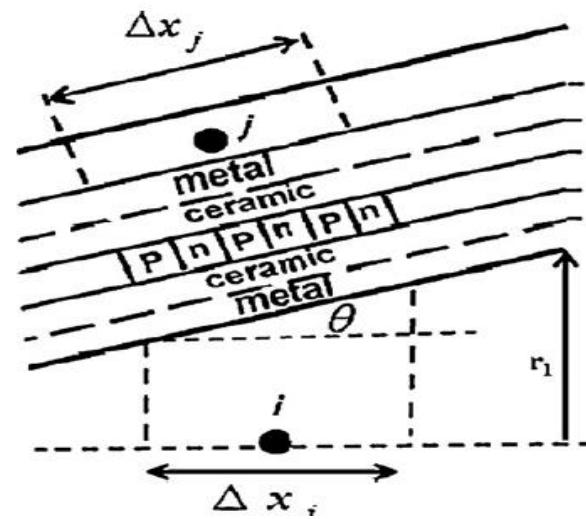
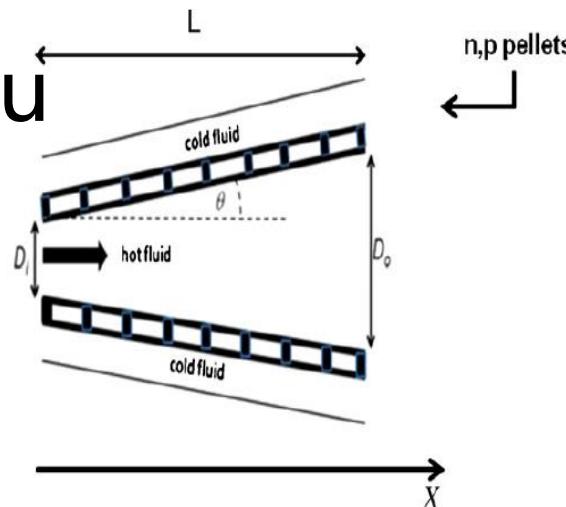
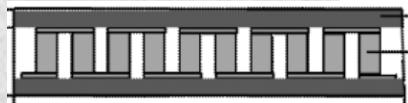
图2-温差发电器实物图



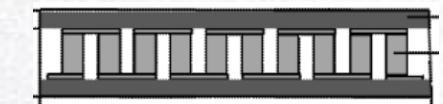
国内外发展现状

直升机喷管处废热处理

Tarik Kousksou



Gequn Shu



Claudio Zilio

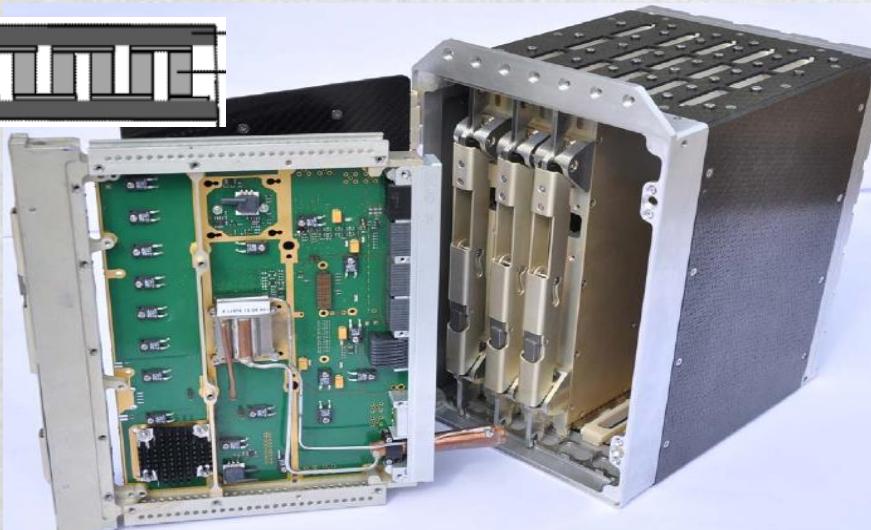


图2-直升机蒸汽循环降温装置

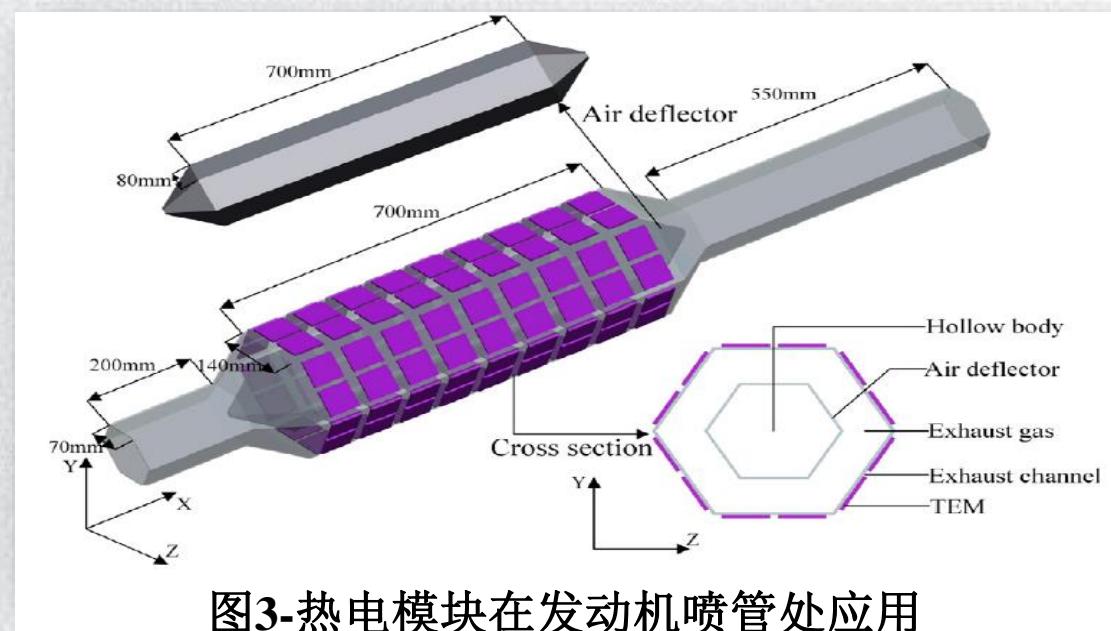


图3-热电模块在发动机喷管处应用



党晓雪

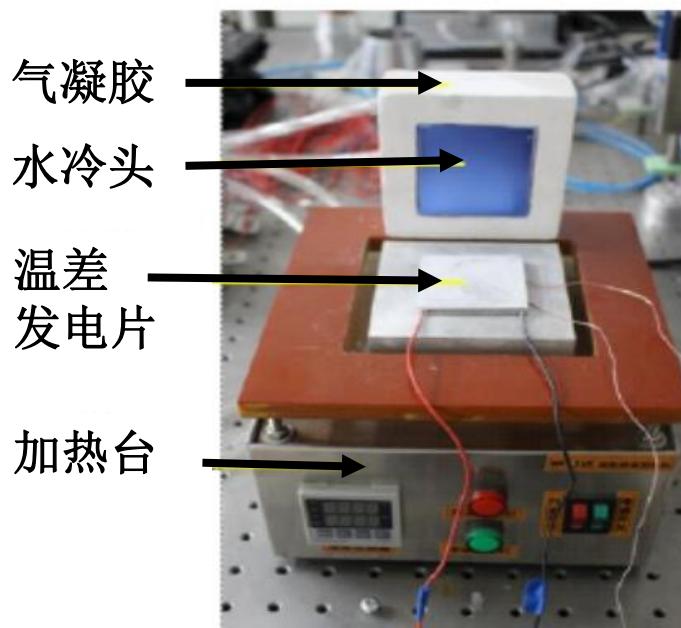
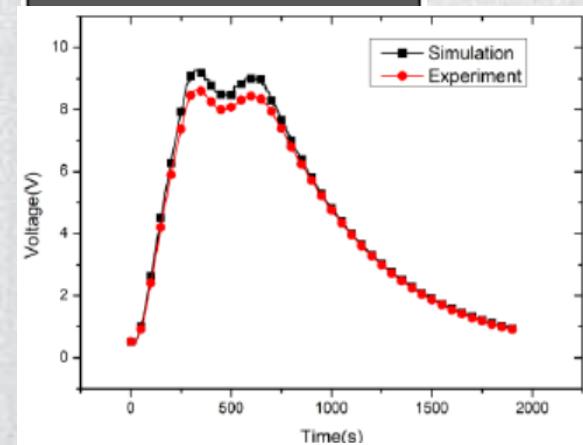
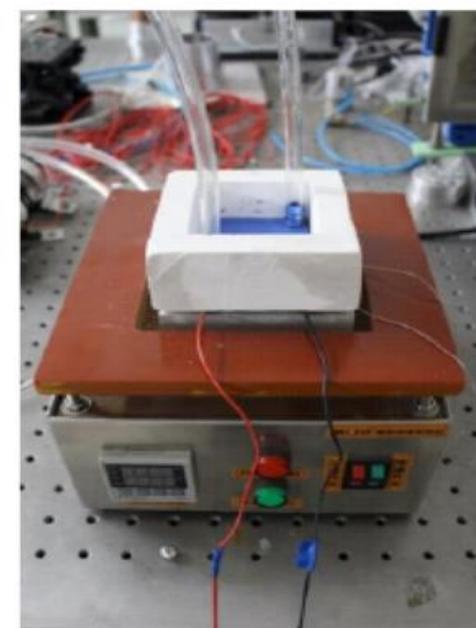


图1-瞬态开路电压对比(左); 热电片实验平台(右)



Ugur Erturun

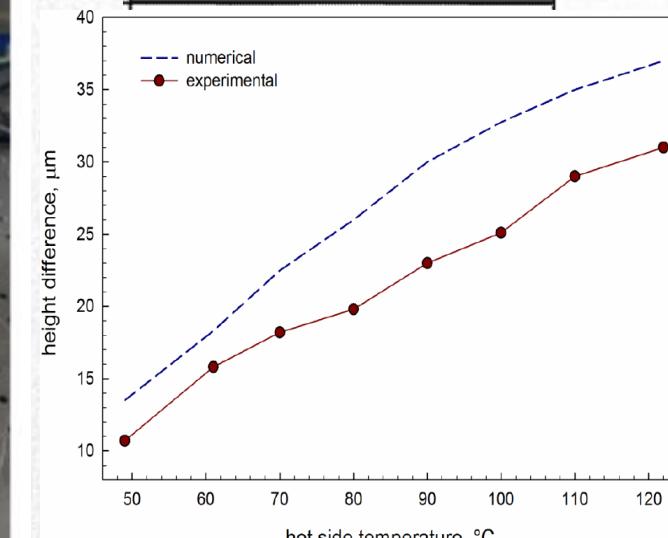
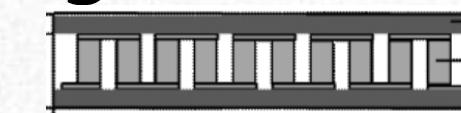


图3-稳态输出功率对比

Ambios XP1 探测轮廓仪

(b)

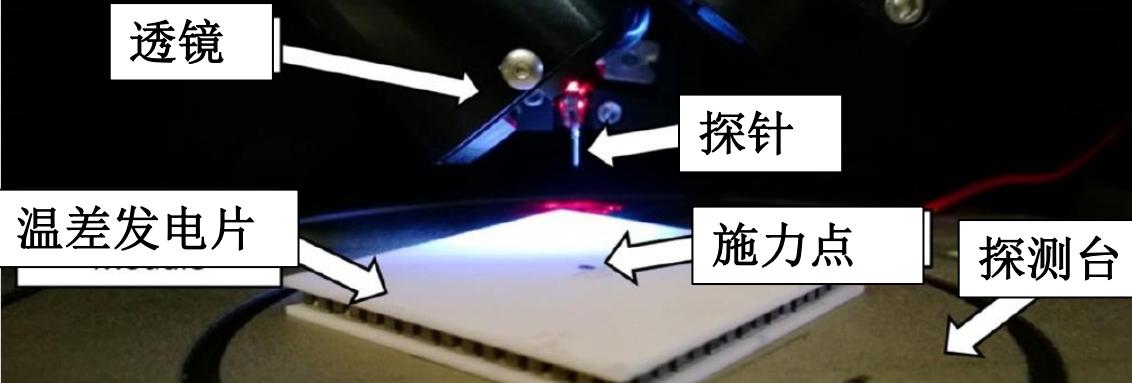


图2-热电片压紧装置(左); 热电片测量系统(右)

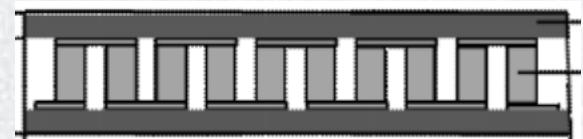
探测系统

(a)



## 第二部分

# 热电原理介绍



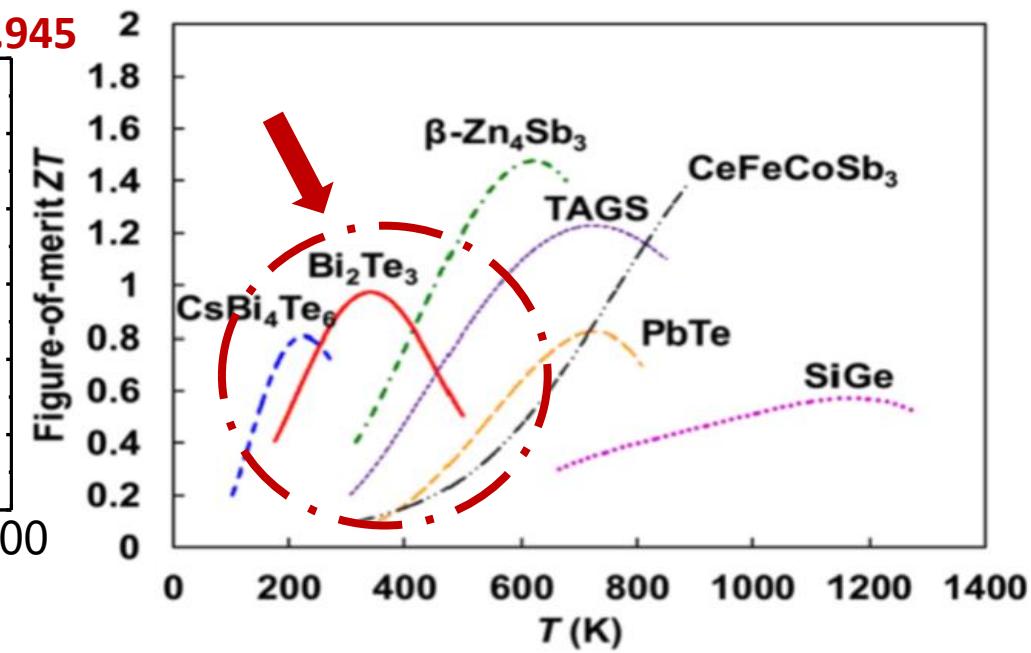
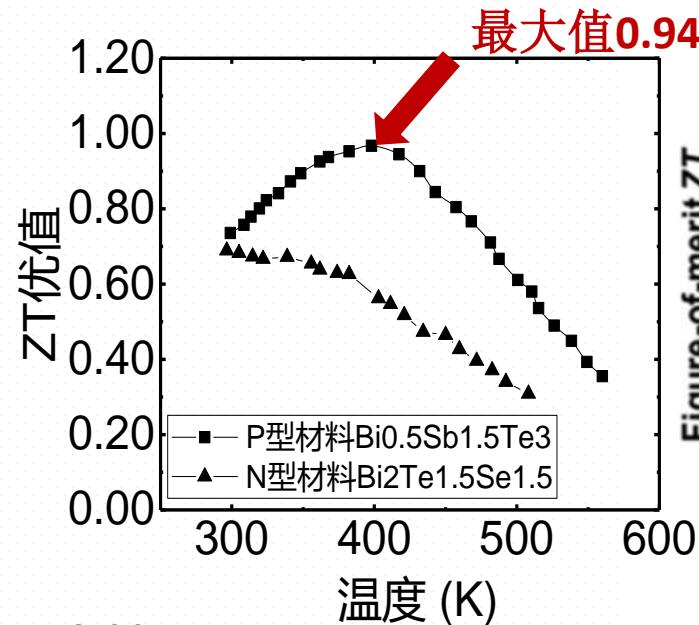
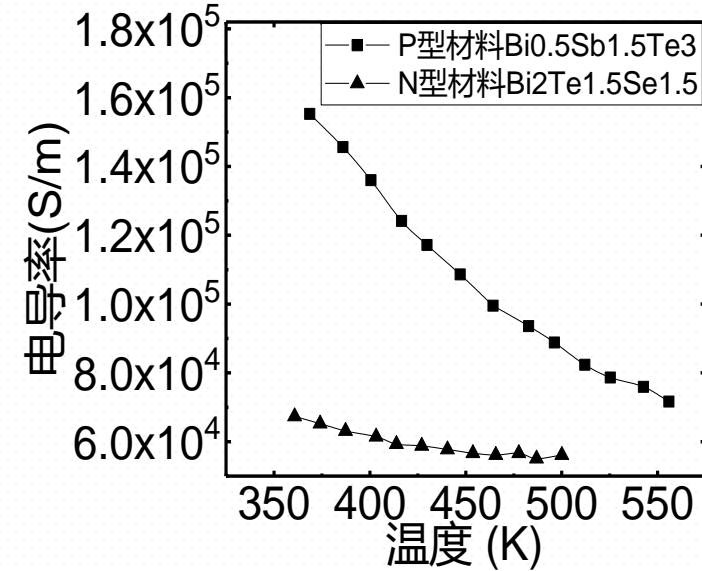


图2-不同材料热电优值对比



热电优值

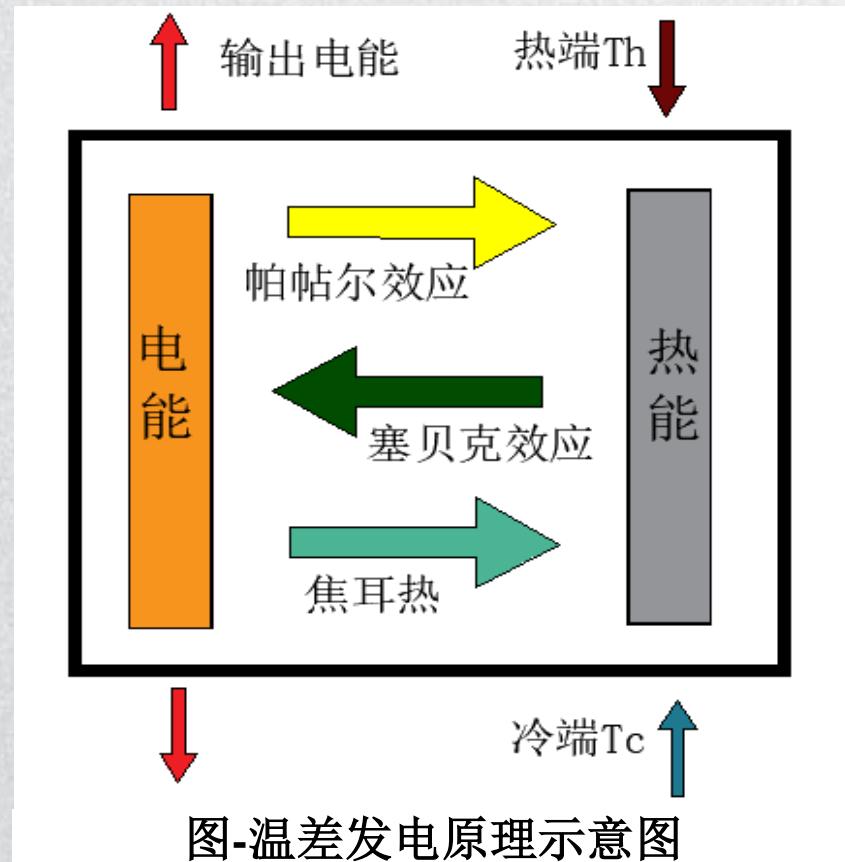
$$ZT = \frac{\alpha^2 \sigma T}{\lambda}$$

P型材料为  $Bi_{0.5}Sb_{1.5}Te_3$

N型材料为  $Bi_2Te_{1.5}Se_{1.5}$

图1- PN型热电材料参数

# 热电原理介绍 | 基本热电效应



**Seebck 效应**

$$S = \lim_{\Delta T \rightarrow 0} \frac{V_{ab}}{\Delta T}$$



**Peltier 效应**

$$Q_p = \pi I T$$



**Thomson 效应**

$$\kappa = \frac{d\pi}{dT} - S$$

$$Q_h = \alpha_{NP} T_h I - \frac{1}{2} I^2 R_0 + k(T_h - T_c)$$

↑                      ↑                      ↑  
Peltier热            焦耳热            传导热



# 热电原理介绍 | 热电性能参数

**Seebach系数** ↓      **温差** ↗

⑥ **开路电压:**  $U_0 = \alpha_{NP}(T_h - T_c)$

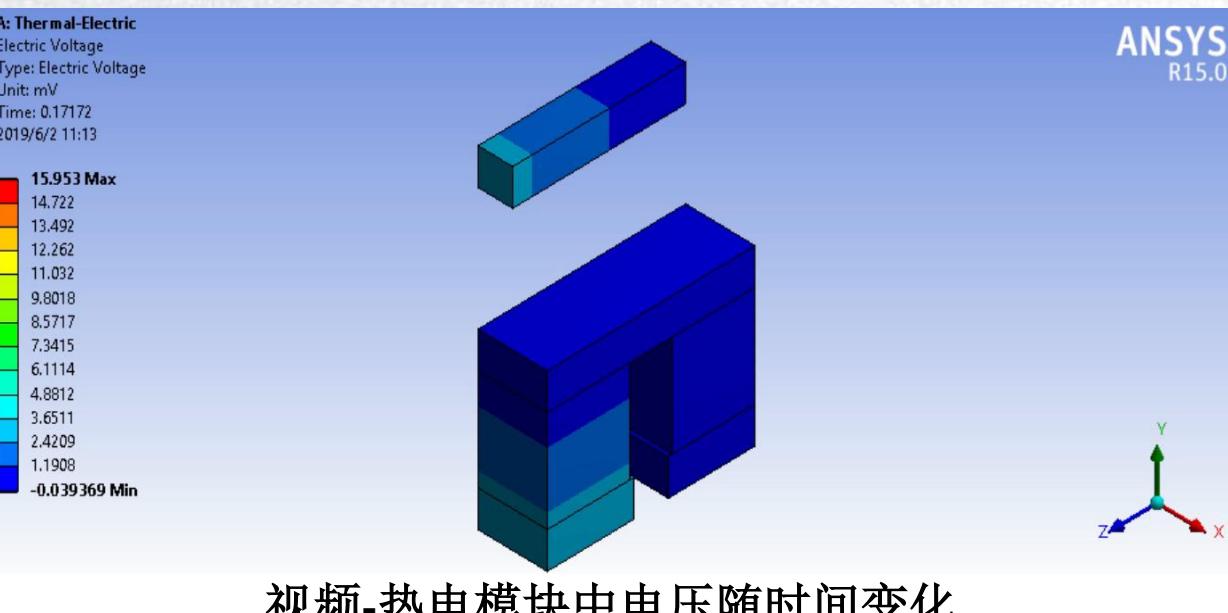
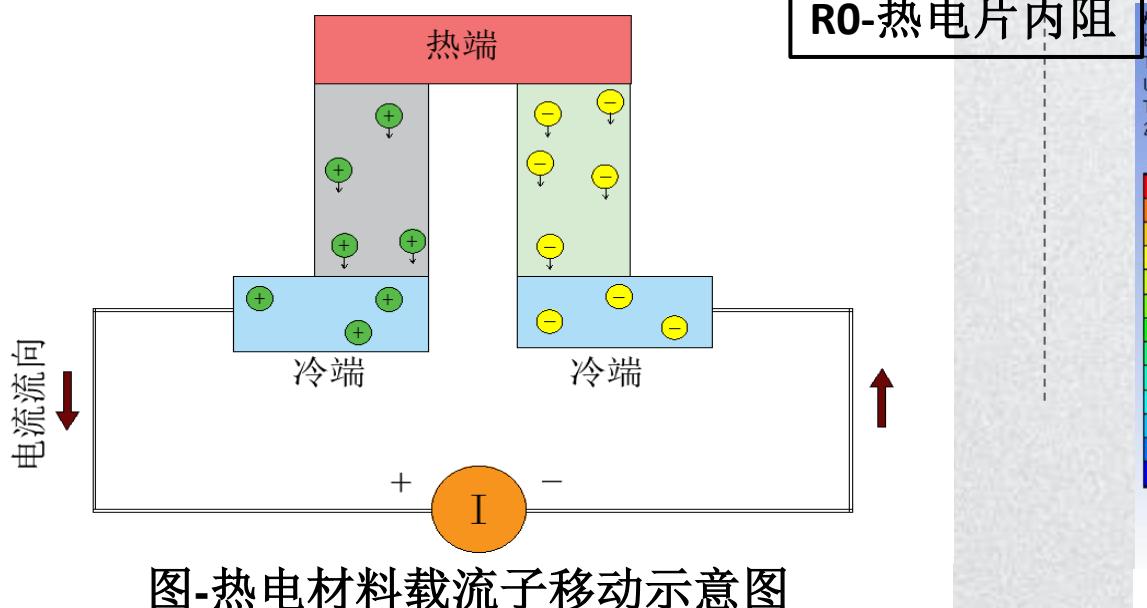
**导热系数** ↓

⑥ **吸收热量:**  $Q_h = \alpha_{NP}T_h I - \frac{1}{2}I^2R_0 + k(T_h - T_c)$

⑥ **输出功率:**  $P = \frac{\alpha_{NP}^2(T_h - T_c)^2 R}{(R + R_0)^2}$

**R-负载电阻** ↗      **R0-热电片内阻** ↘

⑥ **转换效率:**





# 热电单元内阻推导

## 功率极值解



$$P = I^2 R = \frac{\alpha_{NP}^2 (T_h - T_c)^2 R}{(R + R_0)^2}$$

$$= \frac{S}{(S+1)^2} \cdot \frac{\alpha_{NP}^2 (T_h - T_c)^2}{R_0}$$

$$\partial P / \partial S = 0$$

$$S = \frac{R}{R_0} = 1$$

$$R_0 = R$$

## 效率极值解



$$\begin{aligned} \eta &= \frac{I^2 R_L}{\alpha_{NP} T_h I - \frac{1}{2} I^2 R + k(T_h - T_c)} \\ &= \frac{T_h - T_c}{T_h} \cdot \left[ \frac{S}{(1+S) - \frac{T_h - T_c}{2T_h} + \frac{(1+S)^2}{ZT_h}} \right] \end{aligned}$$

$$S = \frac{R}{R_0}$$

$$\frac{\partial \eta}{\partial S} = 0$$

$$S = \sqrt{(1+ZT)}$$

$$R_0 = \sqrt{R^2 - \frac{\alpha^2 R_0}{k} \bar{T}}$$

## 理论解

$$R_0 = \frac{l_N}{A_N} \rho_N + \frac{l_P}{A_P} \rho_P$$

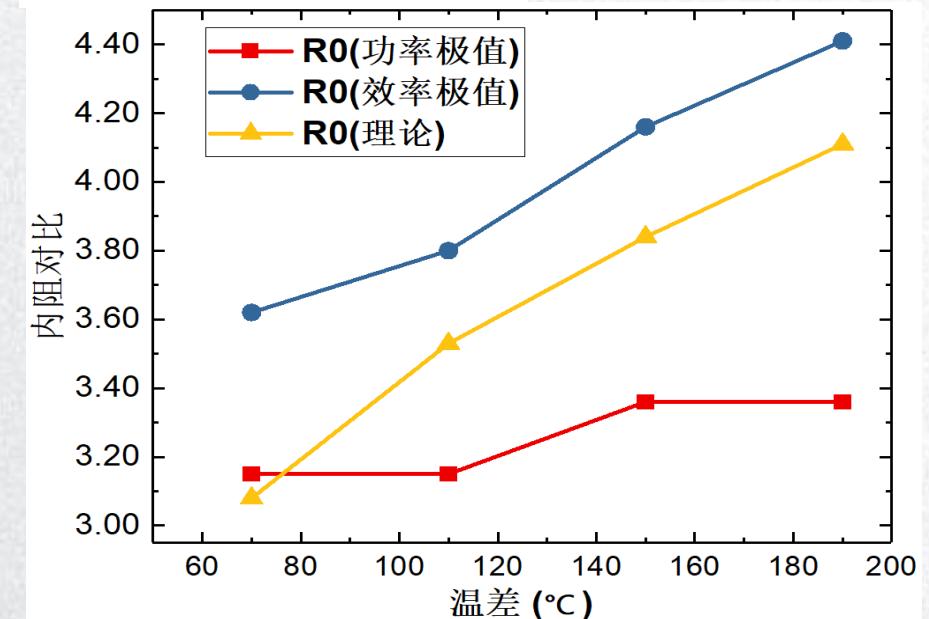
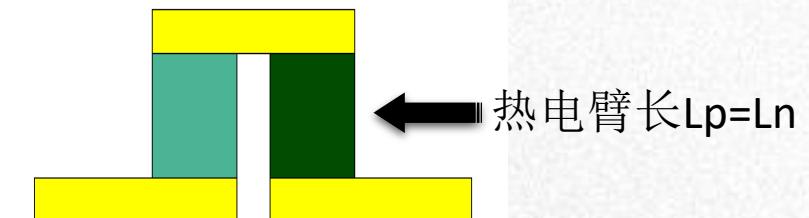
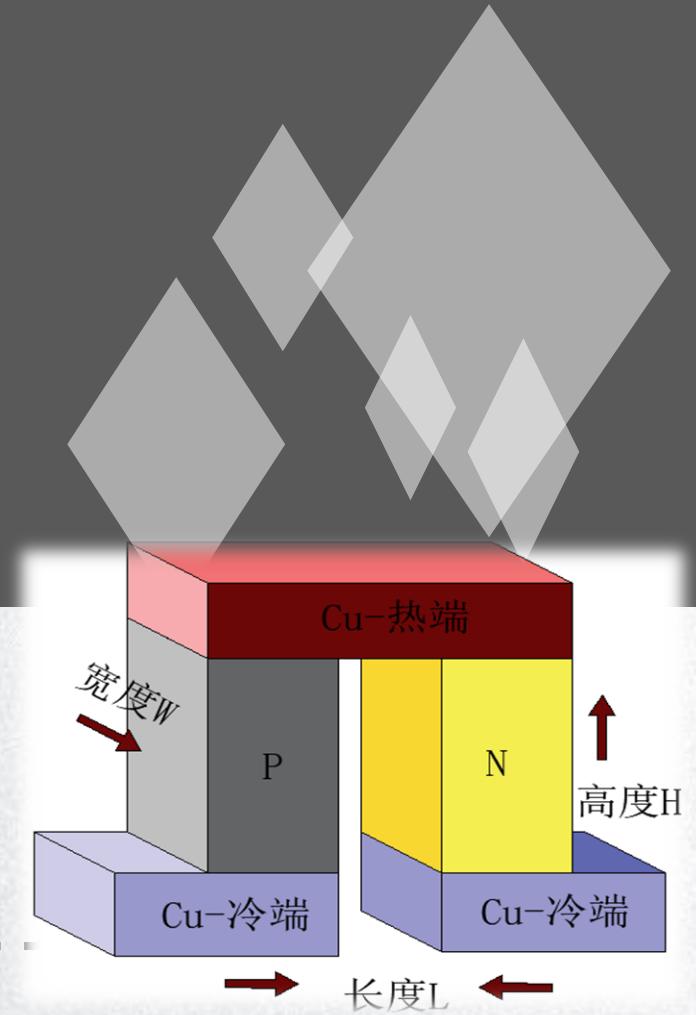


图-热电片内阻理论求解示意图(上); 热电片内阻随温度变化(下)

## 第三部分

# 主要研究内容



# ● 主要研究内容 |



热电耦合  
数值模拟

热电片  
性能实验

直升机喷管  
热电模块  
设计

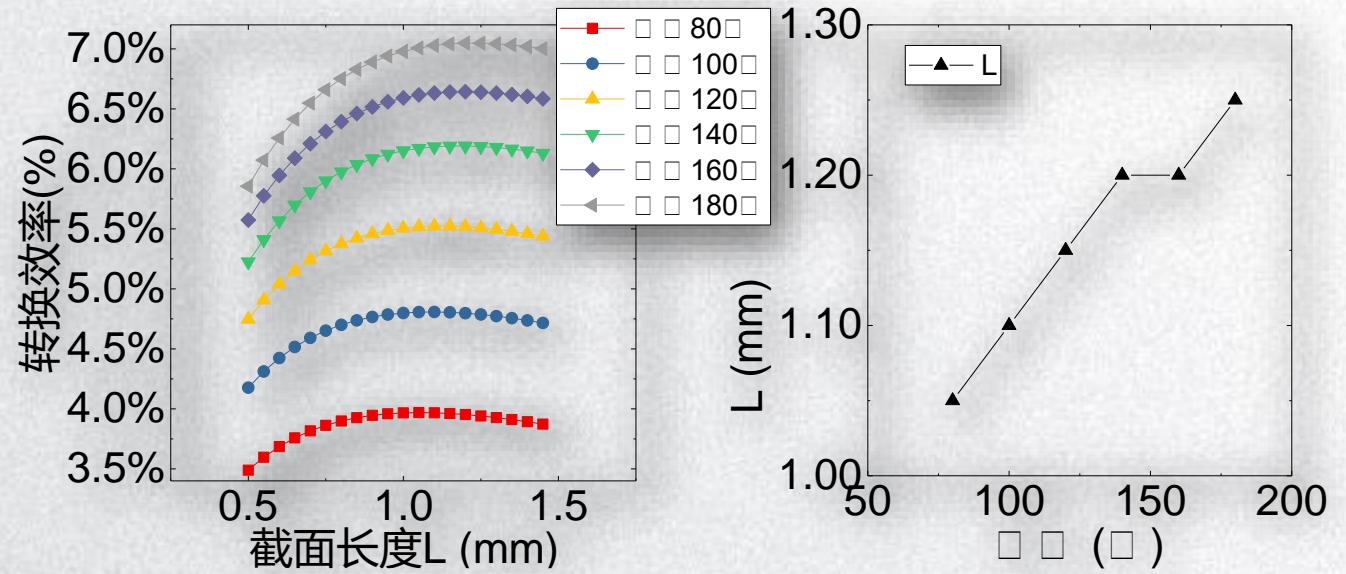
1. 建立**PN结数理模型**。
2. **ANSYS 数值模拟**探究热电性能受影响因素  
变量：尺寸参数、温度差 $\Delta T$ 、负载电阻R。
3. 求解**热电片内阻**。

1. 搭建**热电模块实验平台**，  
测试温差发电性能。
2. 设计**热电片对比试验**，校  
准热电模型。

1. 基于武装直升机喷管外  
形设计**环形热电模块**。
2. 研究**变截面热电模块**性  
能参数。



# 1. 热电耦合数值模拟





# PN结数值模拟

## 网格无关性检验

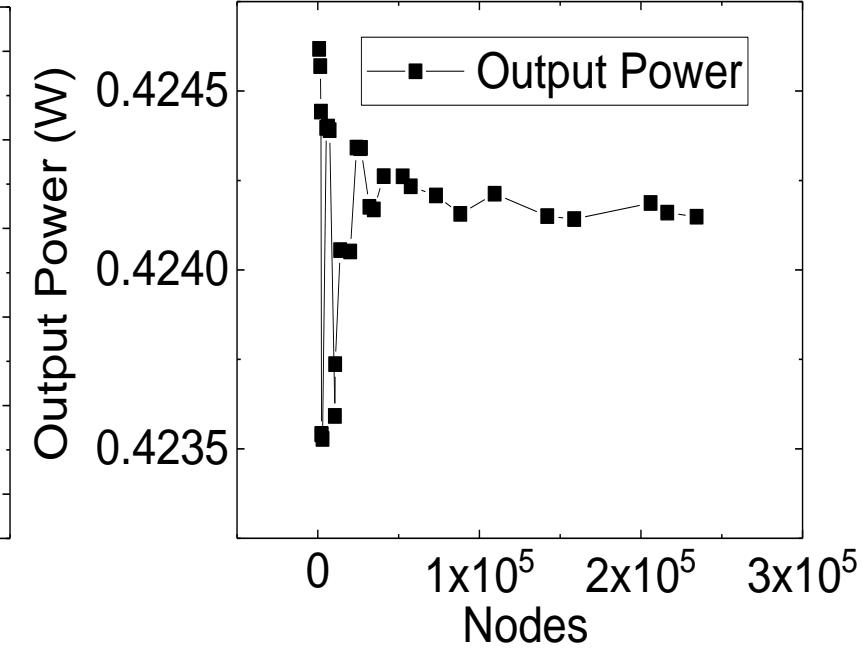
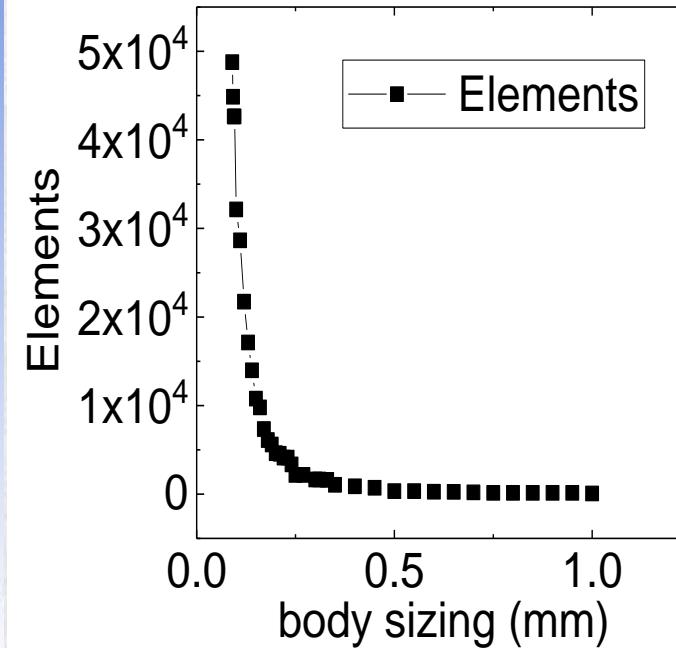
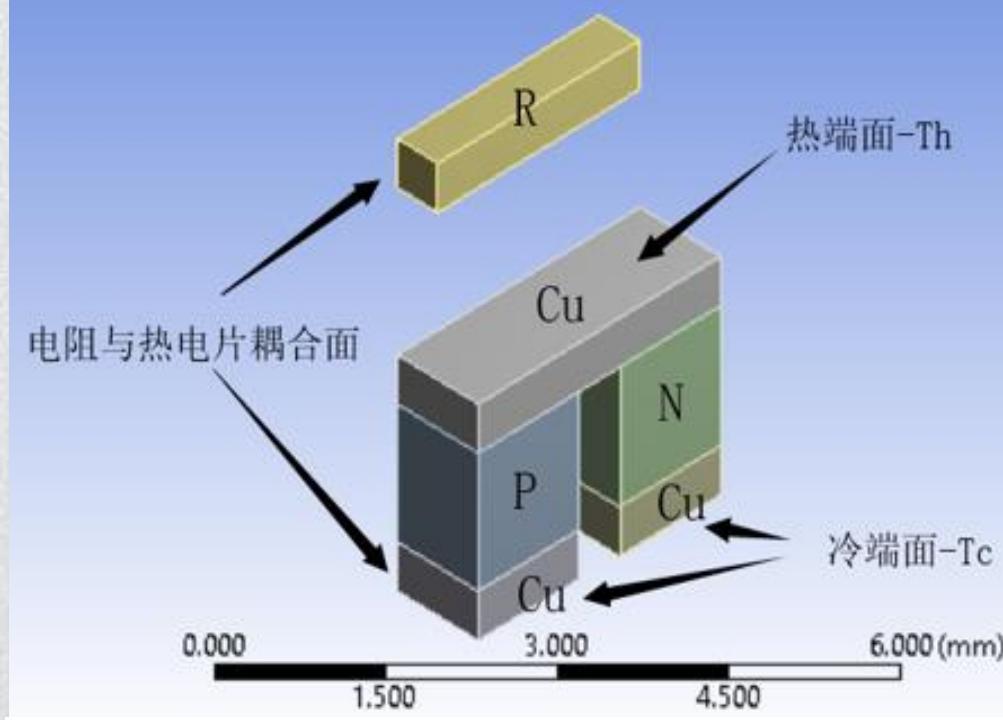


图1-边界条件设置示意图(左); 网格数随单元尺寸变化图(中); 输出功率随节点变化图(右)

## 单一PN结模型建立

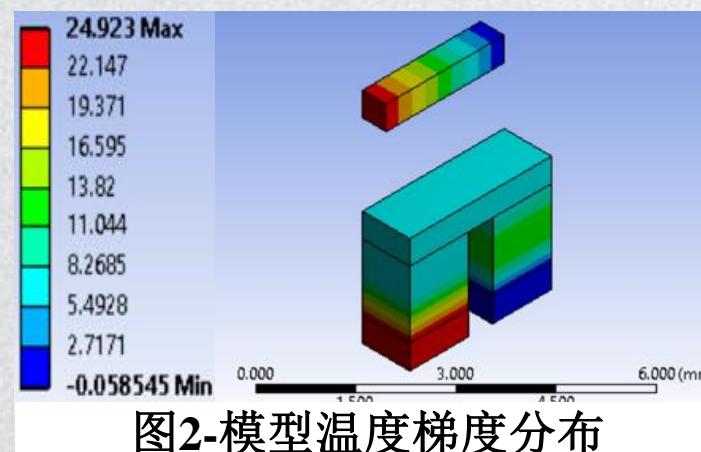


图2-模型温度梯度分布

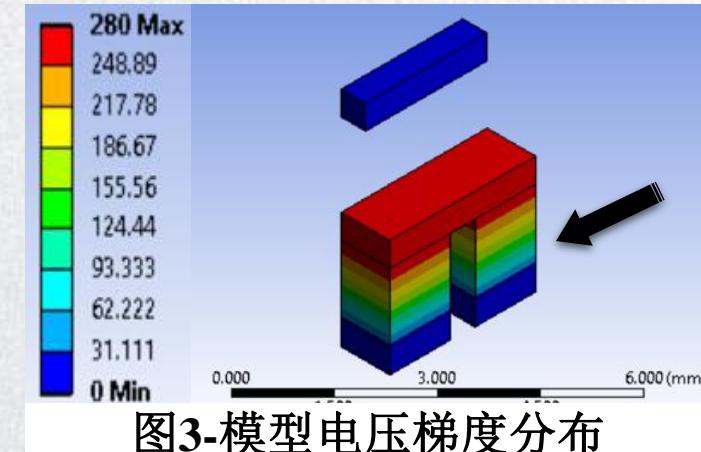


图3-模型电压梯度分布

# PN结尺寸对热电性能影响

$T_h=160^\circ\text{C}$   
 $T_c=20^\circ\text{C}$   
 $T_h-T_c=140^\circ\text{C}$

$$R_0 = \frac{H_N}{(W \times L)_N} \rho_N + \frac{H_P}{(W \times L)_P} \rho_P$$

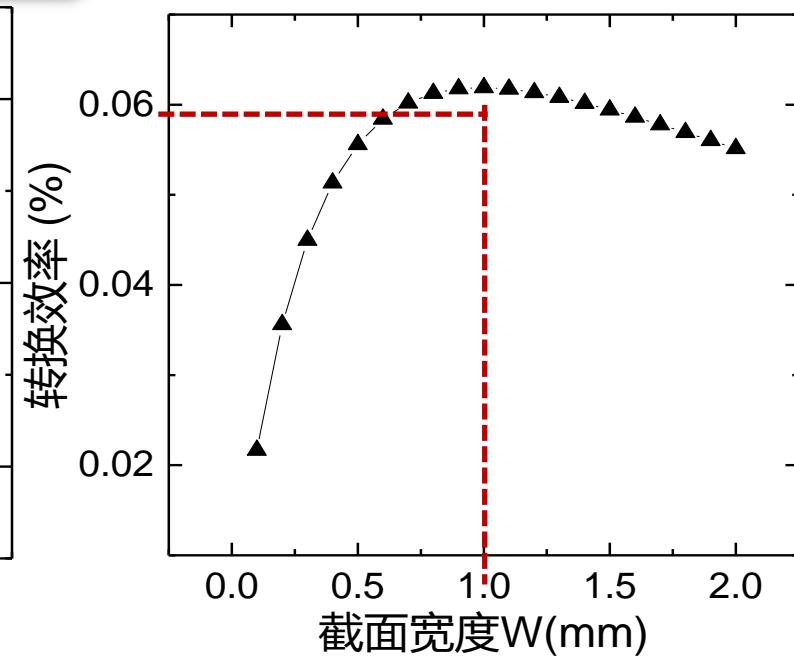
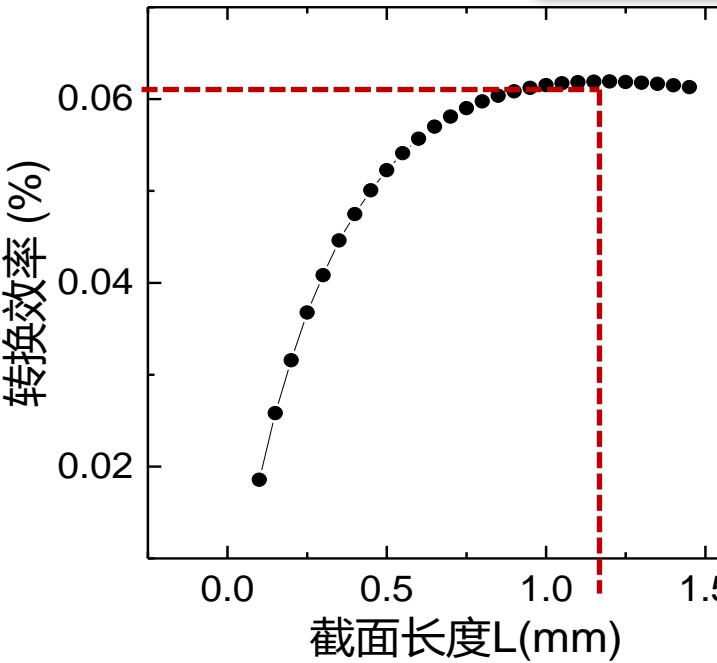
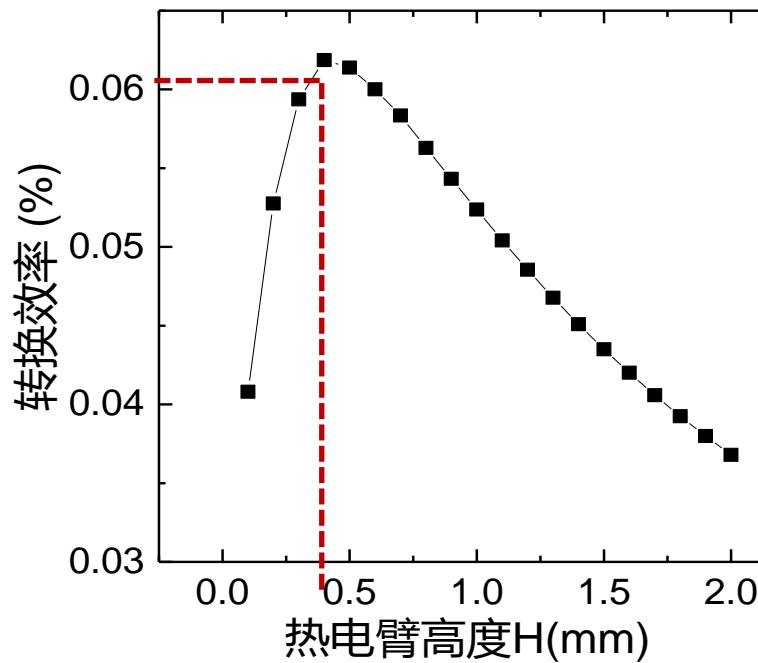


图1-PN结腿长与截面尺寸对转换效率的影响

| 模型   | 初始模型    |               |       | 极值点模型   |               |       | 性能提升                  |
|------|---------|---------------|-------|---------|---------------|-------|-----------------------|
| 参数   | 尺寸 (mm) | η(%)          | P(W)  | 尺寸 (mm) | η(%)          | P(W)  | Δ(%)                  |
| 高度 H | 1.40    |               |       | 0.395   | <b>6.183%</b> | 0.103 |                       |
| 长度 L | 1.25    | <b>4.509%</b> | 0.027 | 1.20    | <b>6.191%</b> | 0.105 | <b>效率 η=37.30%</b> ↑  |
| 宽度 W | 1.00    |               |       | 1.00    | <b>6.191%</b> | 0.105 | <b>功率 P=285.14%</b> ↑ |

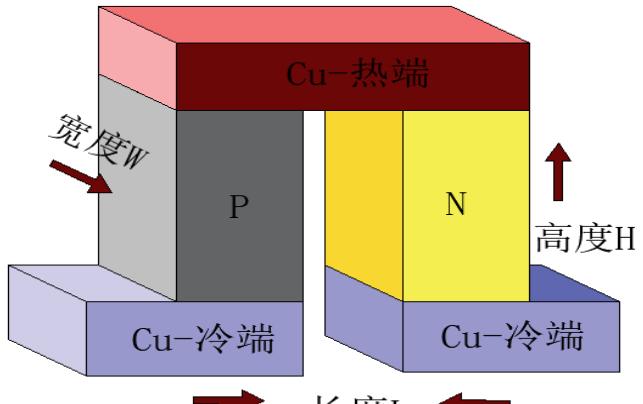


图2-尺寸变化方向示意图



# 温度对热电性能影响

$$Th=80+n\Delta T^{\circ}\text{C}$$

$$Tc=20^{\circ}\text{C}$$

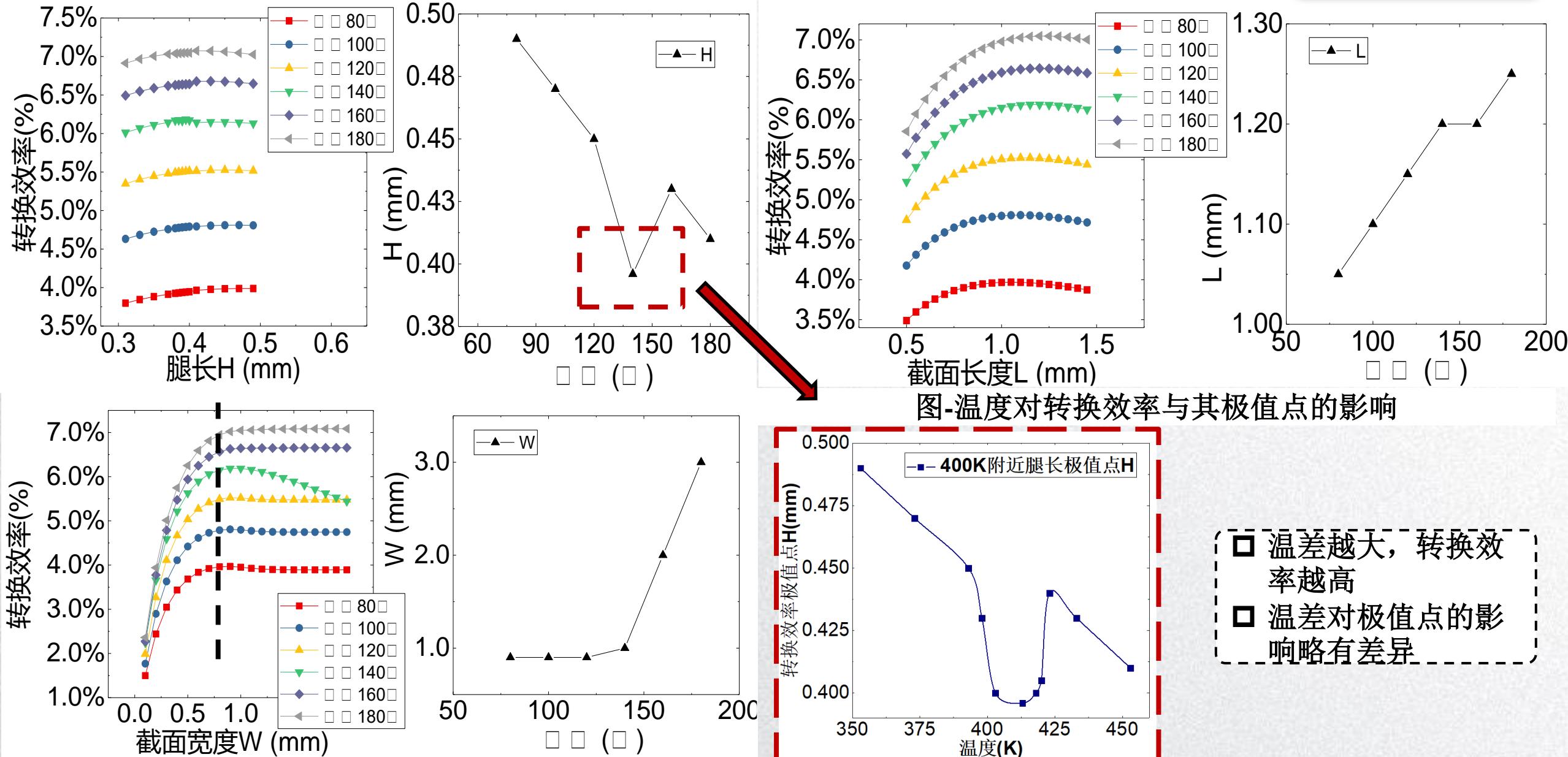


图-温度对转换效率与其极值点的影响

# 负载电阻对热电性能影响

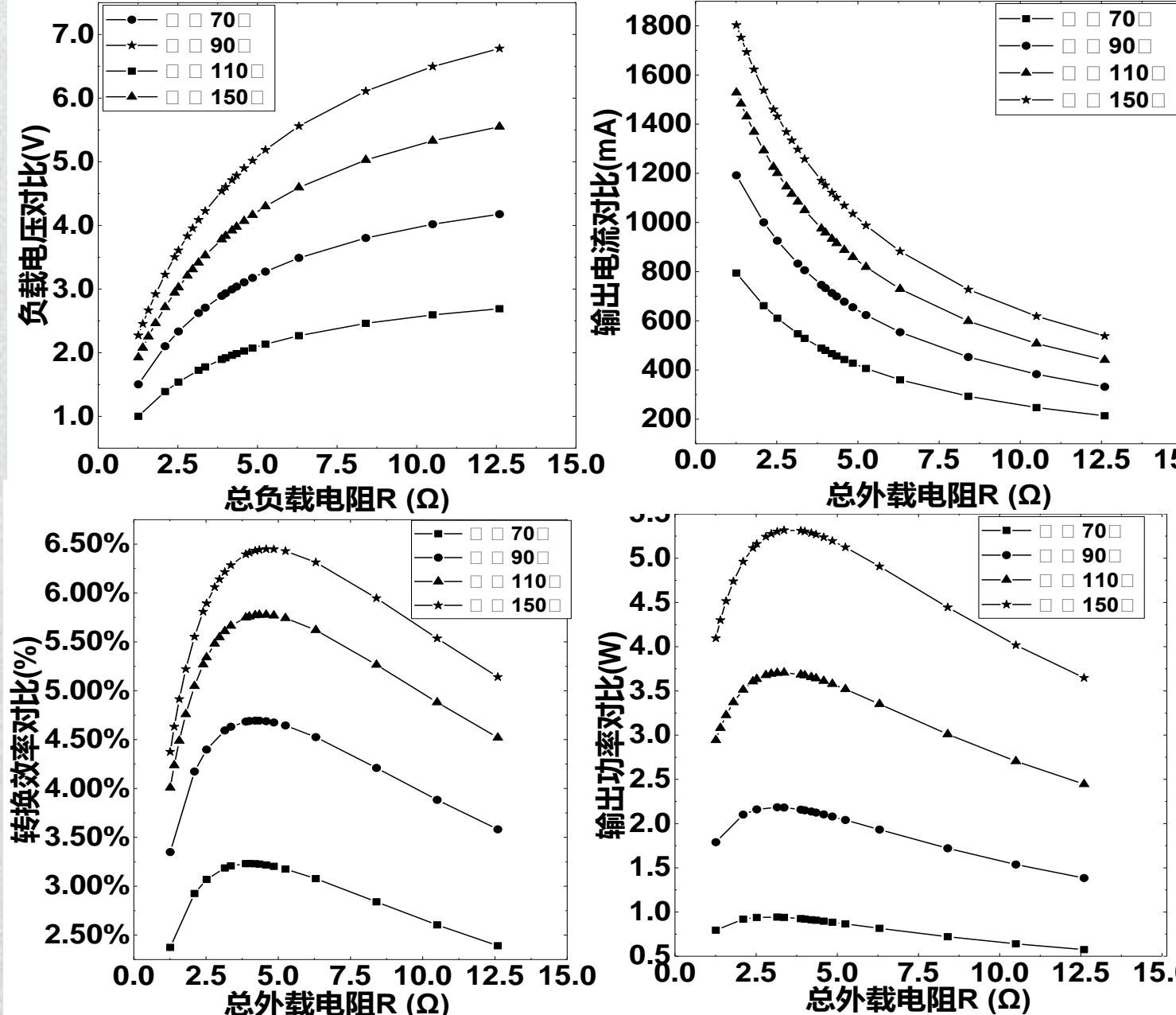
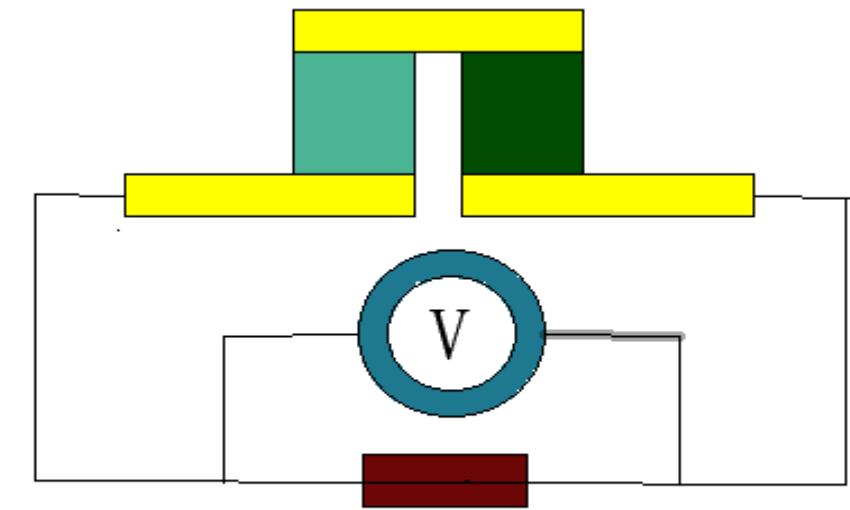


图1-热电性能参数随负载与温度的变化趋势  
电压(左上); 转换效率(左下); 电流(右上); 输出功率(右下)



负载电阻R  
图2-PN结模型电路示意图

负载电阻影响



## 2. 热电片性能试验



# 实验用热电片

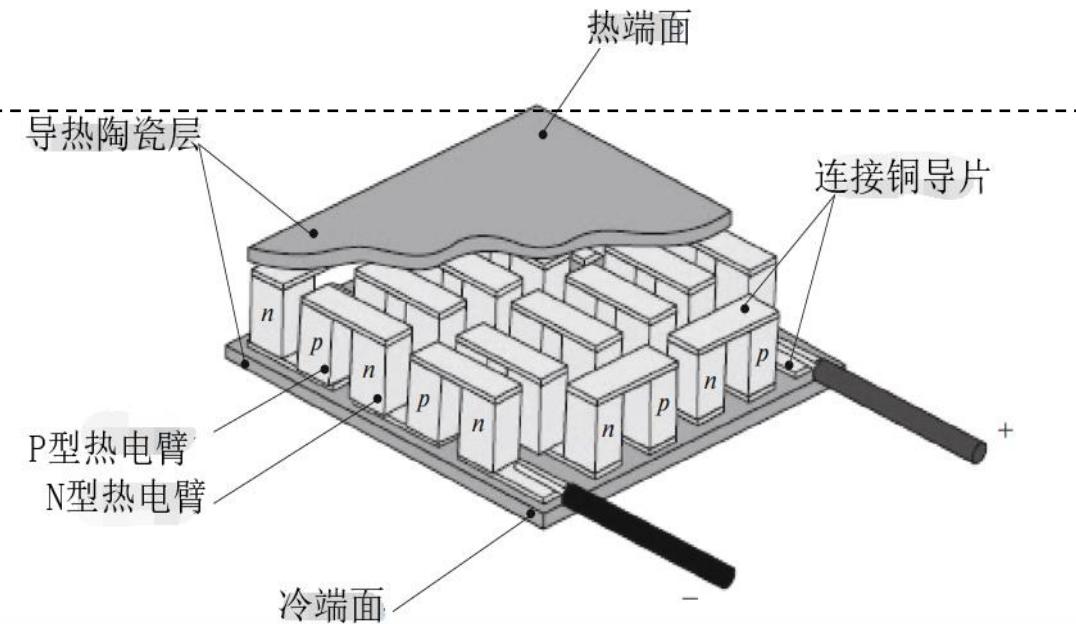


图-热电片(上：内部结构图；下：实物图)

实验用热电片性能参数 ↓

| 性能指标         | 数值                       |
|--------------|--------------------------|
| 型号           | <b>TEHP1-1263-1.5</b>    |
| <b>PN结对数</b> | <b>126对</b>              |
| 整体尺寸         | <b>30mm×30mm×3.787mm</b> |
| 总内阻 $R_0$    | <b>3.15Ω</b>             |
| 总热导率K        | <b>0.4467W/K</b>         |
| 总塞贝克系数α      | <b>0.03037V/K</b>        |

# ● 实验平台搭建

- ◆ 加热装置
- ◆ 冷却装置
- ◆ 热电装置
- ◆ 测量装置
- ◆ 机械装置

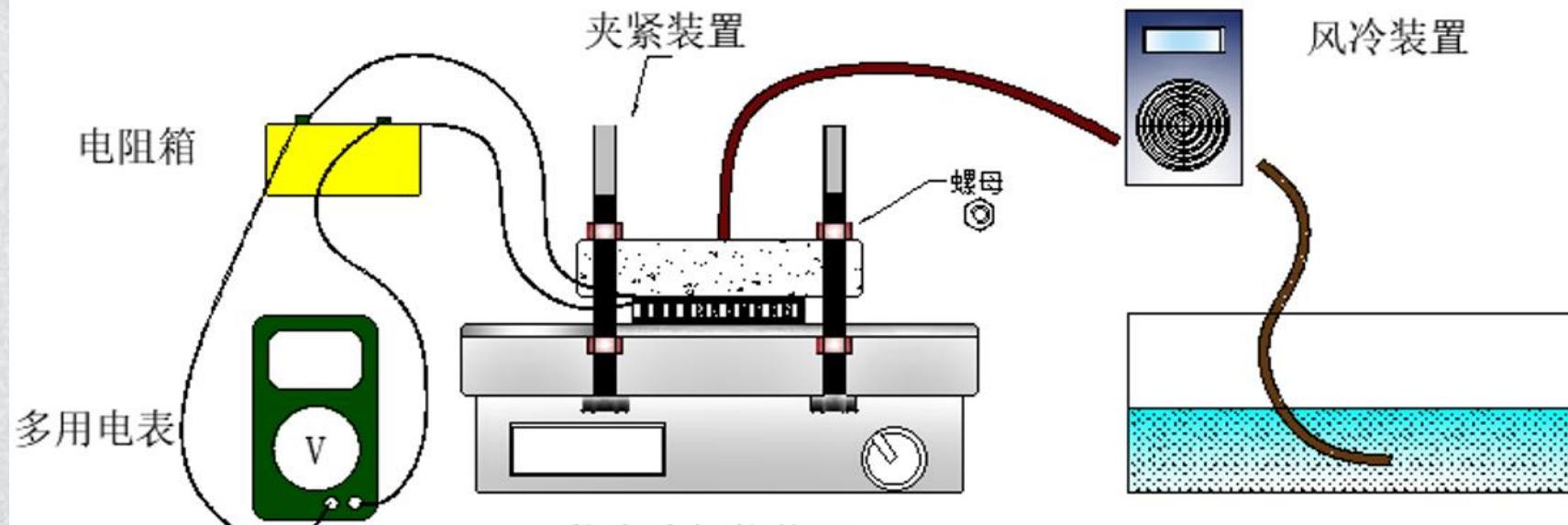
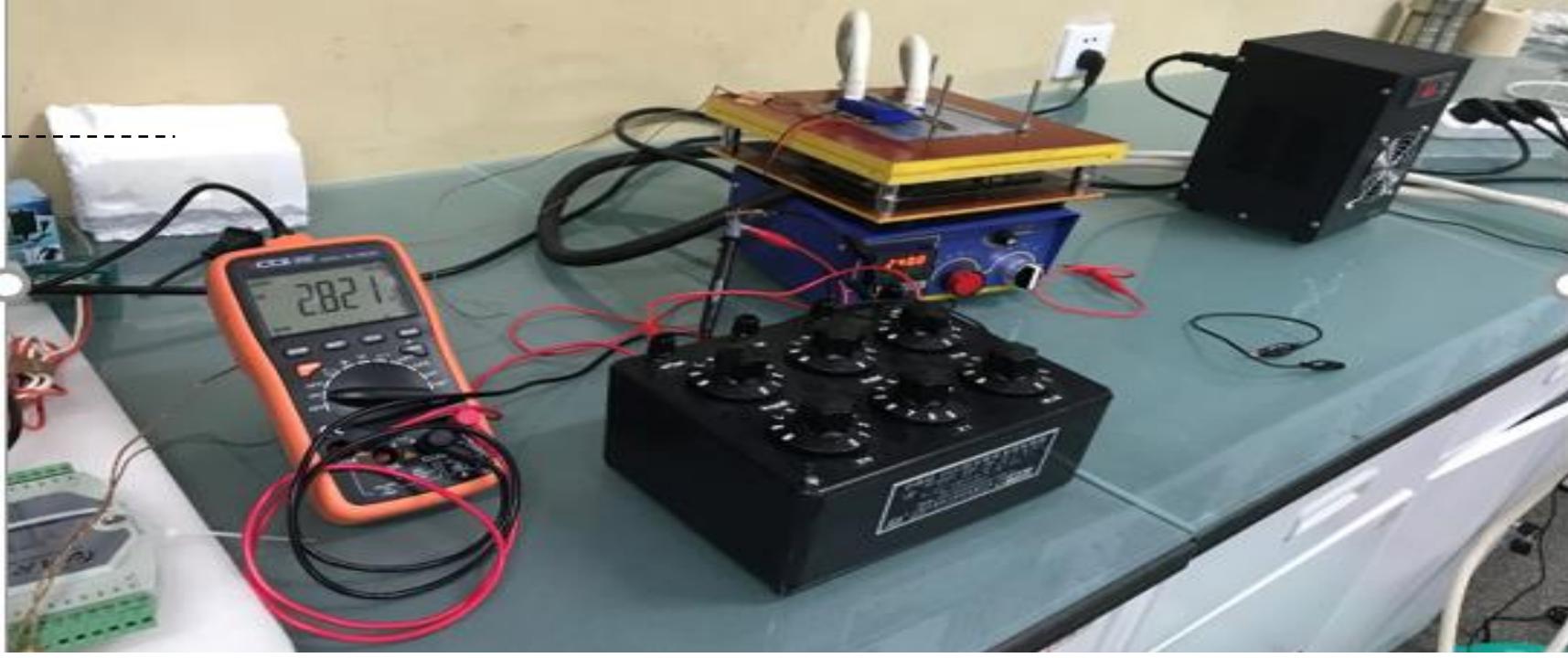
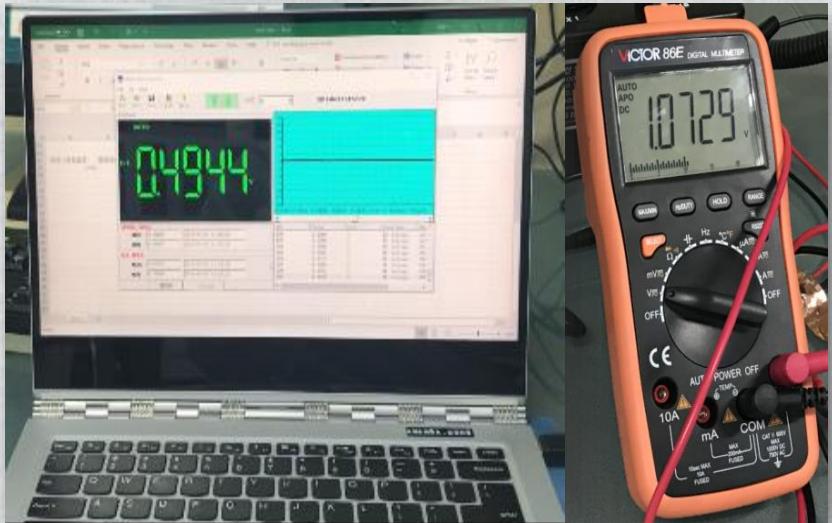


图-实验平台



# 实验平台搭建 |

DMM电压测试系统



热电片加热装置



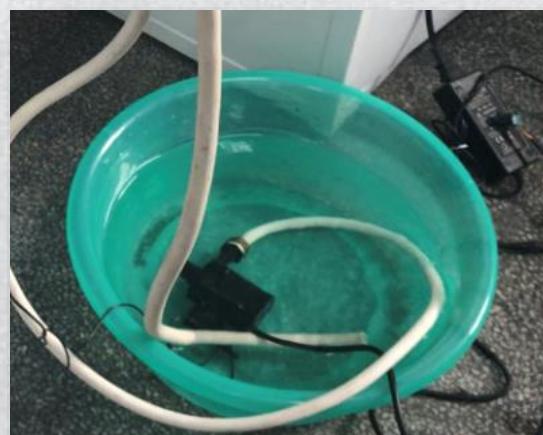
ZX21直流电阻箱



热电偶测温装置



冷却装置：循环水冷+风冷装置





# 实验平台搭建 | 压紧装置对实验数据的影响

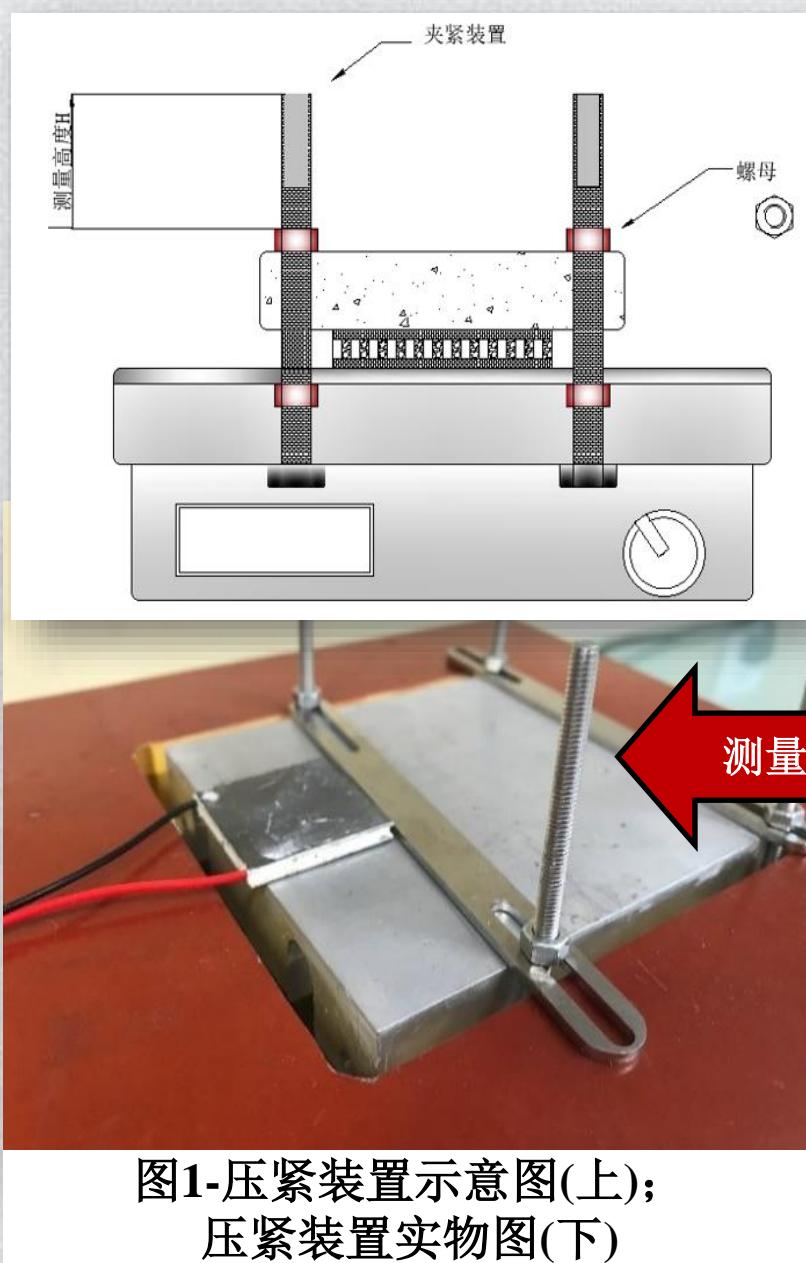


图1-压紧装置示意图(上);  
压紧装置实物图(下)

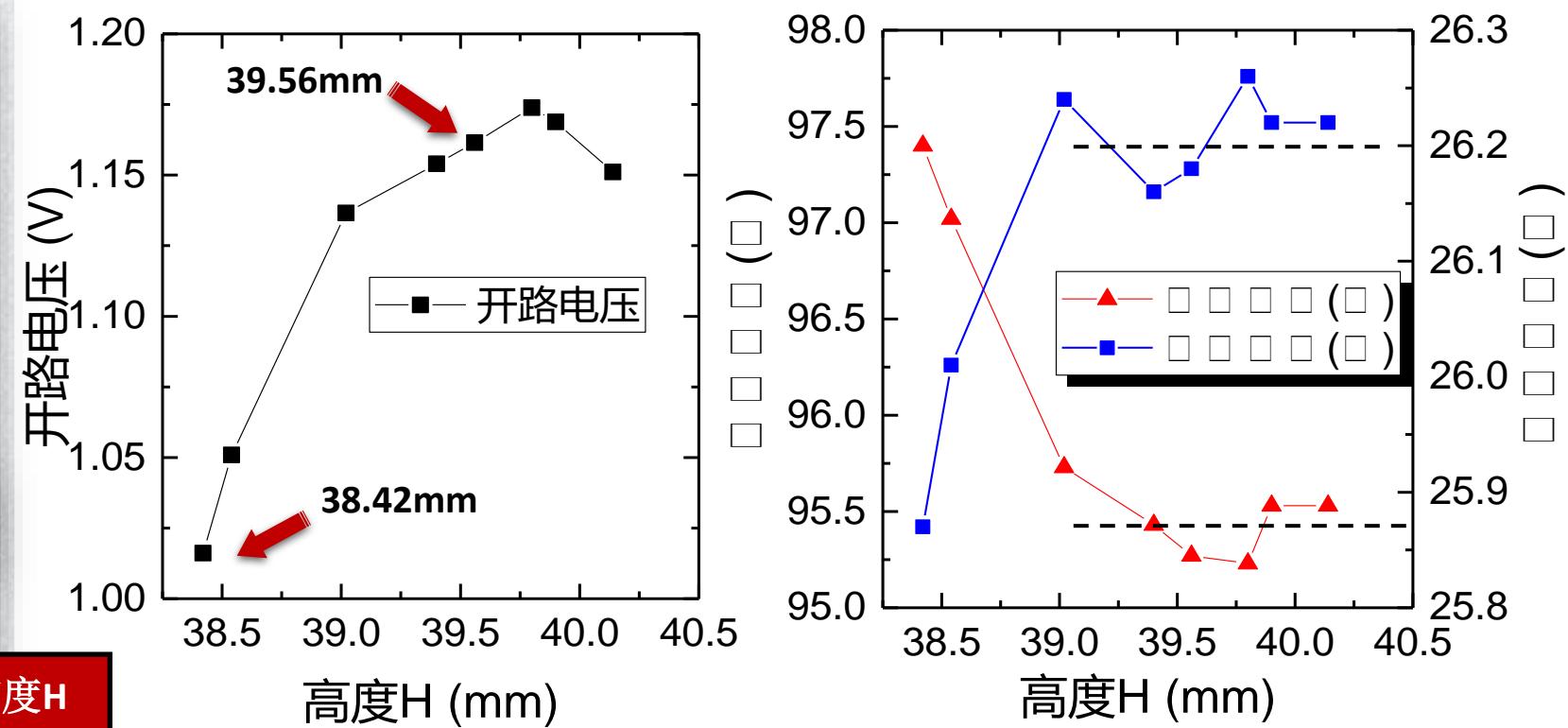


图2-压紧程度对温度与电压的影响

| 测量参数         | 热端温度(°C) | 冷端温度(°C) | 开路电压(V) |
|--------------|----------|----------|---------|
| 预紧点(38.42mm) | 95.41    | 25.86    | 1.032   |
| 压紧点(39.56mm) | 97.25    | 26.17    | 1.162   |
| 变化幅度(%)      | 1.93%    | 1.19%    | 12.60%  |



HY510导热硅脂  
 $\mu = 8$  (W/m · K)

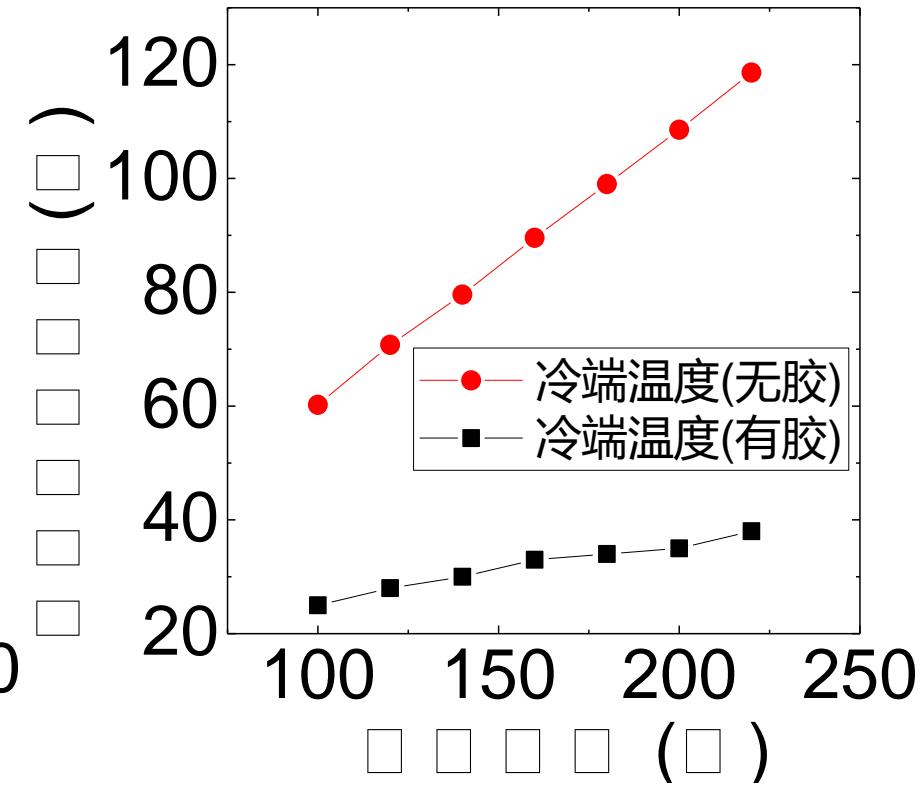
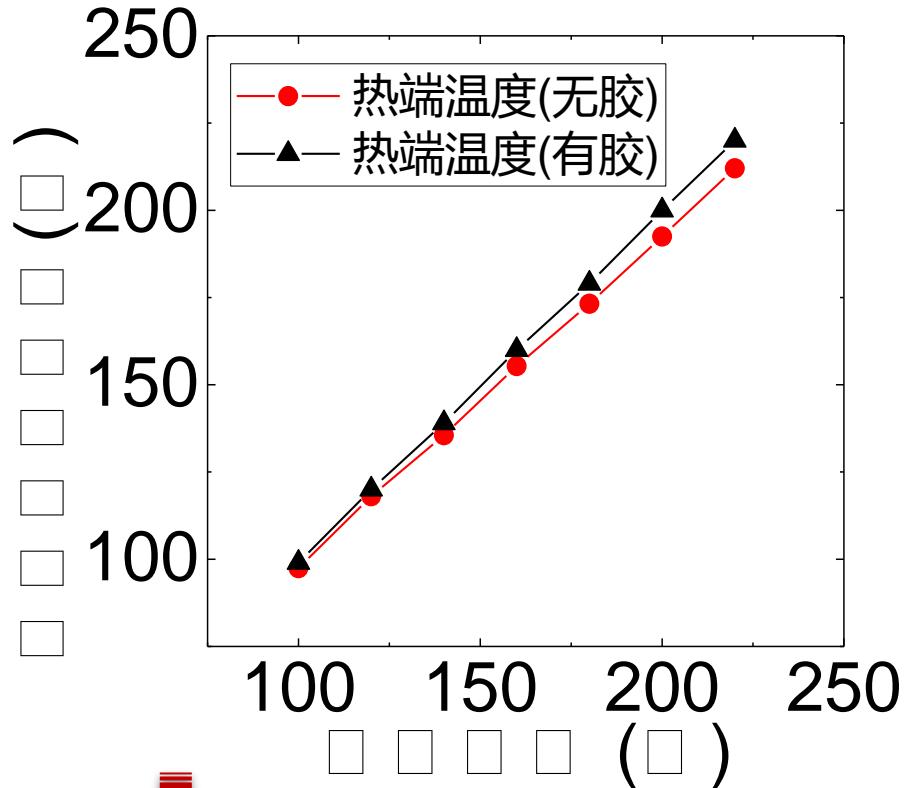
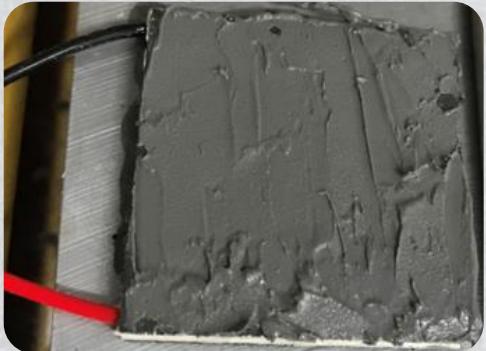


图-导热硅脂对热电片两端温度影响

| 测量参数    | 设定温度(°C) | 热端温度(°C)     | 冷端温度(°C)       |
|---------|----------|--------------|----------------|
| 有导热胶    | 220      | 220          | 38             |
| 无导热胶    | 220      | 212          | 119            |
| 变化幅度(%) | —        | <b>3.62%</b> | <b>213.16%</b> |

# 热电片性能测试实验 |

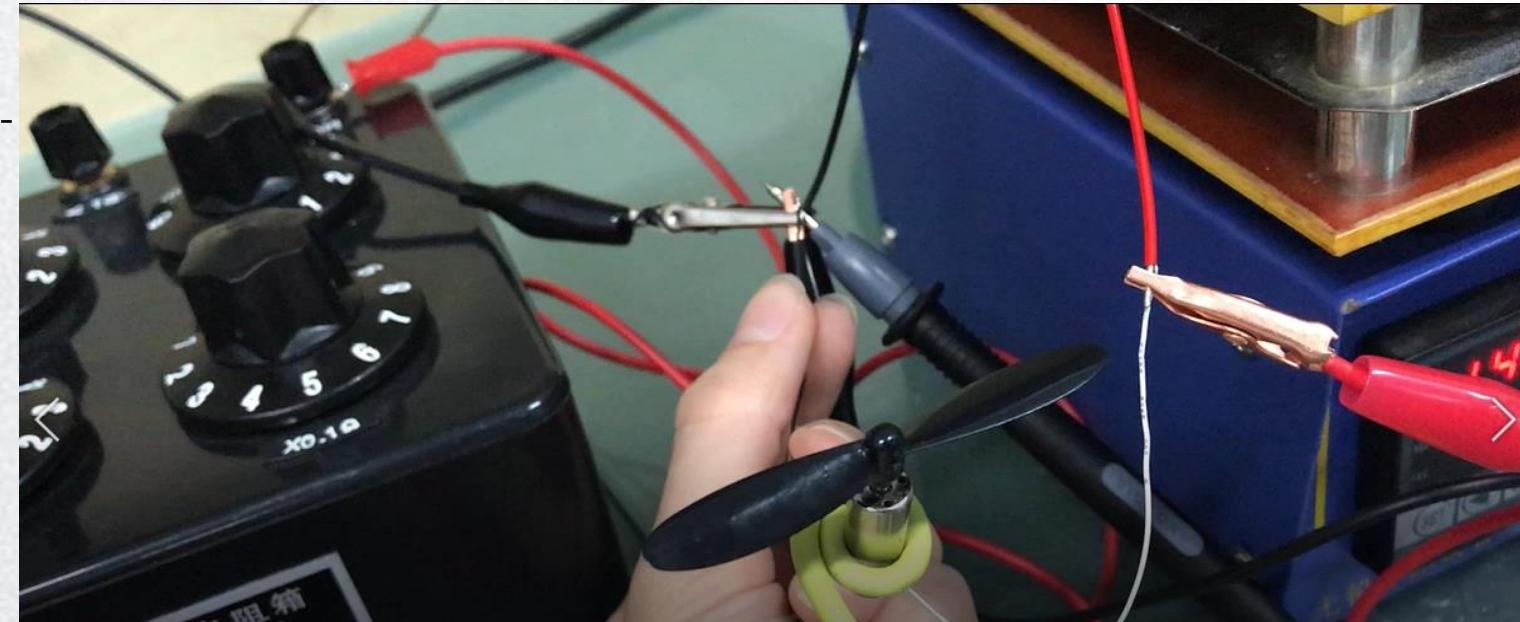


小风扇转动测试

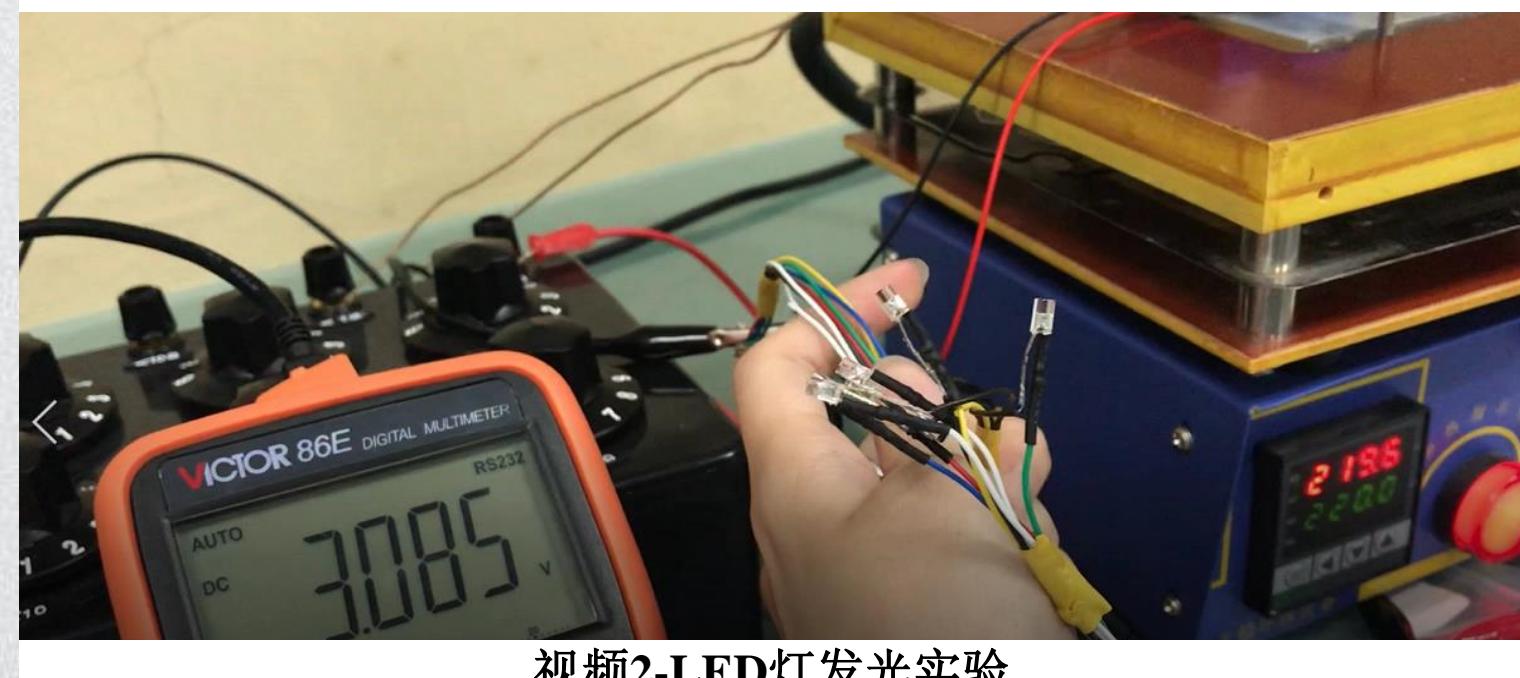


LED灯发光测试

| 名称       | LED灯泡 | 小风扇       |
|----------|-------|-----------|
| 额定电压(V)  | 1.50  | 2.20-2.40 |
| 工作温度(°C) | 140   | 220       |



视频1-风扇转动



视频2-LED灯发光实验

# 热电片对比试验

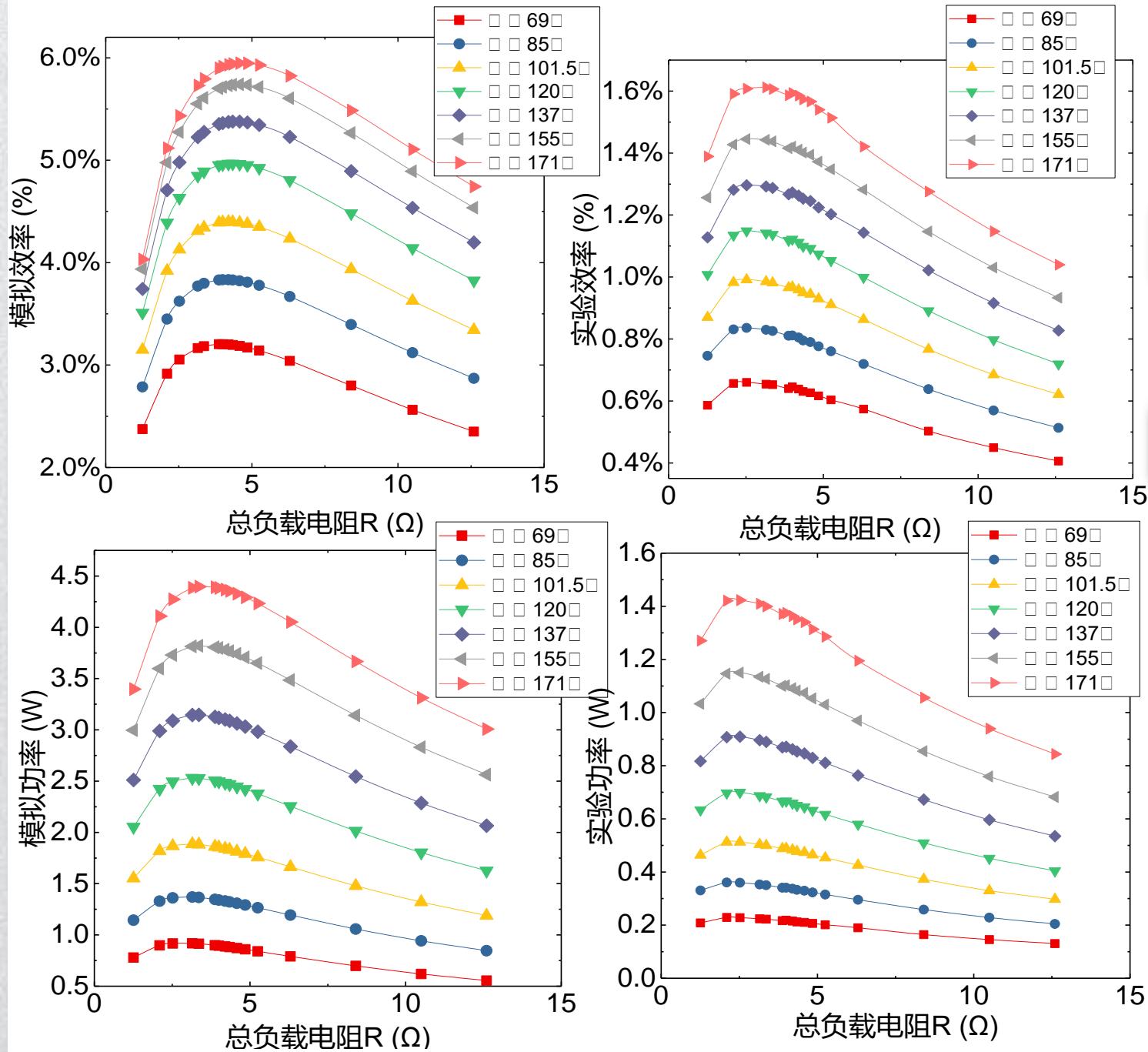


图1-实验模拟热电性能对比

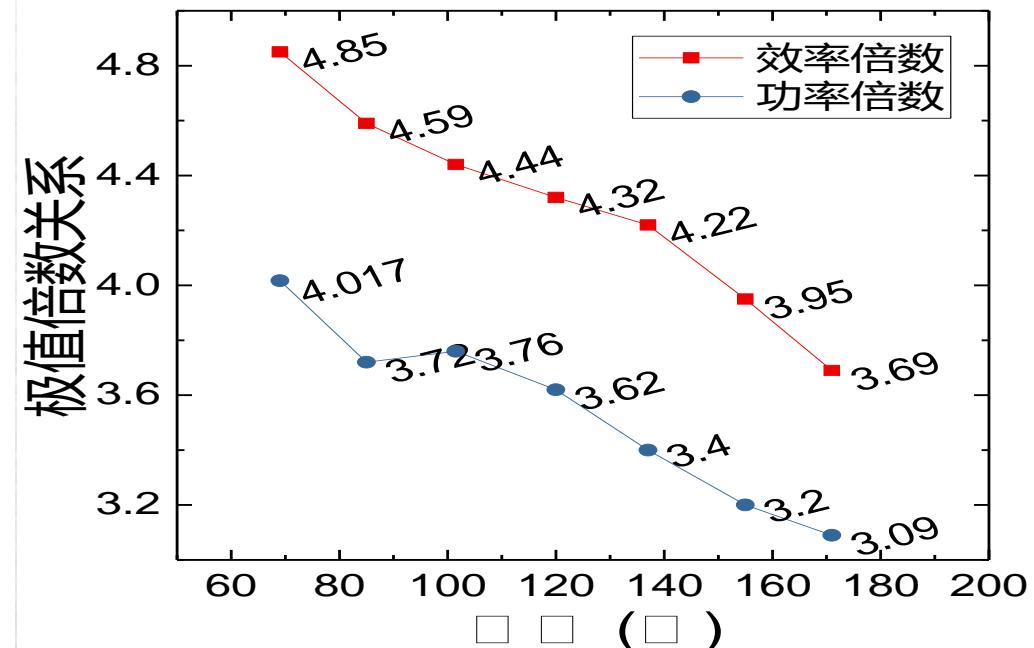
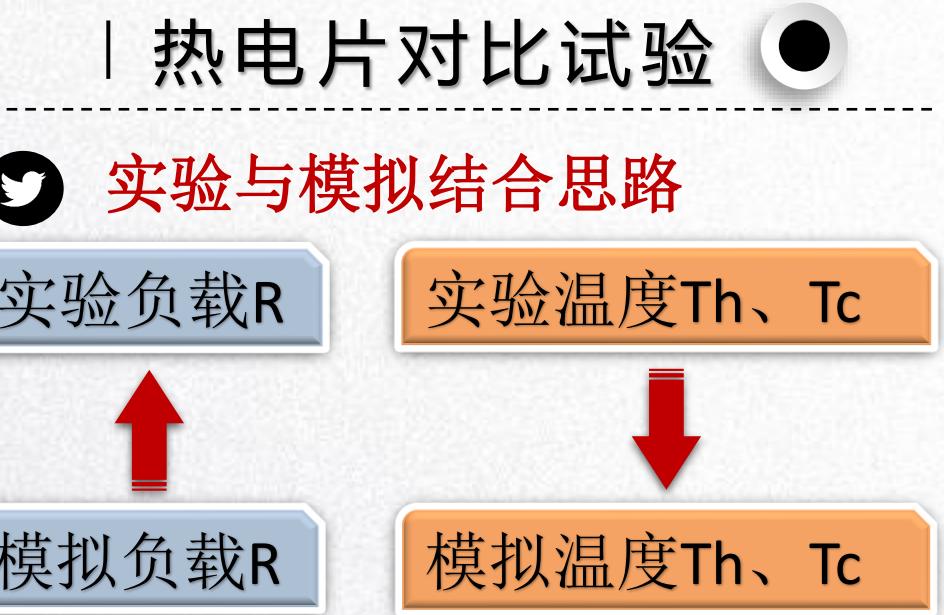


图2-性能极值点的倍数关系

# 热电片对比试验

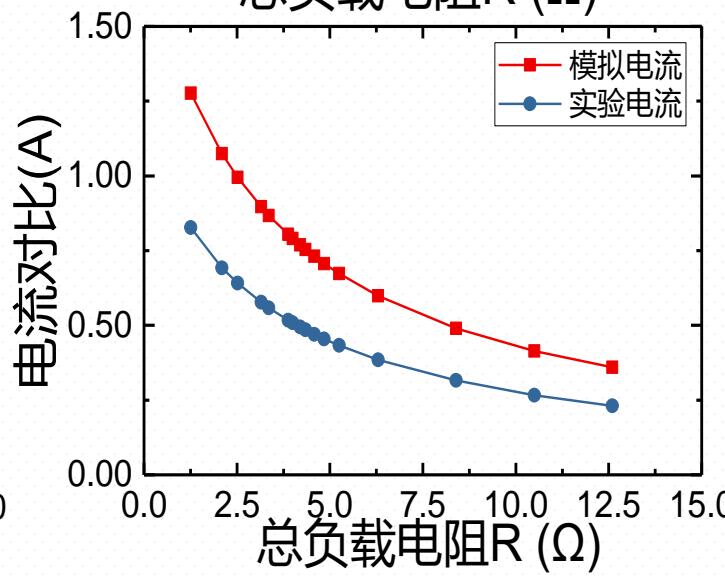
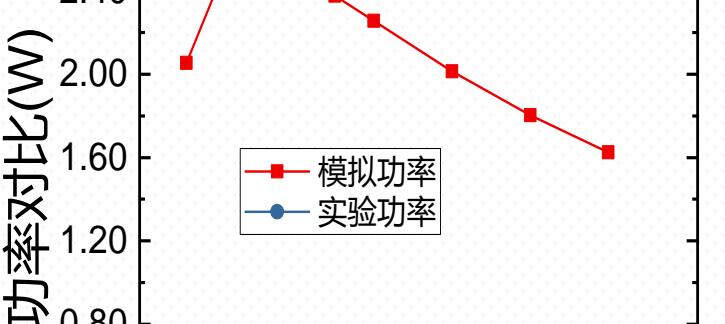
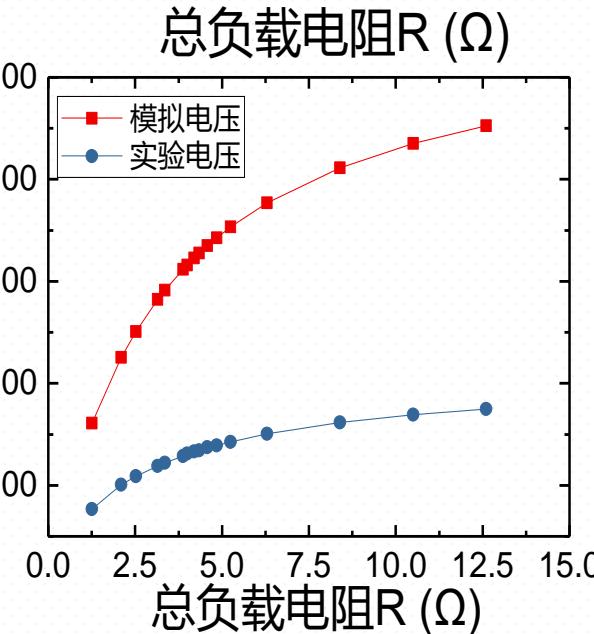
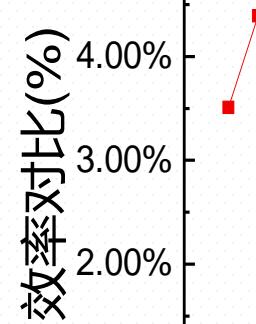


图1-温差120°C时实验与模拟对比

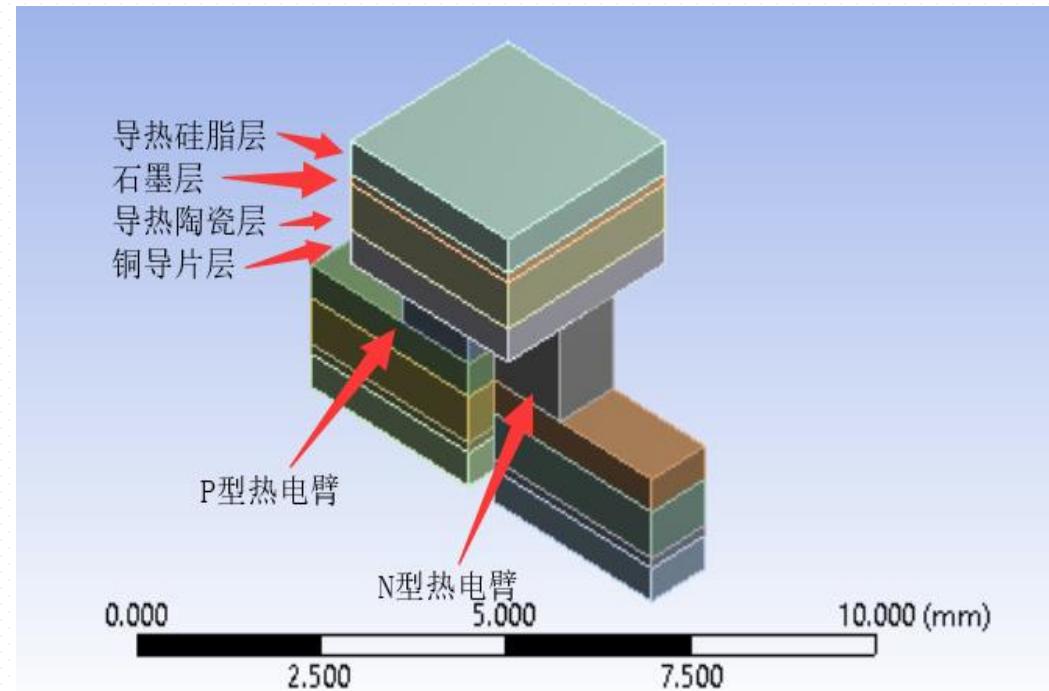


图2-实验用热电模型材料设置



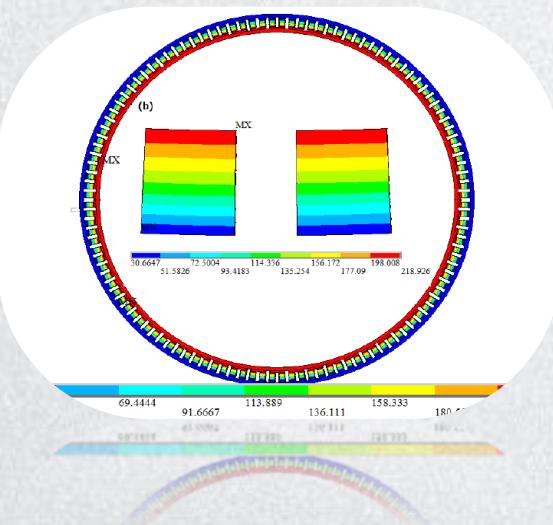
实验与模拟曲线趋势相同



实验与模拟数据呈现倍数关系



### 3. 直升机喷管热电模块设计





## 直升机喷管尺寸参数

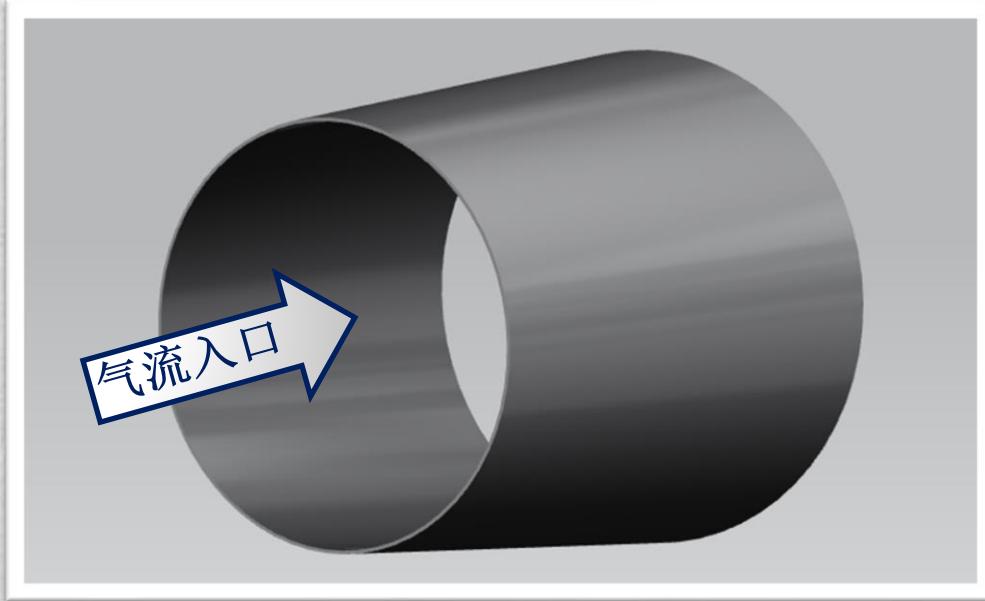


图1- 渐扩型亚音速喷管示意图

| 参数名称    | 尺寸(mm) |
|---------|--------|
| 喷管沿内径长度 | 320    |
| 喷管厚度    | 2      |
| 入口内直径   | 236    |
| 出口内直径   | 306    |

## | 直升机工况分析

- 直升机喷管入口速度: **0.4 Mach**
- 直升机喷管出口速度: **0.1 Mach**

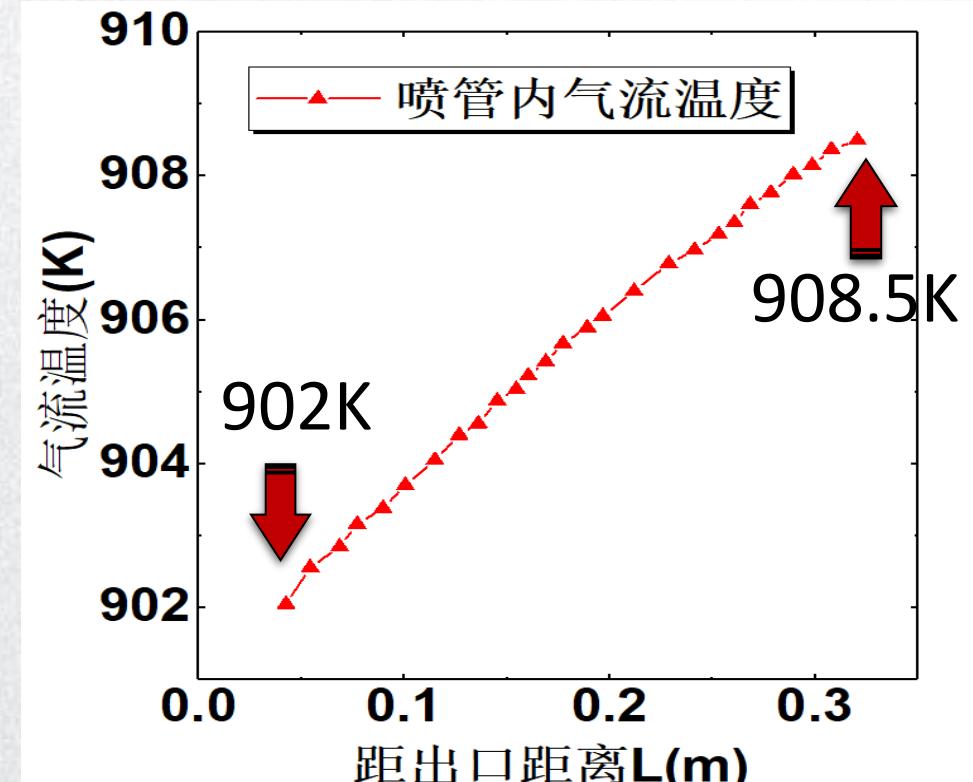
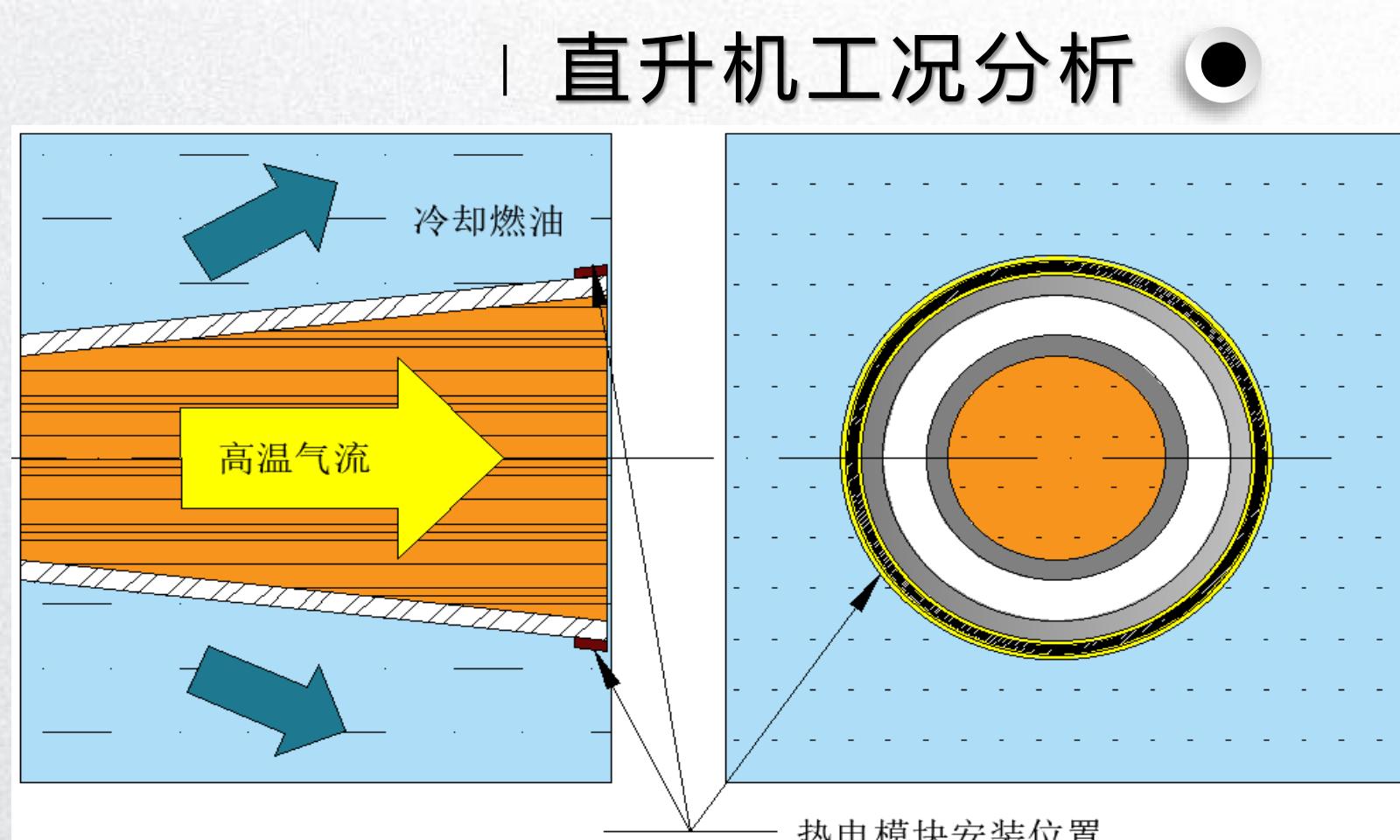
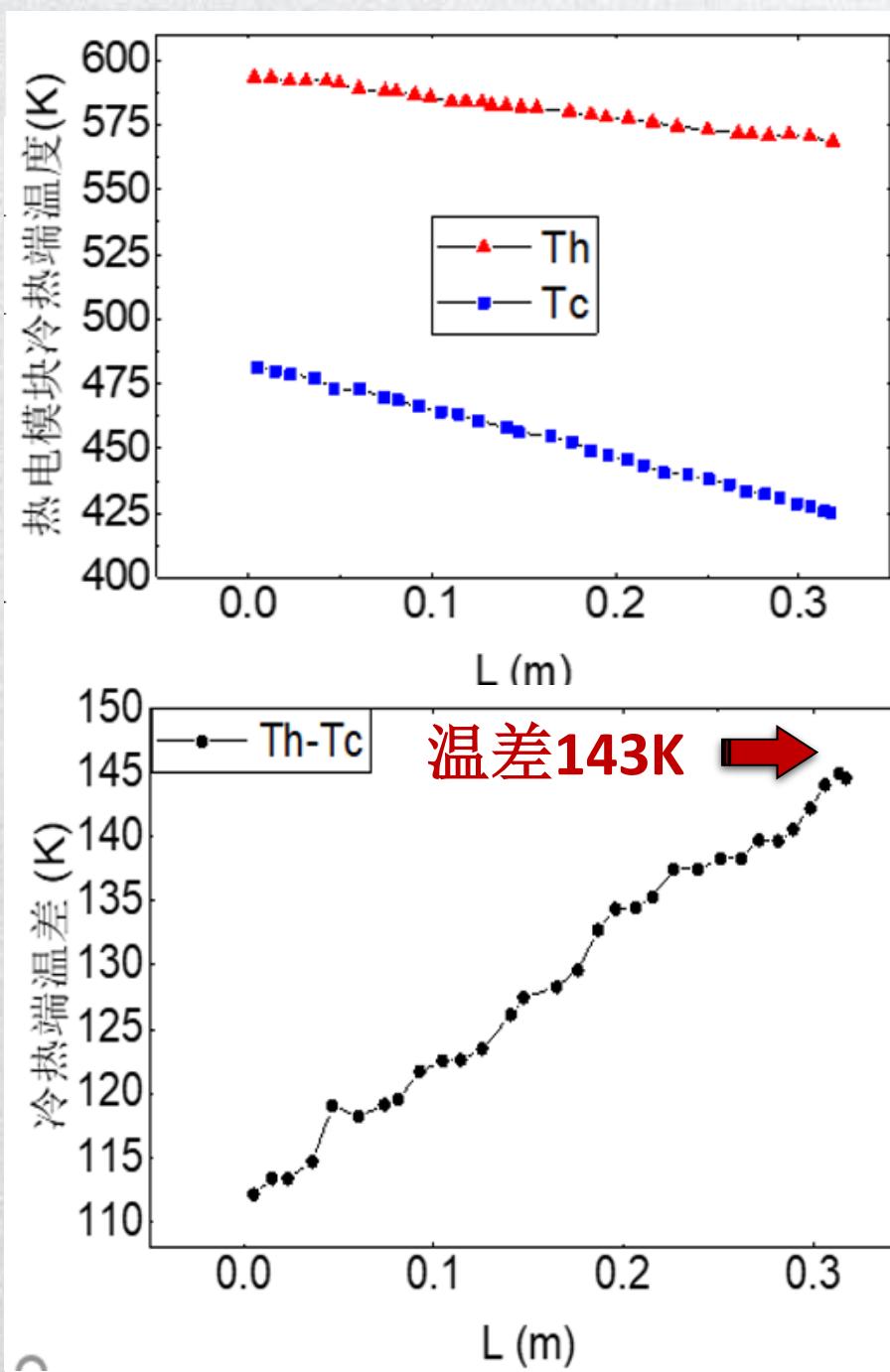


图2- 喷管内热流温度变化



巡航飞行状态

# 直升机工况分析



| 名称   | 压缩性 | 出口温度T(K) | 速度或流量    | 稳态传热 |
|------|-----|----------|----------|------|
| 热气流  | 可压缩 | 565      | 0.4Mach  | 是    |
| 冷却燃油 | 不可压 | 422      | 0.21kg/s | 是    |

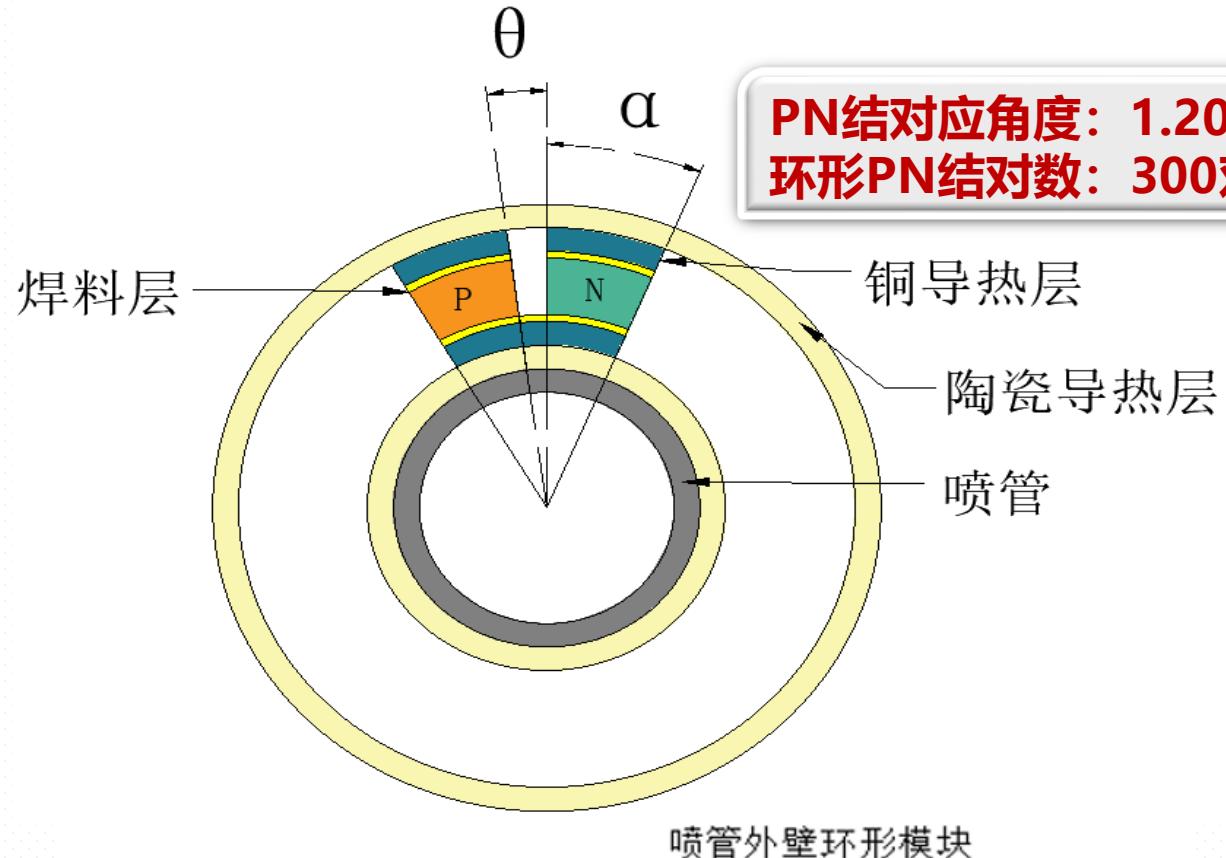


图1- 环形热电片示意图

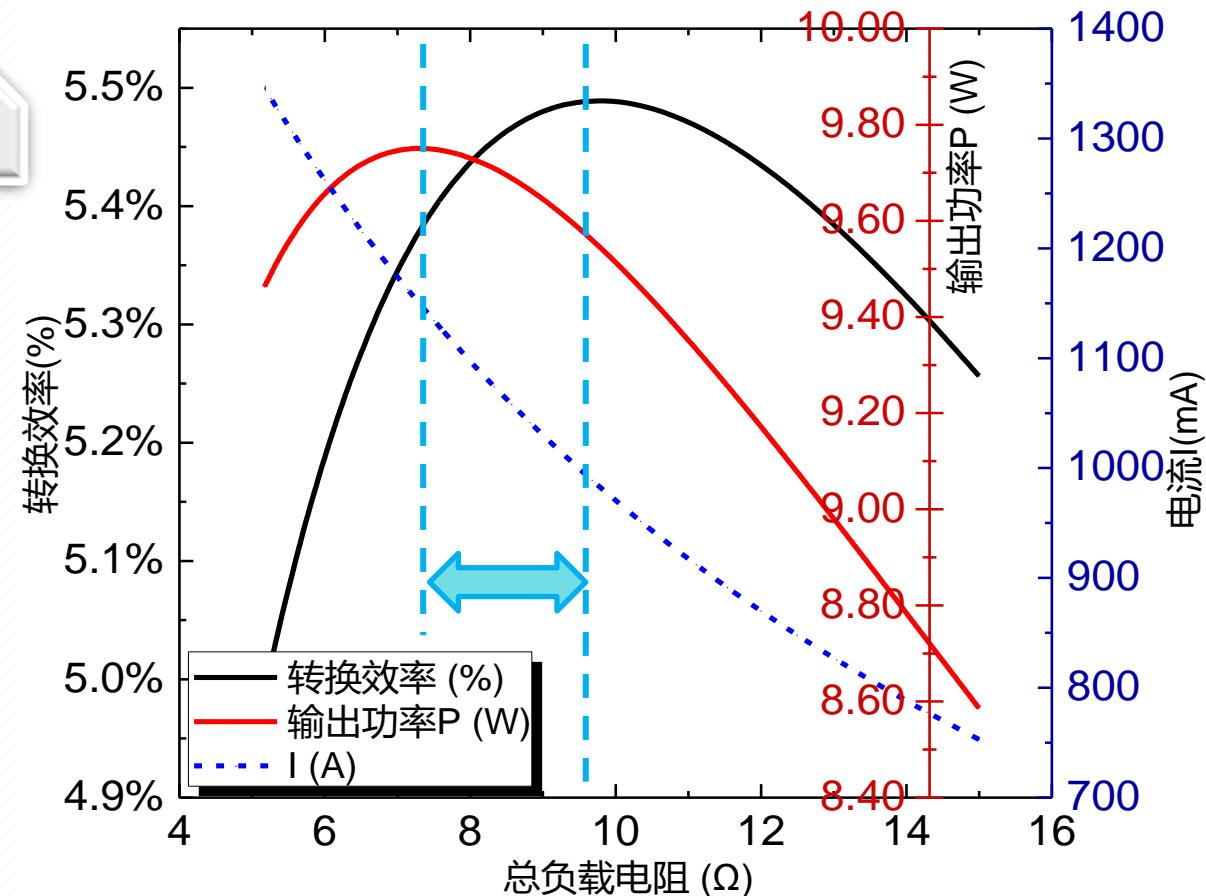


图2- 热电性能随负载电阻变化趋势图

热电性能极值点处于一定负载电阻区域  
效率极值点  $R=8.53\Omega$   
功率极值点  $R=10.34\Omega$

## 环形热电模块形状设计

# 热电片性能对比

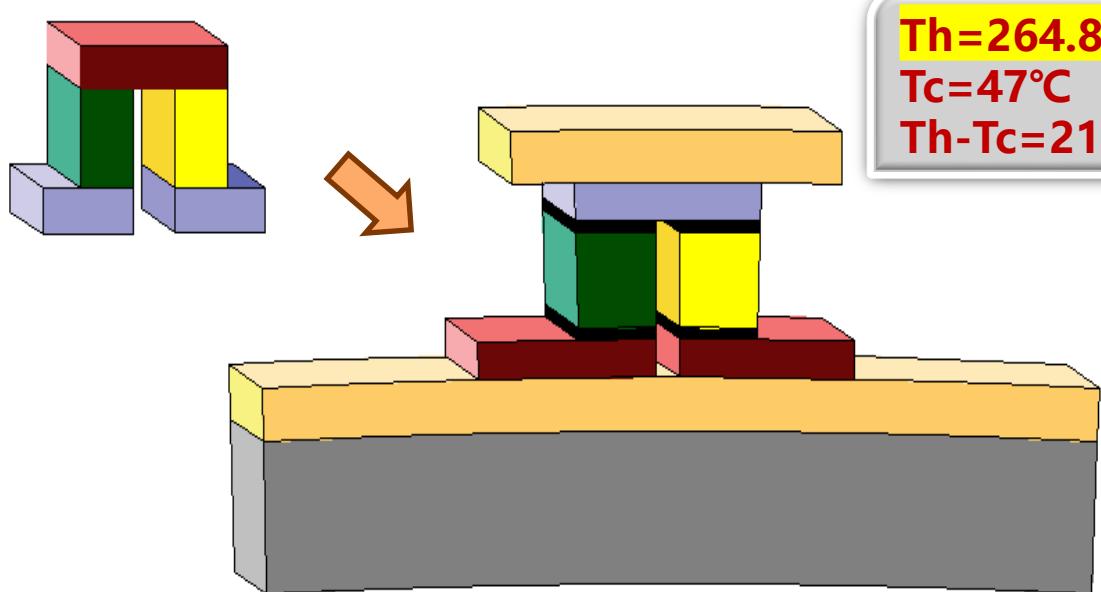
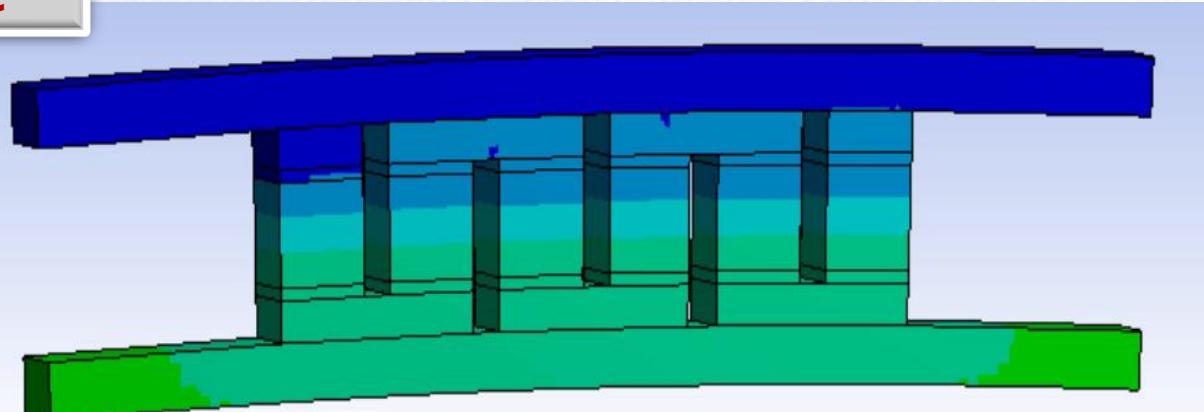


图-热电片对比示意图



视频-环形热电模块导热示意图

| 名称            | 输出电流<br><b>I(mA)</b> | 负载电压<br><b>U(mV)</b> | 吸收热量<br><b>Q(J)</b> | 输出功率<br><b>P(W)</b> | 转换效率<br><b>η(%)</b> |
|---------------|----------------------|----------------------|---------------------|---------------------|---------------------|
| 实验热电片<br>(单元) | 1134.6               | 27.7                 | 0.563               | 0.0314              | 5.581               |
| 环形热电片<br>(单元) | 1148.6               | 28.0                 | 0.598               | 0.0322              | 5.380               |
| 提升百分比%        | <b>1.23%</b>         | <b>1.08%</b>         | <b>6.22%</b>        | <b>2.55%</b>        | <b>-3.60%</b>       |

**环形热电模块:**

$$Q(t) = 178.8 \text{W}$$

$$P = 9.65 \text{W}$$

$$\eta = 5.380\%$$



## 安装接口设计

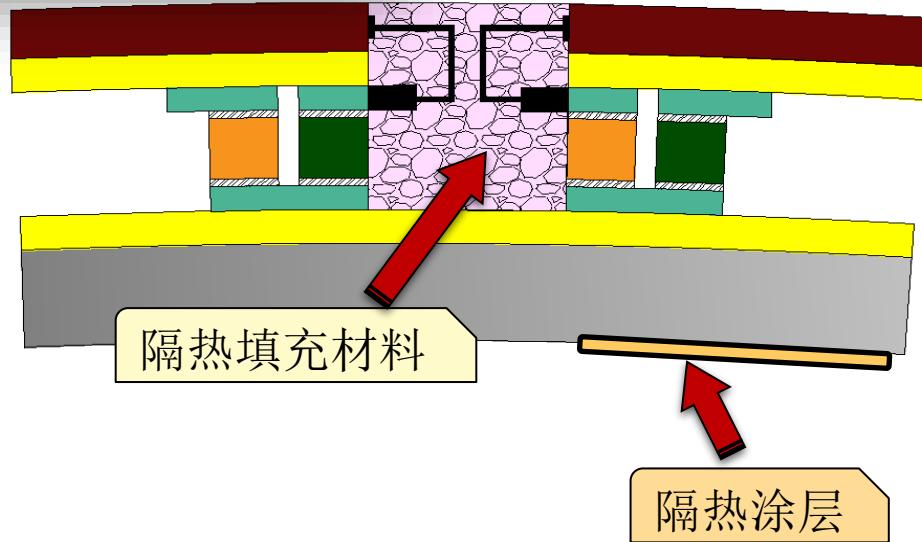


图1-环形热电模块设计



## 热电模块参数

热电模块重量(PN结+电阻+电路)

$$M = M_0 + M_R + M_E = 0.0759\text{kg}$$

功率重量比

$$\omega = \frac{P_{\max}}{M} = \frac{9.62}{0.0759} = 126.72(\text{W/kg})$$

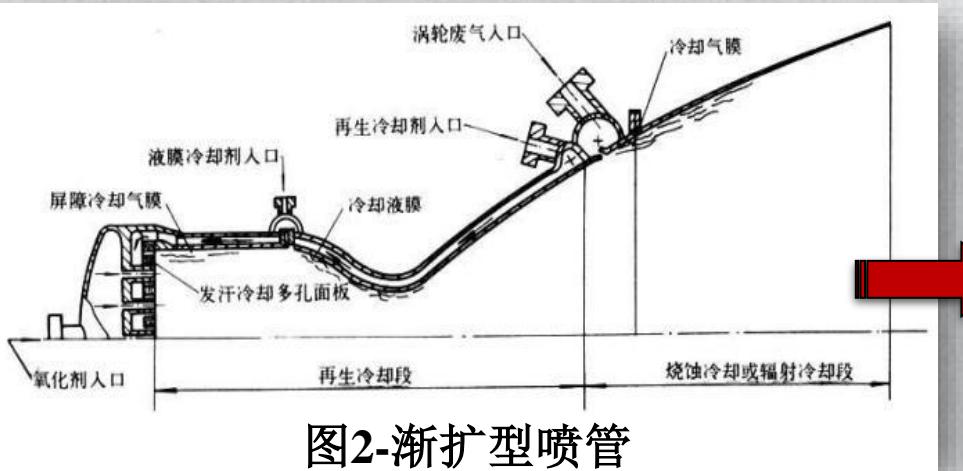
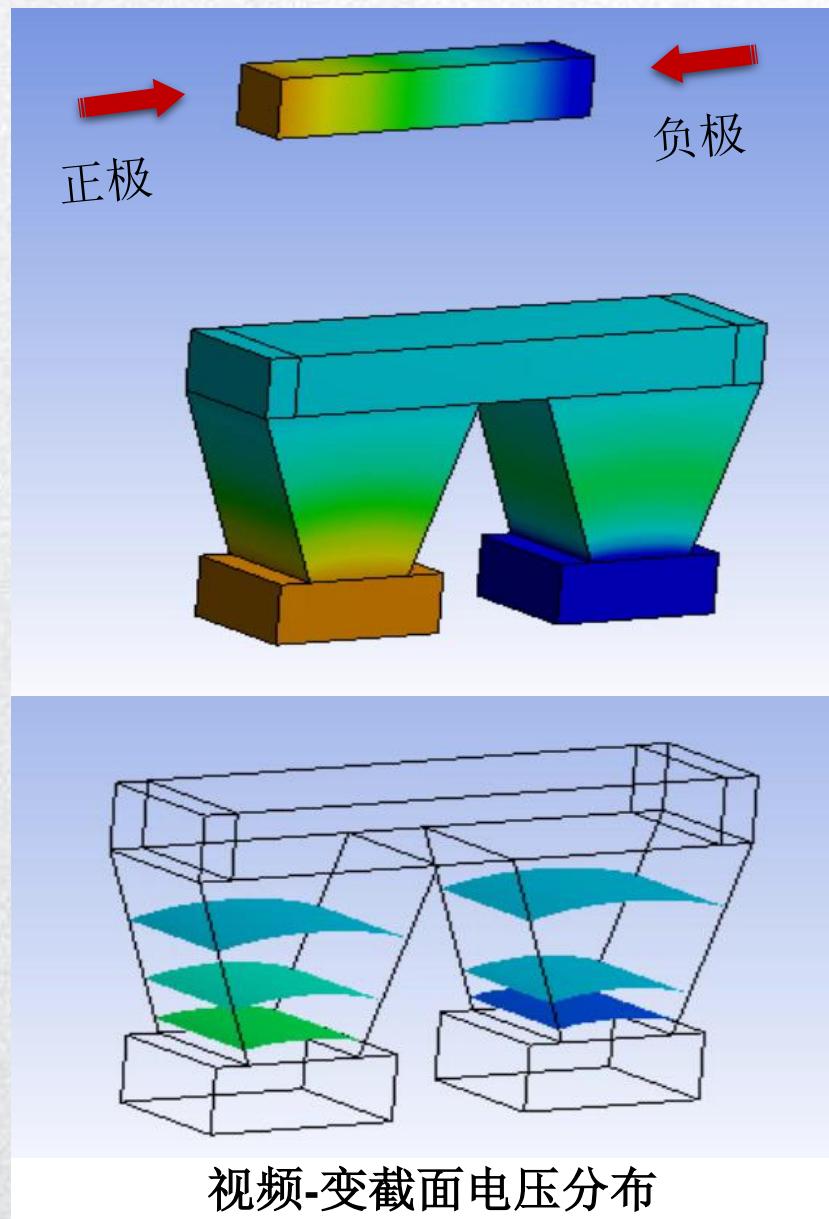
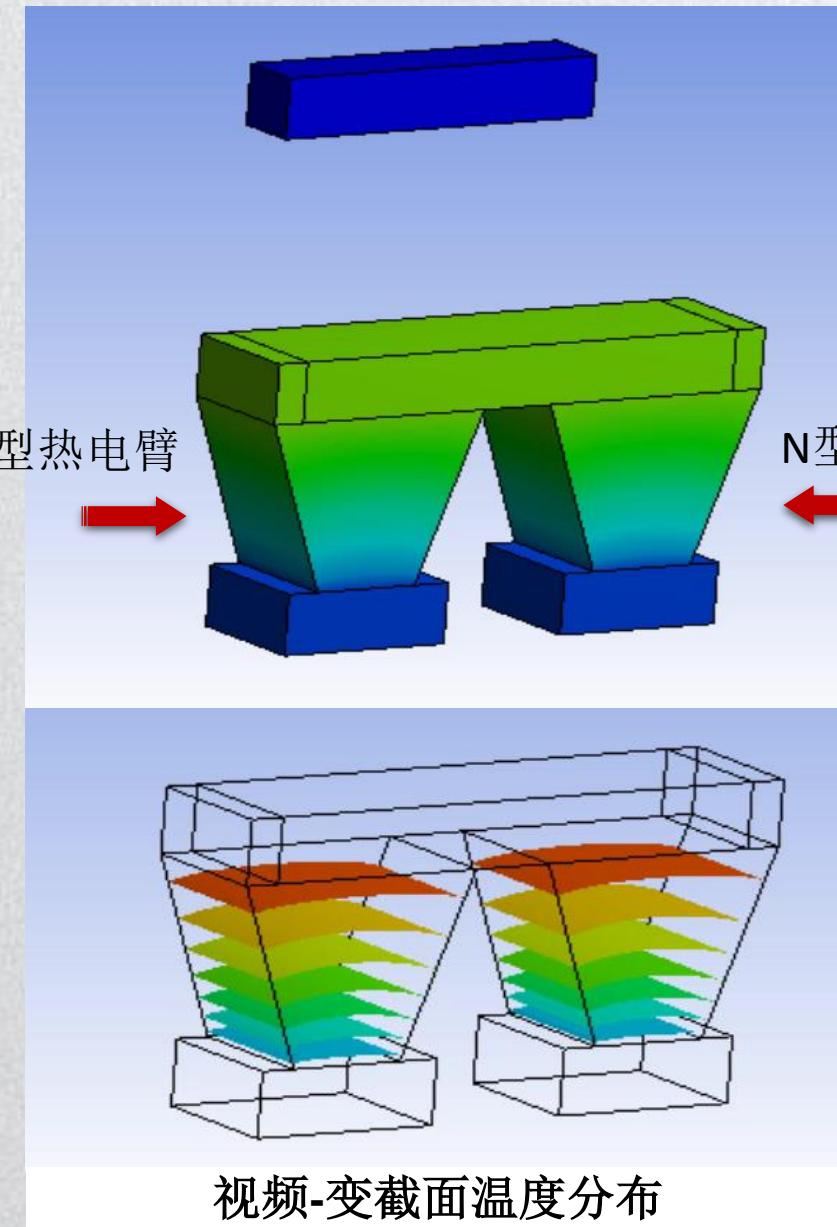


图2-渐扩型喷管

| 喷管材料 | 喷管外壁温度<br>T(°C) | 喷管重量<br>M(kg) | 热电模块比重<br>% |
|------|-----------------|---------------|-------------|
| 钛合金  | 264.8           | 3.426         | 2.22%       |

# ● 变截面热电模块-温度分布

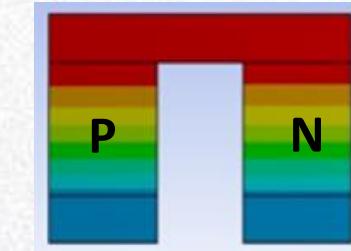


电压分布

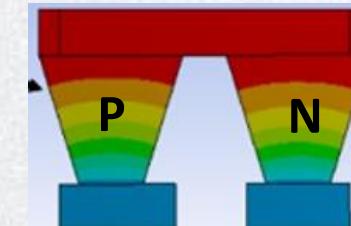
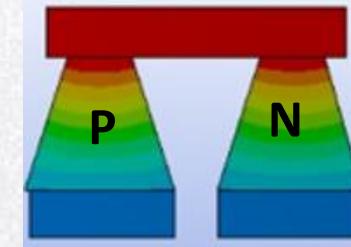
# ● 温度设置

$Th=247^{\circ}\text{C}$   
 $Tc=47^{\circ}\text{C}$   
 $Th-Tc=200^{\circ}\text{C}$

# ● 对照组模型设置



# ● 变截面模型设置



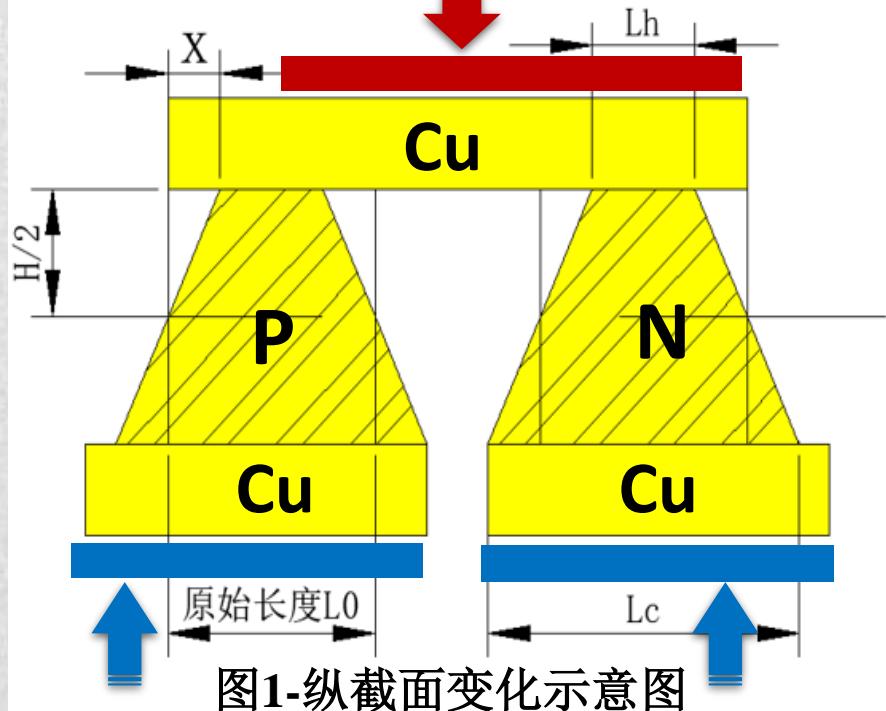


图1-纵截面变化示意图

$$\beta = \frac{L_h}{L_c} = \frac{L_0 + 2x}{L_0 - 2x}$$

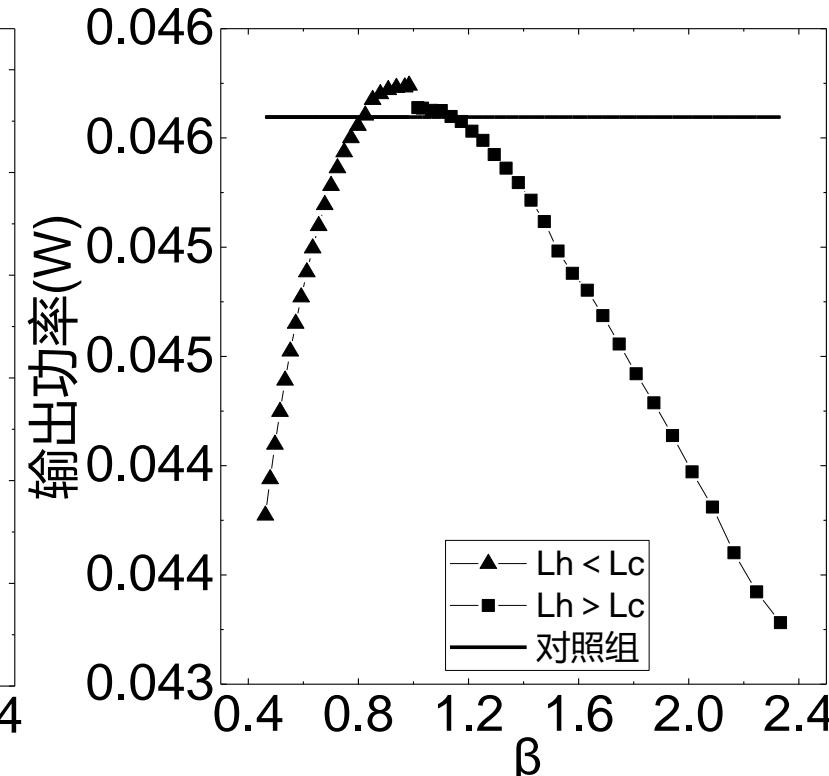
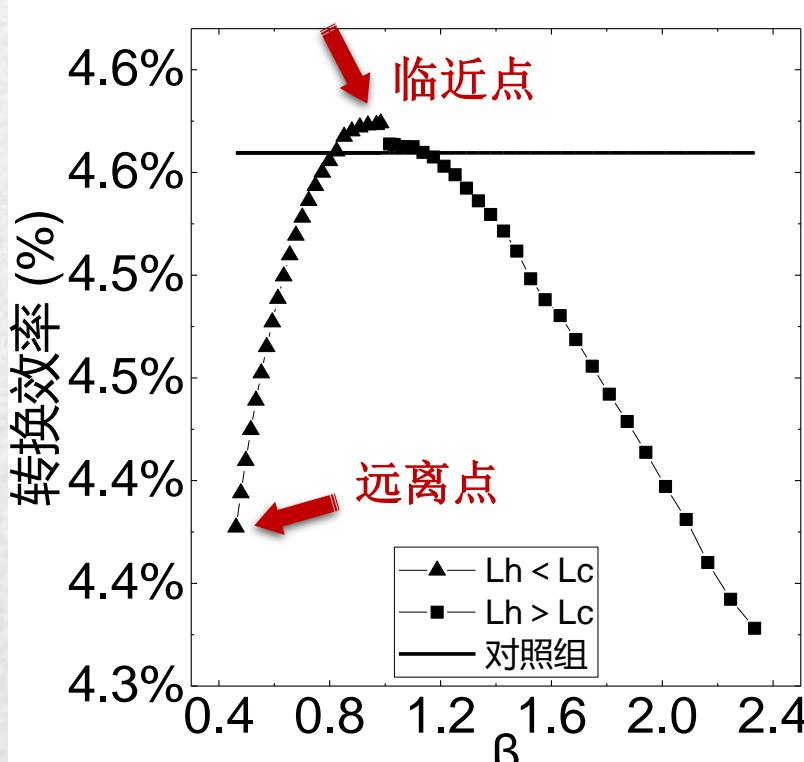
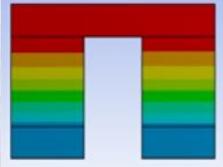


图2-热电性能随纵截面参数变化示意图

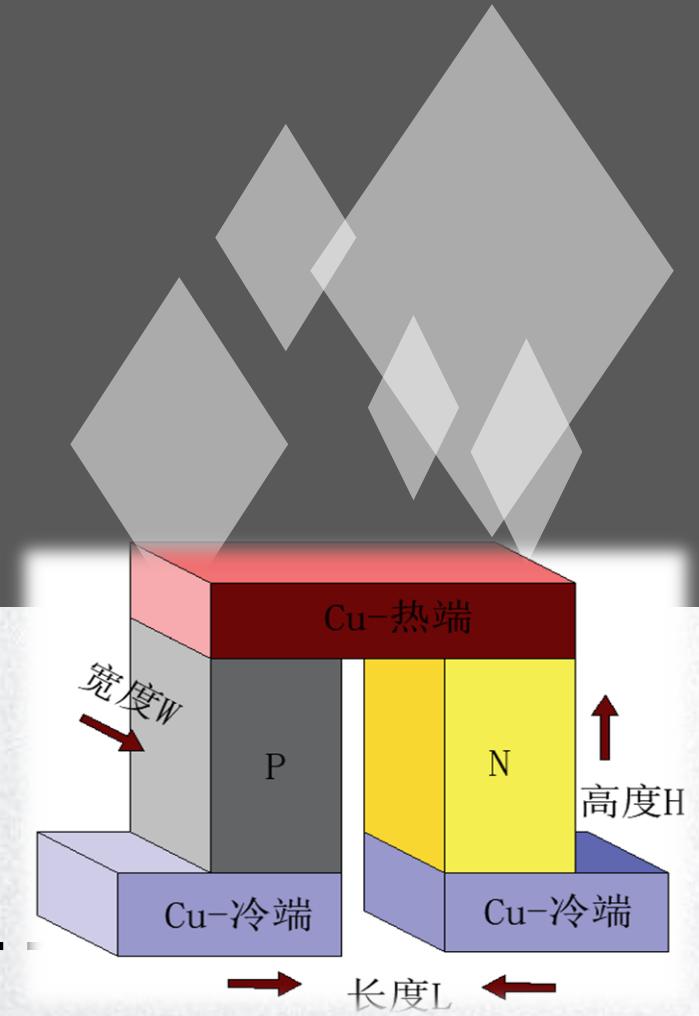
## 变截面热电模块分析

| 名称      | 对照组              | $L_h < L_c$ | $L_h > L_c$ |
|---------|------------------|-------------|-------------|
| 名称      | 转换效率:            | 转换效率        | 输出功率        |
| 临近点     | 4.560%           | 4.574%      | 0.04398W    |
| 远离点     | 输出功率:<br>0.0459W | 4.377%      | 0.03942W    |
| 最大偏离程度% |                  | 4.01%       | 14.12%      |
|         |                  |             | 5.08%       |
|         |                  |             | 20.28%      |

纵截面材料分布越不均匀，温度梯度弯曲程度越大，热电性能越差。

## 第四部分

# 总结



# ● 总结 |



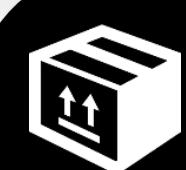
## 结论一

1. 提出基于转换效率极值确定**最佳尺寸方法**，改良后的模型热电转换效率提升了**37.30%**，输出功率提升了**285.14%**。



## 结论二

2. 建立**实验用数值模拟模型**，并对其修正后，模拟与实验的曲线**拟合性良好**，数值呈现变化的倍数关系。



## 结论三

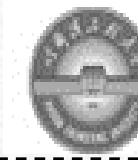
3. **变截面PN结**研究，得出结论为垂直于结厚度截面尺寸越不均匀，热电性能越差；而截面越接近矩形，热电性能越好。



## 结论四

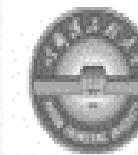
4. 设计了**武装直升机喷管处环形热电模块**、负载电阻与安装接口。直升机巡航飞行时环形热电模块单位时间吸收**178.8W**的热量，提供输出功率**9.62W**，转换效率为**5.380%**，功率质量比达到**126.7W/kg**

# 主要参考资料 |

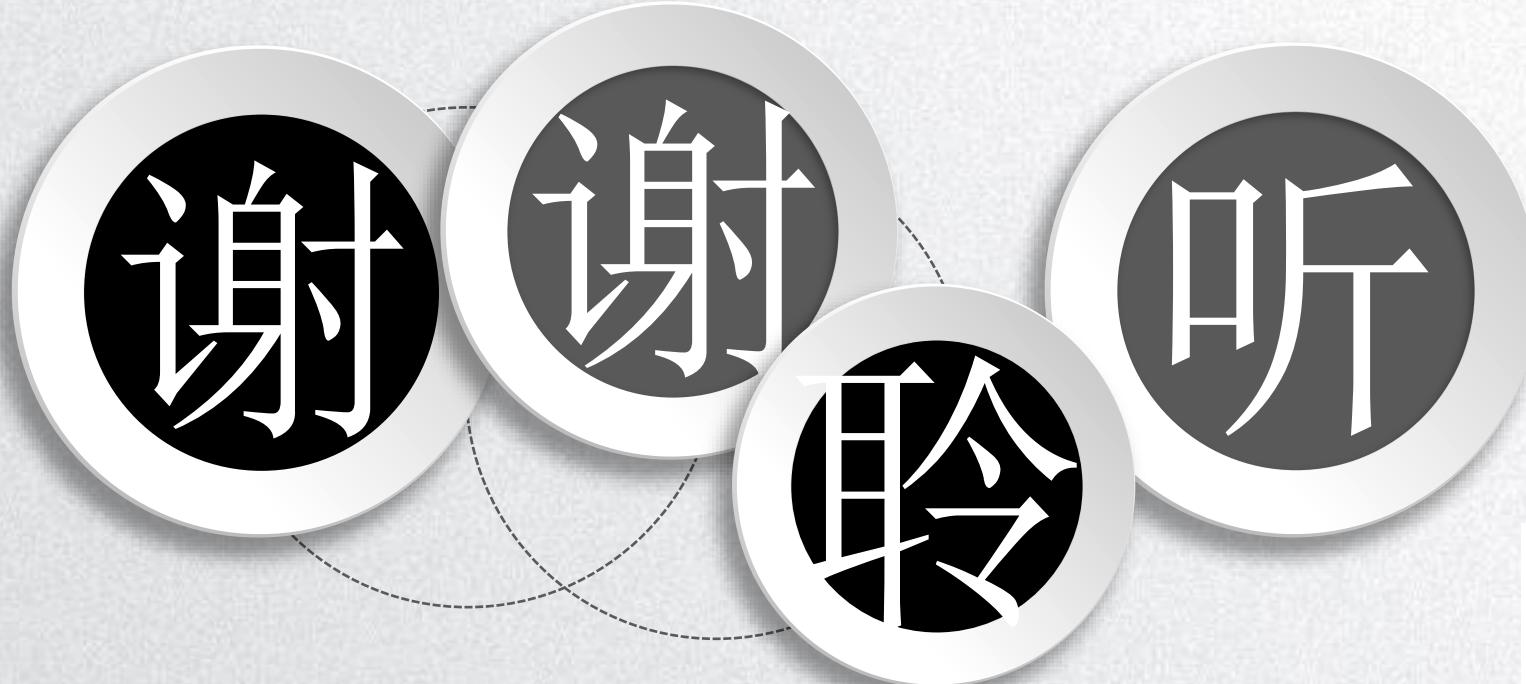


- [1] 党晓雪. 集成热电转换功能的新型热防护系统设计与分析[D]. 哈尔滨工业大学, 2015.
- [2] 许京荆. ANSYS 13.0 Workbench数值模拟技术[M]. 中国水利水电出版社, 2012: 396-401.
- [3] Ugur Erturun. Effect of Leg Geometries Configurations, and Dimensions on Thermo Mechanical and Power-Generation Performance of Thermoelectric Devices[D]. Virginia Commonwealth University, 2015.
- [4] 于凤荣,陈思彤,刘文鑫,等, Bi<sub>2</sub>Te<sub>3</sub>热电材料的研究现状与发展趋势[N]. 燕山大学学报.
- [5] Tarik Kousksoua, Bédécarratsa Jean-Pierre, Champierb Daniel, et al. Numerical study of thermoelectric power generation for an helicopter conical nozzle[J]. Journal of Power Sources, 2011, (196): 4026-4032.
- [6] Gequn Shu, Ma Xiaonan, Tian Hua, et al. Configuration optimization of the segmented modules in an exhaust-based thermoelectric generator for engine waste heat recovery[J]. Energy, 2018, (120): 612-624.

# 主要参考资料 |



- [7] Xiaolin Chen, Liu Yijun. Finite Element Modeling and Simulation with ANSYS Workbench[M]. Boca Raton, FL: CRC Press Taylor & Francis Group, 2014: 22.
- [8] G-P Chhalotra. Electric Engineering Experiments[M]. Boston: Mercury Learning and Information, 2018.
- [9] Shifa Fan, Gao Yuanwen. Numerical Simulation on Thermoelectric and Mechanical Performance of Annular Thermoelectric Generator[J]. Energy, 2018, (124): 1-21.
- [10] A-S Korotkov, Loboda V-V, Makarov S-B, et al. Modeling thermoelectric generators using the ANSYS software platform: Methodology, practical applications, and prospects[J]. Russian Microelectronics, 2017, 46(2): 131-138



哈尔滨工程大学  
Harbin Engineering University

THANKS FOR YOUR TIME!