

# 高温作业专用服装的设计

## 摘 要

本文建立了复合介质中的热传导模型, 单目标最优厚度模型, 双目标最优厚度模型, 一维热传导与傅里叶混合模型差分方程求解的有限元网格模型和多目标进化算法(MOEA)等, 较为全面地对不同温度环境和满足不同限定条件下的多层介质模型, 进行了温度分布的求解以及对对应要求介质层厚度的求解。

对于问题一, 确定温度场模型, 我们首先定性分析, 选取了比热容、密度、热传导率、厚度、传热系数作为影响传热的因素. 通过分离变量法和积分变换法求得了复合介质中的热传导模型的理论解

$$u_i(x, t) = \sum_{m=1}^{\infty} \frac{X_i(\beta_m, x)}{N(\beta_m)} e^{-\beta_m^2 t} \left[ \bar{F}(\beta_m) + \int_0^t e^{\beta_m^2 t'} A(\beta_m, t') dt' \right], \quad x_{i+1} < x < x_i.$$

然后使用牛顿冷却模型的计算和 ANSYS 的模拟, 得出 I 层与空气接触界面的温度变化情况。接着, 通过有限元网格法得出划定边界区域内的热量分布。最后, 反解每个网格节点的温度状况, 进而近似得出各个层次的温度分布数据。

对于问题二, 我们建立单目标最优厚度模型, 并结合问题一中的复合介质模型背景, 结合 MATLAB 和 ANSYS 进行离散化后求解, 设立边界条件, 确定隔热效果和材料使用成本为最优化目标条件, 进而通过单边复合介质的热传导, 完成热传导问题在目标函数条件下的迭代求解过程, 同时考虑题目限制条件, 最终求得 II 层的最优厚度为 6.372 mm.

对于问题三, 我们建立了双目标最优厚度模型, 并利用 Weighted Sum 方法来进行辅助求解. 由于问题一得到的温度场模型求解时间较长, 我们将 II 层等分为步长为 6.1mm 的由 0.6mm 到 25mm 的 4 个厚度梯度, 同样将 IV 层等分为步长为 1.45mm 的由 0.6mm 到 6.4mm 的 4 个厚度梯度。利用问题一中所得出的温度场模型对 16 种情况进行计算, 得出 16 组温度分布数据。并利用超过 44°C 的时间与超过 47°C 的情况进行可行域的计算与 II 层、IV 层的条件多项式计算。最后利用多目标进化模型对最优厚度进行求解。最终得到 II 层的最优厚度为 13.15mm, IV 层的最优厚度为 5.40mm.

**关键词** 复合介质热传导模型 积分变换法 ANSYS 有限元网格法 双目标最优厚度模型

# 一、问题重述

## 1.1 引言

在高温环境下工作时，比如消防员实施救火工作时，深入某些恶劣环境进行科研调查时，人们需要穿着专用的服装来避免灼伤。所谓的专用服装，通常由三层织物材料来构成，记为 I、II、III 层，其中 I 层与外界环境接触，III 层与皮肤之间还存在空隙，将此空隙记为 IV 层；这些间隙都很小，以毫米记。

## 1.2 问题的提出

为设计专用服装，模拟实际情况，现将体内温度控制在  $37^{\circ}\text{C}$  的假人放置在实验室的高温环境中，并以 1 秒为间隔实时测量假人皮肤外侧的温度。为了降低研发成本、缩短研发周期，请你们建立数学模型，来确定假人皮肤外侧的温度变化情况，并解决以下问题：

1. 专用服装材料的某些参数值已经由附件 1 给出，对环境温度为  $75^{\circ}\text{C}$ 、II 层厚度为 6 mm、IV 层厚度为 5 mm、工作时间为 90 分钟的情形开展实验，测量得到假人皮肤外侧的温度（见附件 2）。建立数学模型，计算温度分布，并生成温度分布的 Excel 文件（文件名为 problem1.xlsx）；

2. 当环境温度为  $65^{\circ}\text{C}$ 、IV 层的厚度为 5.5 mm 时，试确定 II 层的最优厚度，以确保工作 60 分钟时，假人皮肤外侧温度不超过  $47^{\circ}\text{C}$ ，且超过  $44^{\circ}\text{C}$  的时间不能超过 5 分钟；

3. 当环境温度为 80 时，试确定 II 层和 IV 层的最优厚度，确保工作 30 分钟时，假人皮肤外侧温度不超过  $47^{\circ}\text{C}$ ，且超过  $44^{\circ}\text{C}$  的时间不能超过 5 分钟。

## 二、问题分析

### 2.1 问题一的分析

问题一要求在给出环境温度和假人外皮肤的温度分布,且各个服装层的参数均确定时,建立其温度场的数学模型,并由此得出温度分布。

首先我们讨论并选取了影响传热的因素,并分析三层专用服装材料的主要传热方式: I-IV 层之间热传递以热传导为主,而 IV 层由于空气层间隙较小,热对流的影响可以忽略,可使用热传导模型进行求解。

建立的模型为微分方程模型,转化为复合介质中的热传导模型后,便可以利用分离变量法和积分变换法获得理论解,也是精确解。然后尝试利用 MATLAB 来求解,对于比较复杂的方程, MATLAB 得不出解。因此我们使用有限元网络法,采用 Implicit-Euler 差分格式以离散连续变量来求解。

之后也确定了空气与 I 层的热对流模型。由于接触面存在热阻,我们应当将接触热阻纳入考虑之中。之后,由外部环境 with I 层的热对流模型以及 I 到 IV 层的热传导模型,可以建立一维温度场与傅里叶混合模型。所建立的模型得到的假人皮肤外侧温度与测量得到温度基本一致。为了验证温度分布的正确性,我们通过 ANSYS APDL 模拟热对流模型,利用 ANSYS workbench 模拟 90 分钟后的稳态热传导模型,得到的结果与温度场模型中的温度分布有较小的出入,我们籍此优化了之前得到的温度场模型。

### 2.2 问题二的分析

在问题一的背景下,我们考虑一个介质参数未知的优化问题。由基本服装设计的要求可以得到 II 层厚度的范围,我们可以假设比热容,热传导率和密度不变,根据两个时间条件写出来又作为约束条件,最后根据满足题目要求,成本尽量低的原则得到目标。

在求解时,受第一问的启发。需要先将连续变量离散化,然后再在问题以求解复合介质的基础上进行求解即可。

### 2.3 问题三的分析

问题三中,情况更为的复杂,因为此时 II 层与 IV 层都是目标,其约束条件与问题二类似,我们仍可以假设比热容,热传导率和密度不变,根据两个时间条件写出来来作为约束条件。

在求解过程中,注意到虽然仍在复合介质的热传导模型背景下,以及使用离散化的方法来作为主要方法求解模型,但是多目标的求解迭代次数更多。鉴于此,我们可以使用 Weighted Sum 方法, Tchebycheff 方法或有界插值方法等进行降维转化,再进行求解。

### 三、模型假设

考虑到高温作业专用服装设计问题的复杂性, 我们提出下列假设来简化问题:

1. 假设热传递是沿垂直于假人皮肤方向进行的, 因此可视为一维 (垂直于皮肤) 的;
2. 服装的 I, II 和 III 层是各向同性的, 并且空气间隙 I 层与环境也是各向同性的;
3. 服装层 I–III 层之间, 服装与假人空气间隙 I 层的温度分布都是连续变化的;
4. 当外界环境温度稳定且较低时, 热辐射相对于热传导和热对流可以忽略不计.

### 四、符号说明

符号	意义
$u_i$	第 $i$ 层的温度分布
$u_\infty$	环境温度
$k_i$	第 $i$ 层的热传导率
$c_i$	第 $i$ 层的比热容
$L_i$	第 $i$ 层的间距
$h_{i,i+1}$	第 $i$ 层与 $i+1$ 层的换热系数
$I_i(x)$	第 $i$ 层的初始条件
$\beta$	本征值
$ M $	$n$ 方阵 $M$ 的行列式
$X(\beta_m, x)$	本征函数
$Q(x, t)$	内热源
$\chi$	特征函数
$Goal_{L_i}$	目标函数
$\lambda_i$	权重向量

## 五、模型的建立与求解

### 5.1 问题一：服装的温度分布

将服装的 I–IV 层视作一个复合介质, 题中给出了该种服装材料的参数, 此时 I 的左边界条件就是测量所得的假人皮肤外侧的温度, 以及由题知 IV 的右边界条件跟环境温度有关, 此时建立的是复合介质中的热传导模型, 来计算服装中 I, II 和 III 层与 IV 层的温度分布.

#### 5.1.1 复合介质的热传导模型

从传热学的基本理论, 我们知道热传递主要存在三种形式, 即热传导, 热对流, 以及热辐射, 为了讨论在本问题中热传递的形式, 我们参照文献 [1], 给出它们的定义如下:

1. **热传导.** 物体各部分之间不发生相对位移时, 依靠分子, 原子及自由电子等微观粒子的热运动而产生的热能传递.
2. **热对流.** 由于流体的宏观运动而引起的流体的各部分之间发生相对位移, 冷, 热流体相互掺混所导致的热量传递过程. 热对流发生在流体中, 并且热对流必然伴随有热传导现象.
3. **热辐射.** 物体通过电磁波来传递能量的方式.

根据假设 1, 温度分布对于空间是一维的, 设 I 层, II 层, III 层和 IV 层的温度分别为  $u_1(x, t)$ ,  $u_2(x, t)$ ,  $u_3(x, t)$ ,  $u_4(x, t)$ , 记  $u_\infty$  为环境温度;

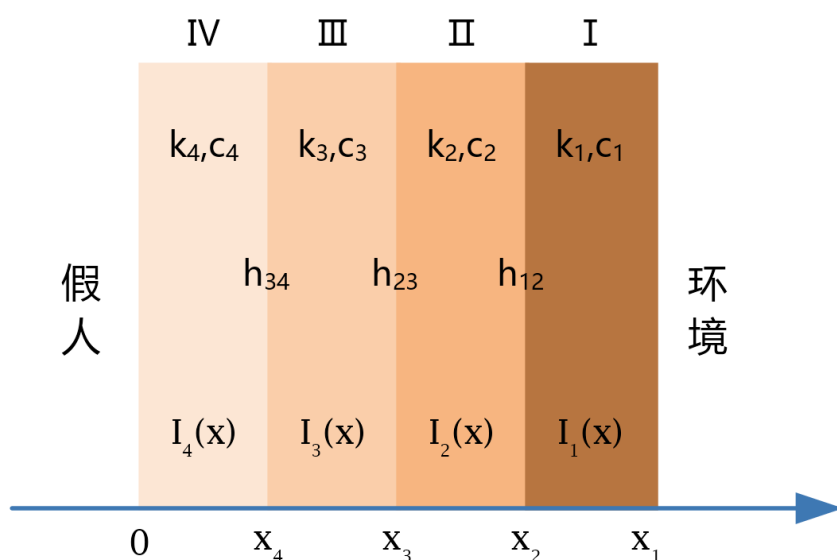


图 1 四层复合介质的热传导

如图 1, 设各层的热传导率分别为  $k_i, i = 1, 2, 3, 4$ , 比热容依次为  $c_i, i = 1, 2, 3, 4$ , 以假人的皮肤为原点  $O$ , 设各个边界的坐标依次为  $x_4, x_3, x_2, x_1$ , 为统一起见, 也记原点为

$x_5$ , 则各层的距离为

$$L_i = |x_i - x_{i+1}|, \quad i = 1, 2, 3, 4. \quad (1)$$

假设中, 由于室温为  $75^\circ\text{C}$  不是特别高, 因此可以不考虑热辐射的影响, 而由文献 [2] 得知, 当假人皮肤与服装之间空气层厚度小于  $6.4 \text{ mm}$  时, 由于空气层间隙太小, 无法形成对流运动, 则此时以热传导为主. 此外, 根据热对流的定义, 在 I–III 层之间热传递都以热传导为主, 在 I 层与外界环境之间, 则存在热对流.

于是按照文献 [3] 的推导, 得到控制方程为

$$\begin{cases} c_1 \rho_1 \frac{\partial u_1}{\partial t} = \frac{\partial}{\partial x} \left( k_1 \frac{\partial u_1}{\partial x} \right), & x_2 < x < x_1, \\ c_2 \rho_2 \frac{\partial u_2}{\partial t} = \frac{\partial}{\partial x} \left( k_2 \frac{\partial u_2}{\partial x} \right), & x_3 < x < x_2, \\ c_3 \rho_3 \frac{\partial u_3}{\partial t} = \frac{\partial}{\partial x} \left( k_3 \frac{\partial u_3}{\partial x} \right), & x_4 < x < x_3, \\ c_4 \rho_4 \frac{\partial u_4}{\partial t} = \frac{\partial}{\partial x} \left( k_4 \frac{\partial u_4}{\partial x} \right), & x_5 < x < x_4. \end{cases} \quad (2)$$

下面我们推导边界条件和初始条件. 对于边界条件, 考虑 IV 层的左边界, 已经由实验测得假人皮肤外侧的温度, 它是时间的函数

$$u_4(x, t) \Big|_{x=0} = f(t), \quad t \geq 0, \quad (3)$$

考虑 IV 层和 III 层的接触面, 此处以对流形式进行换热, 由牛顿冷却定律可以推得

$$-k_3 \frac{\partial u_3}{\partial x} \Big|_{x=x_4} = h_{34}(u_3 - u_4) \Big|_{x=x_4}, \quad (4)$$

式中  $h_{34}$  是换热系数, 与 IV 层的热传导率  $k_4$  有关, 若记  $Nu$  为努塞尔特数, 则

$$h_{34} = Nu \frac{k_4}{L_4}. \quad (5)$$

此时, 应有热量交换值相等, 即

$$k_3 \frac{\partial u_3}{\partial x} \Big|_{x=x_4} = k_3 \frac{\partial u_3}{\partial x} \Big|_{x=x_4}. \quad (6)$$

同理可以推得 I 层与外界环境之间存在关系

$$-k_1 \frac{\partial u_1}{\partial x} \Big|_{x=x_1} = h_{1\infty}(u_1 - u_\infty) \Big|_{x=x_1}, \quad (7)$$

式中  $h_{1\infty}$  是换热系数, 这里我们取  $h_{1\infty} = 20 \text{ W}/(\text{m}^2 \cdot \text{K})$ .

接下来考虑服装内部 I–III 层之间接触面的边界条件, 此时换热系数为界面热阻的倒数, 我们考虑理想情况, 即界面温度连续, 则有

$$u_i \Big|_{x=x_{i+1}} = u_{i+1} \Big|_{x=x_{i+1}}, \quad i = 1, 2, \quad (8)$$

且换热系数  $h_{i,i+1} \rightarrow \infty, i = 1, 2$ , 于是可以写成第 3 类边界条件 (4) 形式, 考虑能量守恒, 又有

$$k_1 \frac{\partial u_1}{\partial x} \Big|_{x=x_2} = k_2 \frac{\partial u_2}{\partial x} \Big|_{x=x_2}, \quad k_2 \frac{\partial u_2}{\partial x} \Big|_{x=x_3} = k_3 \frac{\partial u_3}{\partial x} \Big|_{x=x_3}. \quad (9)$$

现在考虑初始条件. 记  $u(x, t)$  为诸  $u_i(x, t)$  在整个复合介质区间上的温度分布. 一般地, 我们设

$$u(x, t) \Big|_{t=0} = I_i(x), \quad x_i \leq x \leq x_{i+1}, \quad i = 1, 2, 3, 4. \quad (10)$$

为简单起见, 将  $c_i, \rho_i, k_i$  均视为常数, 只和材料有关, 并记

$$\alpha_i = \frac{k_i}{c_i \rho_i}, \quad i = 1, 2, 3, 4. \quad (11)$$

于是结合式 (2) – (10) 可得温度分布的数学模型为

$$\alpha_i \frac{\partial^2 u_i}{\partial x^2} = \frac{\partial u_i}{\partial t}, \quad x_{i+1} < x < x_i, \quad i = 1, 2, 3, 4, \quad (12)$$

$$\begin{cases} -k_i \frac{\partial u_i}{\partial x} \Big|_{x=x_{i+1}} = h_{i,i+1}(u_i - u_{i+1}) \Big|_{x=x_{i+1}}, \\ k_i \frac{\partial u_i}{\partial x} \Big|_{x=x_{i+1}} = k_{i+1} \frac{\partial u_{i+1}}{\partial x} \Big|_{x=x_{i+1}}, \end{cases} \quad i = 2, 3, 4, \quad (13)$$

$$-k_1 \frac{\partial u_1}{\partial x} \Big|_{x=x_1} = h_{1\infty}(u_1 - u_\infty) \Big|_{x=x_1}, \quad (14)$$

$$u_4(x, t) \Big|_{x=0} = f(t), \quad (15)$$

$$u(x, t) \Big|_{t=0} = I_i(x), \quad x_{i+1} \leq x \leq x_i, \quad i = 1, 2, 3, 4. \quad (16)$$

现在我们从理论上来求解此模型, 即求解复合介质的热传导问题. 注意到这个模型不是非齐次的, 于是我们先求解对应齐次问题, 再应用积分变换法求解即可. 首先注意到式 (14) 可化为

$$\left( k_1 \frac{\partial u_1}{\partial x} + h_{1\infty} u_1 \right) \Big|_{x=x_1} = h_{1\infty} u_\infty, \quad (17)$$

于是当上式右端项  $h_{1\infty} u_\infty$  与式 (15) 中  $f(t)$  为 0 时化为齐次类型, 并且此时均能写作式 (17) (右端为 0) 的形式, 记式 (15) 相应系数分别为  $-k_*$ ,  $h_*$ . 于是我们参考文献 [1], 先应用分离变量法来求解齐次模型.

## 分离变量法

现在用分离变量法求解化简后的齐次方程组. 令  $u_i(x, t) = X_i(x)T_i(t), i = 1, 2, 3, 4$ , 带入式 (12) – (16) 中, 按照文献 [1] 的推导, 诸  $T_i$  最多相差一个常系数, 而此常系数可以被相应的  $X_i$  吸收, 于是可令  $T_1 = T_2 = T_3 = T_4$ , 进一步得到

$$T(t) = e^{-\beta^2 t}, \quad (18)$$

和  $X(x) = X_i(\beta, x), x_{i+1} < x < x_i, i = 1, 2, 3, 4$  满足的本征值问题

$$\begin{cases} X'' + \frac{\beta^2}{\alpha_i} = 0, & x_{i+1} < x < x_i, \quad i = 1, 2, 3, 4. \\ \begin{cases} -k_i X'_i \Big|_{x=x_{i+1}} = h_{i,i+1}(X_i - X_{i+1}) \Big|_{x=x_{i+1}}, \\ k_i X'_i \Big|_{x=x_{i+1}} = k_{i+1} X'_{i+1} \Big|_{x=x_{i+1}}, \end{cases} & i = 2, 3, 4. \\ (-k_* X'_4 + h_* X_4) \Big|_{x=0} = 0, \\ (-k_1 X'_1 + h_{1\infty} X_1) \Big|_{x=x_1} = 0, \end{cases} \quad (19)$$

由式 (19) 可以确定本征值  $\beta = \beta_m, m = 1, 2, \dots$  和各本征函数  $X(\beta_m, x) = X_i(\beta_m, x)$ . 此时, 复合介质的本征函数满足正交性:

$$\sum_{i=1}^4 \frac{k_i}{\alpha_i} \int_{x_{i+1}}^{x_i} X_i(\beta_m, x) X_i(\beta_n, x) dx = \begin{cases} 0, & m \neq n; \\ N(\beta_m), & m = n. \end{cases} \quad (20)$$

式中, 模为

$$N(\beta_m) = \sum_{i=1}^4 \frac{k_i}{\alpha_i} \int_{x_{i+1}}^{x_i} X_i^2(\beta_m, x) dx. \quad (21)$$

于是简化的齐次模型的解为

$$u_i(x, t) = \sum_{m=1}^{\infty} c_m e^{-\beta_m^2 t} X_i(\beta_m, x), \quad x_{i+1} < x < x_i, \quad i = 1, 2, 3, 4. \quad (22)$$

此时利用初始条件 (10) 和正交性即可确定系数

$$c_m = \frac{1}{N(\beta_m)} \sum_{i=1}^4 \frac{k_i}{\alpha_i} \int_{x_{i+1}}^{x_i} X_i(\beta_m, x) I_i(x) dx, \quad (23)$$

将之带入式 (22) 即可求出温度函数  $u(x, t)$ .

接下来确定本征函数  $X_i(\beta_m, x)$ . 由方程 (19) 可得本征函数的通解为:

$$X_i(\beta_m, x) = A_{i,m} \sin\left(\frac{\beta_m}{\sqrt{\alpha_i}} x\right) + B_{i,m} \cos\left(\frac{\beta_m}{\sqrt{\alpha_i}} x\right), \quad x_{i+1} < x < x_i, \quad i = 1, 2, 3, 4. \quad (24)$$

只需用本征值问题 (19) 的边界条件等即可求得 (24) 中的本征值  $\beta_m$  和系数  $A_{i,m}, B_{i,m}, i = 1, 2, 3, 4$ , 令向量  $\eta = (A_{1,m}, B_{1,m}, \dots, A_{4,m}, B_{4,m})^T$ , 对应的系数矩阵记为  $M_{8 \times 8}$ , 此时实际上是解齐次方程组

$$M\eta = 0, \quad (25)$$

要使该方程组具有非零解, 必须使行列式

$$|M| = 0, \quad (26)$$



由此方程解出无穷个本征值  $\beta_m, m = 1, 2, \dots$ ; 之后再取出 (25) 一组合适的解  $\eta_0$ , 进一步再完全确定 (24) 的系数  $A_{i,m}, B_{i,m}, i = 1, 2, 3, 4$  即可.

现在回到  $f(t)$  和  $h_{1\infty}u_\infty$  不为 0 的非齐次问题. 对于非齐次问题, 常用的解法有 Green 函数法, 积分变换法以及 Laplace 变换法, 这里我们采用积分变换法来求解.

## 积分变换法

在分离变量法中, 我们求得了本征函数

$$X(\beta_m, x) = X_i(\beta_m, x), \quad x_{i+1} < x < x_i, \quad i = 1, 2, 3, 4.$$

以之为核进行如下正, 逆积分变换:

• 逆变公式:

$$u_i(x, t) = \sum_{i=1}^{\infty} \frac{X_i(\beta_m, x)}{N(\beta_m)} \bar{u}(\beta_m, t), \quad x_{i+1} < x < x_i, \quad i = 1, 2, 3, 4. \quad (27)$$

• 积分变换:

$$\bar{u}(\beta_m, t) = \sum_{i=1}^4 \frac{k_i}{\alpha_i} \int_{x_{i+1}}^{x_i} X_i(\beta_m, x') u_i(x', t) dx'. \quad (28)$$

则可得

$$\bar{u}(\beta_m, t) = e^{-\beta_m^2 t} \left[ \bar{F}(\beta_m) + \int_0^t e^{\beta_m^2 t'} A(\beta_m, t') dt' \right] \quad (29)$$

与复合介质的温度分布

$$u_i(x, t) = \sum_{m=1}^{\infty} \frac{X_i(\beta_m, x)}{N(\beta_m)} e^{-\beta_m^2 t} \left[ \bar{F}(\beta_m) + \int_0^t e^{\beta_m^2 t'} A(\beta_m, t') dt' \right], \quad (30)$$

$$x_{i+1} < x < x_i, \quad i = 1, 2, 3, 4.$$

式中

$$A(\beta_m, t') = \frac{k_4}{h_*} X_4'(\beta_m, x_4) f(t') + h_{1\infty} X_1(\beta_m, x_1), \quad (31)$$

$$\bar{F}(\beta_m) = \sum_{j=1}^4 \frac{k_j}{\alpha_j} \int_{x_{j+1}}^{x_j} X_j(\beta_m, x') I_j(x') dx', \quad (32)$$

$$N(\beta_m) = \sum_{j=1}^4 \frac{k_j}{\alpha_j} \int_{x_{j+1}}^{x_j} X_j^2(\beta_m, x') dx'. \quad (33)$$

至此, 复合介质的热传导问题就从理论上得到了解决.

下面我们结合题目中的具体数据, 尝试利用 MATLAB 编程来求解温度分布.

### 5.1.2 有限元网络法

我们首先利用 MATLAB 来求解式 (26), 以得出本征值  $\beta$ , 但是由于  $M$  是 8 阶方阵, MATLAB 只能解得 0 解, 只能寻求其它方法, 如数值方法, 这里我们综合利用 MATLAB 和 ANSYS, 即有限元网络法来求解符合介质模型.

首先进行左右边界温度由确定数据集的输入, 其中 IV 层左边界为牛顿冷却模型在热对流情形下的求解. 参考文献 [4], 我们使用边界节点法来求解在  $x = 0$  处的温度分布.

复合介质热传导间的方程的解可以写成特解与齐次解和的形式:

$$u_1(x) = u_p(x) + u_h(x), \quad (34)$$

其中  $u_p(x)$  表示特解,  $u_h(x)$  表示齐次解. 引入控制方程 (12) 的非奇异一般解的线性组合来取近似:

$$u_h(x) = \sum_{i=1}^{N_s} \gamma_i u_i^*(x), \quad x_2 < x < x_1, \quad (35)$$

式中  $\gamma_i$  为待求系数,  $u_i^*(x) = u^*(\|x - x_i\|)$  是修正的 Helmholtz 算子的非奇异通解;  $\{x_i\}$  为源点集合,  $N_s$  是源点总数. 由于  $T_h(x)$  满足方程, 所以只要选取适当的系数使之满足边界条件即可.

然后使用 ANSYS 软件模拟边界受热升温情况, 详附录 Excel 表格 data2.xlsx. I 层与环境的热作用, 升温情况如下所示:

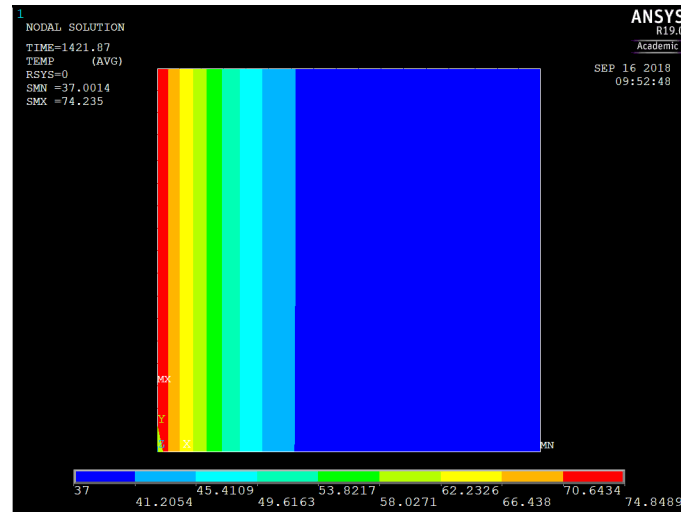


图 2 ANSYS 模拟边界受热情况

其中红色表示高温, 蓝色表示低温, 红色端是 I 层与外界环境接触的右端, 蓝色端是 I 层与 II 层接触面端. 图 2 体现了 I 层各处的分布情况, 离原点越近, 温度越高.

为保证多层热传导模型在相邻边界温度一致, 热量传导连续的条件下运行, 并且摆脱 MATLAB 模拟软件对单一介质热传导模型建立的限制. 我们建立四个相互迭代计算的 PDE 有限差分空间, 进行网格化处理, 并设置好符合求解要求的网格大小.

本文采用 Implicit-Euler 差分格式来离散时间项. 在任意一段时间间隔内, 划分区间段  $[t_n, t_{n+1}] \subset [0, t]$ , 于是当划分区间段很小时, 我们可以用  $u(x, t_{n+1})$  来代替此区间段上的函数值  $u(x, t)$ , 同理, 任一点的内热源  $Q(x, t)$  可以用端点值  $Q(x, t_{n+1})$  来近似, 此时即将  $u, Q$  及其导数离散化:

$$u(x, t) = u(x, t_{n+1}), \quad (36)$$

$$Q(x, t) = Q(x, t_{n+1}), \quad (37)$$

$$\frac{\partial u(x, t)}{\partial t} = \frac{u(x, t_{n+1}) - u(x, t_n)}{t_{n+1} - t_n}. \quad (38)$$

然后再利用 MATLAB 进行迭代求解即可.

具体的迭代过程如下所示:

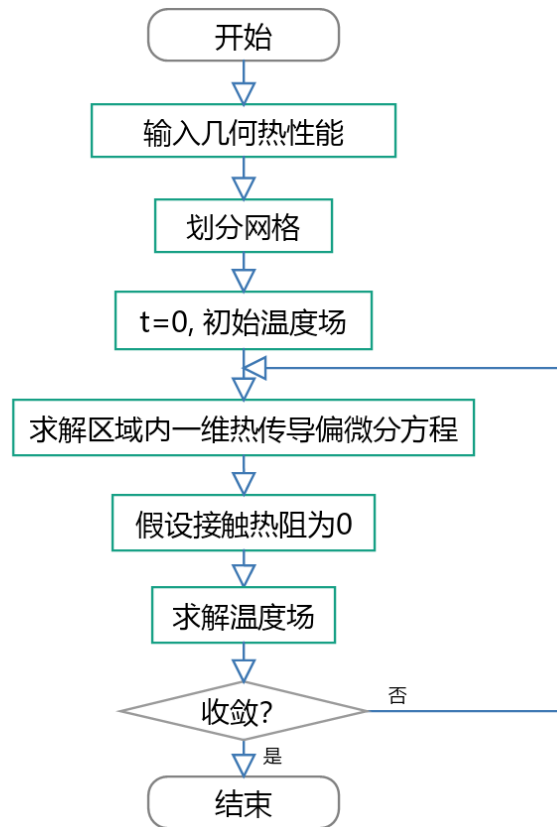


图 3 有限差分迭代流程图

图 3 中, 在求解 I 层热传导模型时, 我们对于四个介质层的温度分布情况都进行建立相应的差分空间.

先使用 MATLAB 中 `specifyCoefficients` 函数, 完全求解该区域内的单一 I 层介质条件下的热传导模型, 再使用 `solvepde` 和 `NodeSolution` 函数, 反求解出各个节点具体的值, 再通过对横纵坐标的判断, 选取 0.6mm 附近节点, 取平均值为该边界温度, 并将该边界条件当作下一个 PDE 空间里的边界温度条件, 进行迭代计算, 完成后面三个空间的求解, 这些操作的一些中间结果应当表示为下图所示:

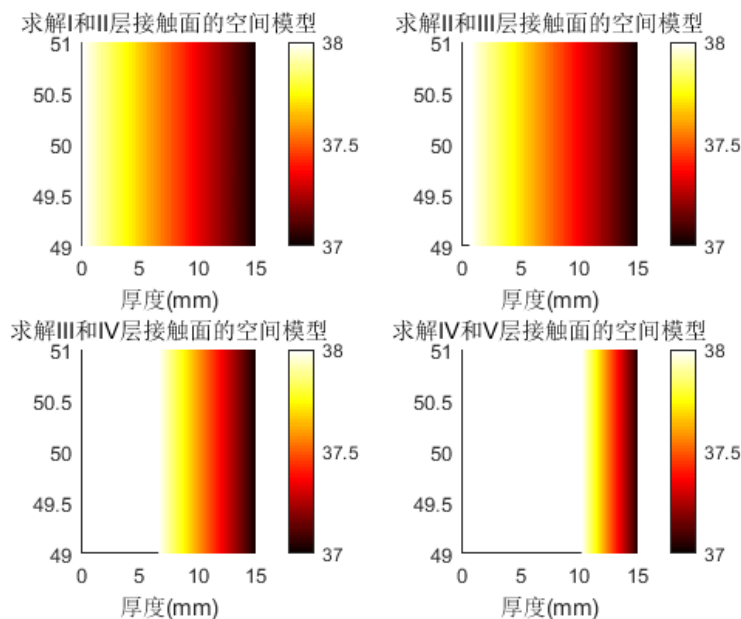


图 4 求解各接触面的空间模型

图中的数值不具有实际意义, 仅表示分布的阶段特征. 此外, 迭代判断条件为 I 层与空气接触界面温度变化收敛于一个极小值, 从而结束迭代更新温度场来求解模型。

由于调用了某些 MATLAB 耗时较大的函数, 计算时间比较漫长, 因此我们只选取了特殊点的温度分布, 即 I – IV 层之间的接触面上的分布, 计算数值结果见附件中的 Excel 表格 problem1.xlsx, 其变化曲线如图所示:

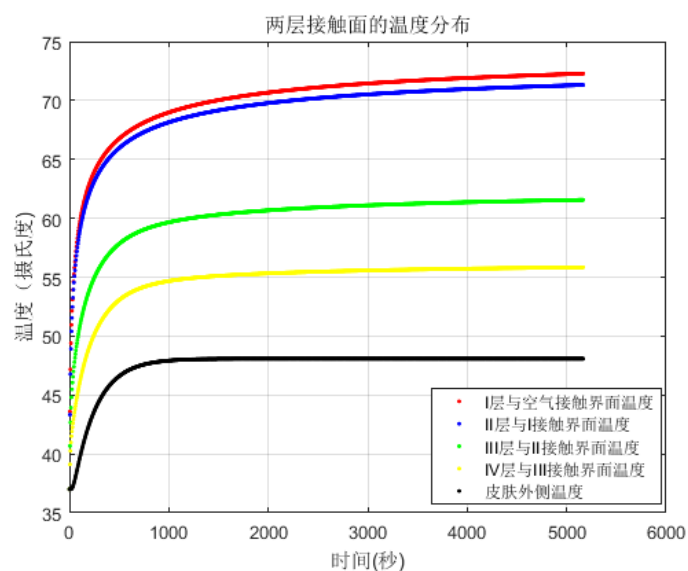


图 5 复合介质接触面温度分布图

从图 5 中可以看出, 各个接触面上的温度分布是有一定的差异的, 这与图 4 一致, 且此差异会随着时间的变化而变化, 时间很大, 如 4000s 之后, 各个层之间温度差就会区域

稳定;此外,各个接触面上的温度分布也具有大致相同的特征,即都是在大约 500s 之内时上升迅速,然后缓慢增加,最后趋于稳定. 利用 MATLAB 进一步的求解,我们得出 4 个接触面最后的温度收敛于各个界面温度收敛于  $72.27^{\circ}\text{C}$ ,  $71.31^{\circ}\text{C}$ ,  $61.56^{\circ}\text{C}$ ,  $55.83^{\circ}\text{C}$ ,  $48.08^{\circ}\text{C}$ , 其中图 5 中黑色的线是题中给的假人皮肤外表面测定的温度.

## 5.2 问题二: 单目标最优厚度

基于第一问建立的复合介质中的热传导方程,我们初步得知了温度遵循的传递模式;虽然没有求解出理论值的各项系数,但是后面利用有限元网络法等离散化的解决方式为本问题提供了思路和解决方案. 我们先来建立一个目标优化模型.

首先,题目中环境温度改为  $65^{\circ}\text{C}$ , 而 IV 层的厚度改为  $5.5\text{ mm}$  时,这是较问题一对于服装隔温更为有利的条件;但本问题又增加了两个时间条件: 即工作 60 分钟时, 假人皮肤外侧温度不能超过  $47^{\circ}\text{C}$ , 且超过  $44^{\circ}\text{C}$  的时间不超过 5 分钟, 问题一中的设置是不符合这一要求的. 因此,从某一程度上来说,问题二的结果与问题一是可以比较的.

其次,注意到服装设计的要求,即对 II 层的厚度  $L_2$ , 有

$$0.6\text{ mm} \leq L_2 \leq 25\text{ mm}, \quad (39)$$

我们可以假设,当 II 层的厚度  $L_2$  变化时,其相应的参数也是不变的,即  $c_i, \rho_i, k_i, i = 1, 2, 3, 4$  保持不变. 当然 I, III 和 IV 层的厚度也是不变的.

现在考虑时间约束. 第一个,工作 60 分钟时, 假人皮肤外侧温度不能超过  $47^{\circ}\text{C}$ , 从问题一的求解结果图 5 中知道, 假人外表皮肤的温度也是逐渐地增加的, 且增幅越来越小, 此时得到约束条件:

$$u_4(x, t) \Big|_{x=0} \leq 47, \quad 0 < t \leq 3600. \quad (40)$$

考虑第二个时间约束. 要求超过  $44^{\circ}\text{C}$  的时间不超过 5 分钟, 从连续的角度看, 若令此情形的集合

$$E_t = \left\{ t : u_4(x, t) \Big|_{x=0} > 44 \right\}, \quad (41)$$

则应有

$$\int_{E_t} \chi_{E_t}(t) dt \leq 300. \quad (42)$$

式中  $\chi$  是特征函数, 含义是

$$\chi_A(x) = \begin{cases} 1, & x \in A, \\ 0, & x \notin A. \end{cases} \quad (43)$$

最后,显然 II 层的厚度越大,在一定范围内隔温效果越好,但是由于高温作业专用服装材料的实际用价,以及造价成本等较高,应当使之在满足以上条件时越小越好,即确定目标

$$Goal_{L_2} = \min L_2. \quad (44)$$

现在综合式 (39) – (44), 即可得高温作业专用服装设计的单目标优化模型

$$Goal_{L_2} = \min L_2, \quad (45)$$

$$\text{s.t.} \begin{cases} u_4(x, t) \Big|_{x=0} \leq 47, & 0 < t \leq 3600, \\ \int \left\{ t: u_4(x, t) \Big|_{x=0} > 44 \right\} \chi \, dt \leq 300, \\ c_i, \rho_i, k_i \text{ 不变}, & i = 1, 2, 3, 4, \\ L_1 = 0.6 \text{ mm}, L_3 = 3.6 \text{ mm}, L_4 = 5.5 \text{ mm}, \\ 0.6 \text{ mm} \leq L_2 \leq 25 \text{ mm}. \end{cases} \quad (46)$$

现在我们来求解此模型. 由于框架仍然是复合介质中的热传导, 则可以按照问题一的过程来进行求解. 在求解过程中我们发现, 热传导模型从双边推导迭代, 转化为了单边推导模型, 这个时候就需要进行对原本的有限元网格法解决一维热传导差分公式过程, 进行细致分析, 从而完成仅靠单边准确地完成热传导迭代过程。

其中一个边界条件, 皮肤边缘温度不得超过 48.08 °C, 这里需要对 47.1 °C 后的温度场变化情况进行参数分析. 并选取迭代步长在 1, 2 ~ 8, 9 ~ 119, 120 ~ 四个阶段下, 皮肤外侧温度的变化情况参数设置.

最终求得最优厚度为  $Goal_{L_2} = 6.372 \text{ mm}$ .

### 5.3 问题三: 双目标最优厚度

问题三是较之于问题二, 更加的复杂, 因为此时的目标是两个, 即在当环境温度为 80°C 时, 仍然要满足工作 30 分钟时, 假人皮肤外侧温度不超过 47°C, 且超过 44°C 的时间不超过 5 分钟两个时间条件时, 确定 II 层和 IV 层的最优厚度.

首先, 根据服装设计的要求条件, 有

$$0.6 \text{ mm} \leq L_2 \leq 25 \text{ mm}, \quad (47)$$

$$0.6 \text{ mm} \leq L_4 \leq 6.4 \text{ mm}, \quad (48)$$

并且认为服装相应的参数也是不变的, 即  $c_i, \rho_i, k_i, i = 1, 2, 3, 4$  保持不变, 此外, I 和 III 层的厚度也是不变的.

考虑时间约束. 对于工作 30 分钟时, 假人皮肤外侧温度不超过 47°C, 应有

$$u_4(x, t) \Big|_{x=0} \leq 47, \quad 0 < t \leq 1800. \quad (49)$$

对于超过 44°C 的时间不超过 5 分钟条件, 若还记  $E_t$  如式 (41), 则同样有

$$\int_{E_t} \chi_{E_t}(t) \, dt \leq 300.$$

基于问题一的讨论, 我们应当使符合上述若干条件的  $L_2$  与  $L_4$  越小越好, 因此可确定目标函数

$$Goal_{L_2} = \min L_2, \quad Goal_{L_4} = \min L_4, \quad (50)$$

综合式 (48) – (50), 即可得高温作业专用服装设计的双目标优化模型

$$Goal_{L_2} = \min L_2, \quad Goal_{L_4} = \min L_4, \quad (51)$$

$$\text{s.t.} \begin{cases} u_4(x, t) \Big|_{x=0} \leq 47, & 0 < t \leq 1800, \\ \int_{E_t} \chi \, dt \leq 300, \\ c_i, \rho_i, k_i \text{ 不变}, & i = 1, 2, 3, 4, \\ L_1 = 0.6 \text{ mm}, L_3 = 3.6 \text{ mm}, \\ 0.6 \text{ mm} \leq L_2 \leq 25 \text{ mm}, \\ 0.6 \text{ mm} \leq L_4 \leq 6.4 \text{ mm}, \end{cases} \quad (52)$$

现在来求解此问题. 由于该问题是多(双)目标的, 比单目标更加复杂, 因此考虑使用 Weighted Sum 方法, Tchebycheff 方法或有界插值方法, 其简单介绍可见 [8,9], 这里我们使用 Weighted Sum 方法来降维求解.

### Weighted Sum 方法

该方法给出一个降维表达式:  $\min g_{ws}(x|\lambda) = \sum_{i=1}^2 \lambda_i L_i$ . 式中,  $\lambda_i$  为权重向量. 该方法是将目标点与原点连接构成新向量, 右端和是将该向量与对应权重向量点乘. 如图:

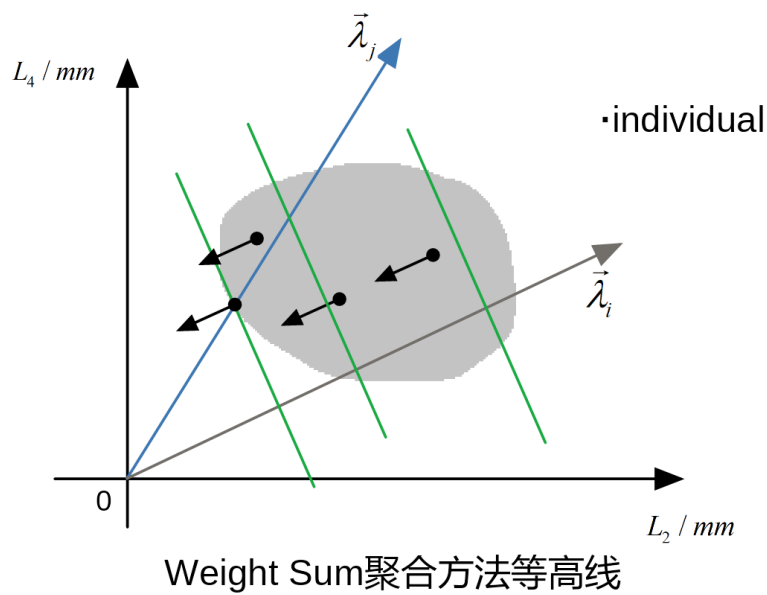


图 6 Weighted Sum 方法示意图

对于降维后的问题, 与问题二相似, 利用 MATLAB 编程, 在复合介质中热传导问题的背景下, 由于温度场模型求解温度分布所需时间较长, 若用问题二的方法求解 II 层与 IV 层的最优厚度将花费过多时间, 故而我们在此处使用多目标进化模型对最优厚度进行求解。

将 II 层等分为步长为 6.1mm 的由 0.6mm 到 25mm 的 4 个厚度梯度, 同样将 IV 层等分为步长为 1.45mm 的由 0.6mm 到 6.4mm 的 4 个厚度梯度。利用问题一中所得出的温度场模型对 II 层与 IV 层的 16 种厚度梯度组合进行计算, 可以得出 16 组温度分布数据。对 16 组温度数据进行分析, 利用超过 47°C 的情况进行可行域的划分, 并利用超过 44°C 的情况作为判定标准进行 II 层、IV 层的条件多项式计算。

最后求得双目标优化的最优值为:

$$Goal_{L_2} = 13.15 \text{ mm}, \quad Goal_{L_4} = 5.40 \text{ mm}, \quad (53)$$

这个结果是合乎题目要求的。

## 六、模型的评价与改进

问题一中, 为了简化问题, 我们在进行热传导模型的解析同时, 通过 Matlab 和 Ansys 软件建立了一维上的温度场模型对温度分布进行数值分析。优点: 便于计算以及生成; 因为有网格随实际情况的细化, 可以使得有限元的数值解精度得到较大程度提高; 丰富的可视化图便于热传导模型的理解。缺点: 考虑到实际情况, 由于人体表面存在弧度, 使用一维温度场模型存在误差; 如果要对皮肤外侧温度得到高精度的数值, 还需要考虑人体血流模型。改进: 建立三维温度场模型; 多考虑人体血流模型和排汗系统对皮肤外侧温度的影响。

问题二中, 模型优点是建立的模型简单直观, 缺点是求解较为困难, 可以尝试一些新的方法。

问题三中, 与问题二相似, 进一步的优点是使用了 Weighted Sum 方法来实现了降维, 进一步可考虑其它方法来求解进行比较。

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## 附录

我们提供必要的 Excel 数据文件 (见附件), 以及实现的 MATLAB 代码如下:

```
1 clc, close all, clear all;
  x = xlsread('data4.xlsx', 'A1:B721')
3 temperature01list = x(:, 2); %读取I层靠近环境数据, 作为模型另一边的温度情况
  numberOfPDE = 1;
5 pdem1 = createpde(numberOfPDE);
  numberOfPDE = 1;
7 pdem2 = createpde(numberOfPDE);
  numberOfPDE = 1;
9 pdem3 = createpde(numberOfPDE);
```

```

numberOfPDE = 1;
11 pdem4 = createpde(numberOfPDE);
    rho1 = 300; % 密度
13 Cp1 = 1377; % 比热
    k1 = 0.082; % 热导率
15 h1 = 0.6;

17 rho2 = 862; % 密度
    Cp2 = 2100; % 比热
19 k2 = 0.37; % 热导率
    h2 = 11;%设置的厚度为0.1 5 10 15 20 25
21
    rho3 = 74.2; % 密度
23 Cp3 = 1726; % 比热
    k3 = 0.045; % 热导率
25 h3 = 3.6;

27 rho4 = 1.18; % 密度
    Cp4 = 1005; % 比热
29 k4 = 0.028; % 热导率
    h4 = 5;
31
R1 = [3 4 0 h1+h2+h3+h4 h1+h2+h3+h4 0 0 0 100 100]';
33 R2 = [3 4 h1 h1+h2+h3+h4 h1+h2+h3+h4 h1 0 0 100 100]';
    R3 = [3 4 h1+h2 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2 0 0 100 100]';
35 R4 = [3 4 h1+h2+h3 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2+h3 0 0 100 100]';

37 rat1 = h1/(h1+h2+h3+h4)
    rat2 = h2/(h1+h2+h3+h4)
39 rat3 = h3/(h1+h2+h3+h4)
    rat4 = h4/(h1+h2+h3+h4)
41
    rate1 = rat1
43 rate2 = rate1 + rat2
    rate3 = rate2 + rat3
45 rate4 = rate3 + rat4

47 g1 = decsg(R1);
    geometryFromEdges(pdem1 ,g1);
49 %figure(1)
    %pdegplot(pdem1,'EdgeLabels','on');
51 %axis([-1 15.3 49 51]);

53 g2 = decsg(R2);
    geometryFromEdges(pdem2 ,g2);
55 %figure(2)
    %pdegplot(pdem2,'EdgeLabels','on');

```

```

57 %axis([-1 15.3 5 6]);

59 g3 = decsg(R3);
    geometryFromEdges(pdem3 ,g3);
61 %figure(3)
    %pdegplot(pdem3,'EdgeLabels','on');
63 %axis([-1 15.3 5 6]);

65 g4 = decsg(R4);
    geometryFromEdges(pdem4 ,g4);
67 %figure(4)
    %pdegplot(pdem4,'EdgeLabels','on');
69 %axis([-1 15.3 5 6]);

71
    %虽然希望三角网格的划分越精细越好，但是由于上下边界无穷远的设定，导致这部分无用网格
    太多，
73 %所以注意大小
    hmax = .2; % element size
75 msh1=generateMesh(pdem1,'Hmax',hmax);
    %figure
77 %pdeplot(pdem1);
    %axis([-1 .7 5 6]);
79
    hmax = .5; % element size
81 msh2=generateMesh(pdem2,'Hmax',hmax);
    %figure
83 %pdeplot(pdem2);
    %axis([.5 6.7 2 8]);
85
    hmax = .5; % element size
87 msh3=generateMesh(pdem3,'Hmax',hmax);
    %figure
89 %pdeplot(pdem3);
    %axis([6.5 10.3 3 7]);
91
    hmax = .5; % element size
93 msh4=generateMesh(pdem4,'Hmax',hmax);
    %figure
95 %pdeplot(pdem4);
    %axis([10.1 15.3 2 8]);
97

99
    temperature = 65;%环境温度已经在另一个模型中应用
101 temperature01 = 37
    temperature12 = 37

```

```

103 temperature23 = 37
    temperature34 = 37
105
107 temperature12list = ones(1,1000)
    temperature23list = ones(1,1000)
109 temperature34list = ones(1,1000)
    temperature45list = ones(1,1000)
111 temperature45list(1) = 37
113
    time = 1;
115 for i2 = 1:1000
        if time == 1
117             a2 = 1
                b1 = 1
119             b2 = 1
                c1 = 1
121             c2 = 1
                d1 = 1
123             d2 = 1
                d3 = 1
125         end
            if (time>1&&time<8)
127                 a2 = 1
                    b1 = 0.99
129                 b2 = 0.99
                    c1 = 0.997
131                 c2 = 0.996
                    d1 = 0.999
133                 d2 = 0.99975
                    d3 = 0.999
135             end
                if (time>7)
137                     a2 = 1
                            b1 = 0.99
139                     b2 = 0.9875
                            c1 = 0.997
141                     c2 = 0.996
                            d1 = 0.997
143                     d2 = 0.997
                            d3 = 0.9985
145                 end
                    if (time>160)
147                         a2=1;
                            b1=0.99;
149                         b2=0.9875;

```

```

151     c1=0.9965;
152     c2=0.995;
153     d1=0.9965;
154     d2=0.996;
155     d3=0.9985;
156
157     end
158
159     if (temperature01list(time+1) - temperature01list(time) > 0.1)
160         %第一层
161         temperature01 = temperature01list(time,1);
162         temperature45 = temperature45list(time);%每隔5秒作为一次迭代，所以选取5秒后的皮肤外侧温度
163         applyBoundaryCondition(pdem1,'dirichlet','Edtimege',4,'u',temperature01);
164         applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
165         applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
166         c = k1;
167         a = 0;
168         f = 0;
169         d = rho1*Cp1;
170         specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
171         tlist = 0:.1:5;
172         setInitialConditions(pdem1, 0);
173         R = solvepde(pdem1,tlist);
174         u = R.NodalSolution;%反解每个节点的温度
175         p = pdem1.Mesh.Nodes;%得出每个mesh后的节点坐标
176         x = p(1,:);
177         y = p(2,:);
178         num1 = 1;
179         %figure
180         %pdeplot(pdem1,'XYData',u(:,1),'Contour','off','ColorMap','hot');
181         %axis([-1 15 49 51]);
182         nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
183         num2 = length(x)
184         for i = 1:num2
185             if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
186                 nodechoose(num1) = i;
187                 num1 = num1 + 1;
188             end
189         end
190         num3 = 0;
191         temperature12 = 0
192         nodechoose(1)
193         for i = 1:1000
194             if((nodechoose(i)) ~=0)
195                 temperature12 = temperature12 + u(nodechoose(i));
196                 num3 = num3 + 1;
197             end
198         end
199     end

```

```

197     temperature12 = temperature12/num3;

199     temperature12list(time) = temperature12*a2;

201 %第二层
    applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',b1*temperature12);
    applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
203    applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
    c = k2;
205    a = 0;
    f = 0;
207    d = rho2*Cp2;
    specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
209    tlist = 0:1:5;
    setInitialConditions(pdem2, 0);
211    R = solvepde(pdem2,tlist);
    u = R.NodalSolution;%反解每个节点的温度
213    p = pdem2.Mesh.Nodes;%得出每个mesh后的节点坐标
    x = p(1,:);
215    y = p(2,:);
    num1 = 1;
217    %figure
    %pdeplot(pdem2,'XYData',u(:,1),'Contour','off','ColorMap','hot');
219    %axis([-1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
221    num2 = length(x)
    for i = 1:num2
223        if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
            nodechoose(num1) = i;
225            num1 = num1 + 1;
        end
227    end
    num3 = 0;
229    temperature23 = 0
    nodechoose(1)
231    for i = 1:1000
        if((nodechoose(i)) ~=0)
233            temperature23 = temperature23 + u(nodechoose(i));
            num3 = num3 +1;
235        end
    end
237    temperature23 = temperature23/num3;
    temperature23list(time) = temperature23*b2;
239    %temperature23

241    %第三层
    applyBoundaryCondition(pdem3,'dirichlet','Edge',4,'u',c1*temperature23);

```

```

243 applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 2, 'u', temperature45);
    applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', [1,3], 'u', 37);
245 c = k3;
    a = 0;
247 f = 0;
    d = rho3*Cp3;
249 specifyCoefficients(pdem3, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
    tlist = 0:1:5;
251 setInitialConditions(pdem3, 0);
    R = solvepde(pdem3, tlist);
253 u = R.NodalSolution;%反解每个节点的温度
    p = pdem3.Mesh.Nodes;%得出每个mesh后的节点坐标
255 x = p(1,:);
    y = p(2,:);
257 num1 = 1;
    %figure
259 %pdeplot(pdem3, 'XYData', u(:,1), 'Contour', 'off', 'ColorMap', 'hot');
    %axis([-1 15 49 51]);
261 nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
263 for i = 1:num2
        if ((x(i)>(h1+h2+h3-0.6)) && (x(i)<(h1+h2+h3+0.6)) && (y(i)>35) && (y(i) <65)
            )
265             nodechoose(num1) = i;
            num1 = num1 + 1;
267         end
    end
269 num3 = 0;
    temperature34 = 0
271 nodechoose(1)
    for i = 1:1000
273         if((nodechoose(i)) ~=0)
            temperature34 = temperature34 + u(nodechoose(i));
275             num3 = num3 + 1;
        end
277     end
    temperature34 = temperature34/num3;
279 temperature34list(time) = temperature34*c2
    %temperature34
281 %if(time>5)
        %chazhi1 = temperature01list(time-1)-temperature12list(time-1);
283         %chazhi2 = temperature12list(time-1)-temperature23list(time-1);
        %chazhi3 = temperature23list(time-1)-temperature34list(time-1);
285         %chazhi4 = temperature34list(time-1)-temperature45;
        %sumchazhi = chazhi1+chazhi2+chazhi3+chazhi4;
287         %temperature12list(time-1) = temperature01list(time-1) + sumchazhi*rate1
        %temperature23list(time-1) = temperature01list(time-1) + sumchazhi*rate2

```

```

289     %temperature34list(time-1) = temperature01list(time-1) + sumchazhi*rate3
    %temperature45list(time) = temperature01list(time) + sumchazhi*rate4
291
293     %chazhi2 = rat2*chazhi1/rat1;
    %chazhi3 = rat3*chazhi1/rat1;
295     %chazhi4 = rat4*chazhi1/rat1;
    %temperature23list(time) = temperature12list(time)-chazhi2;
297     %if(temperature23list(time)<temperature23list(time-1))
    % temperature23list(time) = temperature23;
299     %end
    %temperature34list(time) = temperature23list(time)-chazhi3;
301     %if(temperature34list(time)<temperature34list(time-1))
    % temperature34list(time) = temperature34;
303     %end
    %temperature45list(time) = temperature34list(time)-chazhi4;
305     %if(temperature45list(time)<temperature45list(time-1))
    % temperature45list(time) = temperature45;
307     %end
309
311     %end
313
314 %第四层
315     applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',d1*temperature34);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',d2*temperature45);
317     applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
    c = k4;
319     a = 0;
    f = 0;
321     d = rho4*Cp4;
    specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
323     tlist = 0:1:5;
    setInitialConditions(pdem4, 0);
325     R = solvepde(pdem4,tlist);
    u = R.NodalSolution;%反解每个节点的温度
327     p = pdem4.Mesh.Nodes;%得出每个mesh后的节点坐标
    x = p(1,:);
329     y = p(2,:);
    num1 = 1;
331 %figure
    %pdeplot(pdem4,'XYData',u(:,1),'Contour','off','ColorMap','hot');
333 %axis([-1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
335     num2 = length(x)

```



```

337     for i = 1:num2
339         if ((x(i)>(h1+h2+h3+h4-0.5)) && (x(i)<(h1+h2+h3+h4+0.5)) && (y(i)>35) && (y(i)
            ) <65))
            nodechoose(num1) = i;
            num1 = num1 + 1;
        end
    end
    num3 = 0;
    temperature45 = 0
    nodechoose(1)
    for i = 1:1000
        if((nodechoose(i)) ~=0)
            temperature45 = temperature45 + u(nodechoose(i));
            num3 = num3 +1;
        end
    end
    temperature45 = temperature45/num3;

    if(time<3)
        temperature45 = 37;
        d2=1;
    end

    time = time+1
    temperature45list(time) = temperature45*d3
    %temperature45

else
    i2 = 1000;
end
end
end

```

codes/best.m

```

clc , close all , clear all ;
2 x = xlsread('data4.xlsx','A1:B721')
    temperature01list = x(:,2);%读取I层靠近环境数据，作为模型另一边的温度情况
4 numberOfPDE = 1;
    pdem1 = createpde(numberOfPDE);
6 numberOfPDE = 1;
    pdem2 = createpde(numberOfPDE);
8 numberOfPDE = 1;

```

```

pdem3 = createpde(numberOfPDE);
10 numberOfPDE = 1;
pdem4 = createpde(numberOfPDE);
12 rho1 = 300; % 密度
Cp1 = 1377; % 比热
14 k1 = 0.082; % 热导率
h1 = 0.6;
16
rho2 = 862; % 密度
18 Cp2 = 2100; % 比热
k2 = 0.37; % 热导率
20 h2 = 11;%设置的厚度为0.1 5 10 15 20 25

rho3 = 74.2; % 密度
Cp3 = 1726; % 比热
24 k3 = 0.045; % 热导率
h3 = 3.6;
26
rho4 = 1.18; % 密度
28 Cp4 = 1005; % 比热
k4 = 0.028; % 热导率
30 h4 = 5;

32 R1 = [3 4 0 h1+h2+h3+h4 h1+h2+h3+h4 0 0 0 100 100]';
R2 = [3 4 h1 h1+h2+h3+h4 h1+h2+h3+h4 h1 0 0 100 100]';
34 R3 = [3 4 h1+h2 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2 0 0 100 100]';
R4 = [3 4 h1+h2+h3 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2+h3 0 0 100 100]';
36
rat1 = h1/(h1+h2+h3+h4)
38 rat2 = h2/(h1+h2+h3+h4)
rat3 = h3/(h1+h2+h3+h4)
40 rat4 = h4/(h1+h2+h3+h4)

42 rate1 = rat1
rate2 = rate1 + rat2
44 rate3 = rate2 + rat3
rate4 = rate3 + rat4
46
g1 = decsg(R1);
48 geometryFromEdges(pdem1 ,g1);
%figure(1)
50 %pdegplot(pdem1,'EdgeLabels','on');
%axis([-1 15.3 49 51]);
52
g2 = decsg(R2);
54 geometryFromEdges(pdem2 ,g2);
%figure(2)

```

```

56 %pdegplot(pdem2,'EdgeLabels','on');
    %axis([-1 15.3 5 6]);
58
    g3 = decsg(R3);
60 geometryFromEdges(pdem3 ,g3);
    %figure(3)
62 %pdegplot(pdem3,'EdgeLabels','on');
    %axis([-1 15.3 5 6]);
64
    g4 = decsg(R4);
66 geometryFromEdges(pdem4 ,g4);
    %figure(4)
68 %pdegplot(pdem4,'EdgeLabels','on');
    %axis([-1 15.3 5 6]);
70
72 %虽然希望三角网格的划分越精细越好，但是由于上下边界无穷远的设定，导致这部分无用网格
    太多，
    %所以注意大小
74 hmax = .2; % element size
    msh1=generateMesh(pdem1,'Hmax',hmax);
76 %figure
    %pdeplot(pdem1);
78 %axis([-1 .7 5 6]);
80
    hmax = .5; % element size
    msh2=generateMesh(pdem2,'Hmax',hmax);
82 %figure
    %pdeplot(pdem2);
84 %axis([.5 6.7 2 8]);
86
    hmax = .5; % element size
    msh3=generateMesh(pdem3,'Hmax',hmax);
88 %figure
    %pdeplot(pdem3);
90 %axis([6.5 10.3 3 7]);
92
    hmax = .5; % element size
    msh4=generateMesh(pdem4,'Hmax',hmax);
94 %figure
    %pdeplot(pdem4);
96 %axis([10.1 15.3 2 8]);
98
100 temperature = 65%环境温度已经在另一个模型中应用
    temperature01 = 37

```

```

102 temperature12 = 37
    temperature23 = 37
104 temperature34 = 37

106
    temperature12list = ones(1,1100)
108 temperature23list = ones(1,1100)
    temperature34list = ones(1,1100)
110 temperature45list = ones(1,1100)
    temperature45list(1) = 37
112

114 time = 1;
    for i2 = 1:1000
116     if time == 1
        a2 = 1
118         b1 = 1
        b2 = 1
120         c1 = 1
        c2 = 1
122         d1 = 1
        d2 = 1
124         d3 = 1
    end
126     if (time>1&&time<11)
        a2 = 1
128         b1 = 0.99
        b2 = 0.99
130         c1 = 0.998
        c2 = 0.998
132         d1 = 0.999
        d2 = 0.9995
134         d3 = 0.999
    end
136     if (time>7)
        a2 = 1
138         b1 = 0.99
        b2 = 0.9875
140         c1 = 0.997
        c2 = 0.996
142         d1 = 0.998
        d2 = 0.995
144         d3 = 0.998
    end
146     if (temperature01list(time+1) - temperature01list(time) >0.1)
        %第一层
148         temperature01 = temperature01list(time,1);

```

```

temperature45 = temperature45list(time);%每隔5秒作为一次迭代，所以选取5秒后的皮
    肤外侧温度
150 applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
152 applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
    c = k1;
154 a = 0;
    f = 0;
156 d = rho1*Cp1;
    specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
158 tlist = 0:1:5;
    setInitialConditions(pdem1, 0);
160 R = solvepde(pdem1,tlist);
    u = R.NodalSolution;%反解每个节点的温度
162 p = pdem1.Mesh.Nodes;%得出每个mesh后的节点坐标
    x = p(1,:);
164 y = p(2,:);
    num1 = 1;
166 %figure
    %pdeplot(pdem1,'XYData',u(:,1),'Contour','off','ColorMap','hot');
168 %axis([-1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
170 num2 = length(x)
    for i = 1:num2
172         if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
                nodechoose(num1) = i;
174         num1 = num1 + 1;
        end
176    end
    num3 = 0;
178    temperature12 = 0
    nodechoose(1)
180    for i = 1:1000
        if((nodechoose(i)) ~=0)
182            temperature12 = temperature12 + u(nodechoose(i));
            num3 = num3 +1;
184        end
    end
186    temperature12 = temperature12/num3;

188    temperature12list(time) = temperature12*a2;

190 %第二层
    applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',b1*temperature12);
192    applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
194    c = k2;

```

```

196     a = 0;
197     f = 0;
198     d = rho2*Cp2;
199     specifyCoefficients(pdem2, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
200     tlist = 0:1:5;
201     setInitialConditions(pdem2, 0);
202     R = solvepde(pdem2, tlist);
203     u = R.NodalSolution;%反解每个节点的温度
204     p = pdem2.Mesh.Nodes;%得出每个mesh后的节点坐标
205     x = p(1,:);
206     y = p(2,:);
207     num1 = 1;
208     %figure
209     %pdeplot(pdem2, 'XYData', u(:,1), 'Contour', 'off', 'ColorMap', 'hot');
210     %axis([-1 15 49 51]);
211     nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
212     num2 = length(x)
213     for i = 1:num2
214         if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
215             nodechoose(num1) = i;
216             num1 = num1 + 1;
217         end
218     end
219     num3 = 0;
220     temperature23 = 0
221     nodechoose(1)
222     for i = 1:1000
223         if((nodechoose(i)) ~=0)
224             temperature23 = temperature23 + u(nodechoose(i));
225             num3 = num3 +1;
226         end
227     end
228     temperature23 = temperature23/num3;
229     temperature23list(time) = temperature23*b2;
230     %temperature23
231
232     %第三层
233     applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 4, 'u', c1*temperature23);
234     applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 2, 'u', temperature45);
235     applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', [1,3], 'u', 37);
236     c = k3;
237     a = 0;
238     f = 0;
239     d = rho3*Cp3;
240     specifyCoefficients(pdem3, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
241     tlist = 0:1:5;
242     setInitialConditions(pdem3, 0);

```

```

242 R = solvepde(pdem3,tlist);
    u = R.NodalSolution;%反解每个节点的温度
244 p = pdem3.Mesh.Nodes;%得出每个mesh后的节点坐标
    x = p(1,:);
246 y = p(2,:);
    num1 = 1;
248 %figure
    %pdeplot(pdem3,'XYData',u(:,1),'Contour','off','ColorMap','hot');
250 %axis([-1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
252 num2 = length(x)
    for i = 1:num2
254         if ((x(i)>(h1+h2+h3-0.6)) && (x(i)<(h1+h2+h3+0.6)) && (y(i)>35) && (y(i) <65)
                )
                nodechoose(num1) = i;
256         num1 = num1 + 1;
        end
258     end
    num3 = 0;
260     temperature34 = 0
    nodechoose(1)
262     for i = 1:1000
        if((nodechoose(i)) ~=0)
264             temperature34 = temperature34 + u(nodechoose(i));
            num3 = num3 +1;
266         end
        end
268     temperature34 = temperature34/num3;
    temperature34list(time) = temperature34*c2
270 %temperature34
    %if(time>5)
272         %chazhi1 = temperature01list(time-1)-temperature12list(time-1);
        %chazhi2 = temperature12list(time-1)-temperature23list(time-1);
274         %chazhi3 = temperature23list(time-1)-temperature34list(time-1);
        %chazhi4 = temperature34list(time-1)-temperature45;
276         %sumchazhi = chazhi1+chazhi2+chazhi3+chazhi4;
        %temperature12list(time-1) = temperature01list(time-1) + sumchazhi*rate1
278         %temperature23list(time-1) = temperature01list(time-1) + sumchazhi*rate2
        %temperature34list(time-1) = temperature01list(time-1) + sumchazhi*rate3
280         %temperature45list(time) = temperature01list(time) + sumchazhi*rate4

282
        %chazhi2 = rat2*chazhi1/rat1;
284         %chazhi3 = rat3*chazhi1/rat1;
        %chazhi4 = rat4*chazhi1/rat1;
286         %temperature23list(time) = temperature12list(time)-chazhi2;
        %if(temperature23list(time)<temperature23list(time-1))

```

```

288     % temperature23list(time) = temperature23;
        %end
290     %temperature34list(time) = temperature23list(time)-chazhi3;
        %if(temperature34list(time)<temperature34list(time-1))
292     % temperature34list(time) = temperature34;
        %end
294     %temperature45list(time) = temperature34list(time)-chazhi4;
        %if(temperature45list(time)<temperature45list(time-1))
296     % temperature45list(time) = temperature45;
        %end
298
300 %end
302
304 %第四层
        applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',d1*temperature34);
306        applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',d2*temperature45);
        applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
308        c = k4;
        a = 0;
310        f = 0;
        d = rho4*Cp4;
312        specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
        tlist = 0:1:5;
314        setInitialConditions(pdem4, 0);
        R = solvepde(pdem4,tlist);
316        u = R.NodalSolution;%反解每个节点的温度
        p = pdem4.Mesh.Nodes;%得出每个mesh后的节点坐标
318        x = p(1,:);
        y = p(2,:);
320        num1 = 1;
        %figure
322        %pdeplot(pdem4,'XYData',u(:,1),'Contour','off','ColorMap','hot');
        %axis([-1 15 49 51]);
324        nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
        num2 = length(x)
326        for i = 1:num2
            if ((x(i)>(h1+h2+h3+h4-0.5)) && (x(i)<(h1+h2+h3+h4+0.5)) && (y(i)>35) && (y(i)
                ) <65))
328                nodechoose(num1) = i;
                num1 = num1 + 1;
330            end
        end
332        num3 = 0;
        temperature45 = 0

```



```

334     nodechoose(1)
      for i = 1:1000
336         if((nodechoose(i)) ~=0)
            temperature45 = temperature45 + u(nodechoose(i));
338             num3 = num3 +1;
            end
340         end
            temperature45 = temperature45 /num3;
342
            if (time <3)
344                 temperature45 = 37;
                    d2=1;
346             end
348
            time = time+1
350             temperature45list(time) = temperature45*d3
            %temperature45
352
354
356
            else
358                 i2 = 1000;
            end
360 end

```

codes/best21.m

```

clc
2 clear
close all
4
% 原图像
6 subplot(1,2,1)
    skintem=xlsread('mydata.xlsx','附件2','A3:B5403');
8 [h1,h2]=deal(skintem(:,1),skintem(:,2));
    plot(h1,h2)
10
    a=37;
12 b=75;
    mn=0:5400;
14 subplot(1,2,2)
    plot(mn,log(100+mn)*37/4.5)
16
% 所需

```

```

18 time_h=0:5:1000;
   tem_h=log(100+time_h)*37/4.5;
20 xlswrite('temp_bound.xlsx',[time_h;tem_h]')

22 % 找出最小间距
   tem_h2=tem_h;
24 tem_h2(1)=[];
   tem_h2(201)=inf;
26 disp('最小间距是:')
   min(tem_h2-tem_h)

28
30 % 温度2
   time_h=0:5:3600;
   tem_h=log(200+time_h)*37/4.5*75/65-13;
32 figure
   plot(time_h,tem_h)
34 xlswrite('temp_bound2.xlsx',[time_h;tem_h]')

```

codes/bound\_tem.m

```

1 clc,close all,clear all;
   x = xlsread('data5.xlsx','A1:B361')
3 numberOfPDE = 1;
   pdem1 = createpde(numberOfPDE);
5 numberOfPDE = 1;
   pdem2 = createpde(numberOfPDE);
7 numberOfPDE = 1;
   pdem3 = createpde(numberOfPDE);
9 numberOfPDE = 1;
   pdem4 = createpde(numberOfPDE);
11 rho1 = 300; % 密度
   Cp1 = 1377; % 比热
13 k1 = 0.082; % 热导率
   h1 = 0.6;

15
   rho2 = 862; % 密度
17 Cp2 = 2100; % 比热
   k2 = 0.37; % 热导率
19 h2 = 11.686;%设置的厚度为0.1 5 10 15 20 25

21 rho3 = 74.2; % 密度
   Cp3 = 1726; % 比热
23 k3 = 0.045; % 热导率
   h3 = 3.6;

25
   rho4 = 1.18; % 密度
27 Cp4 = 1005; % 比热

```

```

k4 = 0.028; % 热导率
29 h4 = 5.264;

31 R1 = [3 4 0 h1+h2+h3+h4 h1+h2+h3+h4 0 0 0 100 100]';
R2 = [3 4 h1 h1+h2+h3+h4 h1+h2+h3+h4 h1 0 0 100 100]';
33 R3 = [3 4 h1+h2 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2 0 0 100 100]';
R4 = [3 4 h1+h2+h3 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2+h3 0 0 100 100]';
35
rat1 = h1/(h1+h2+h3+h4)
37 rat2 = h2/(h1+h2+h3+h4)
rat3 = h3/(h1+h2+h3+h4)
39 rat4 = h4/(h1+h2+h3+h4)

41 rate1 = rat1
rate2 = rate1 + rat2
43 rate3 = rate2 + rat3
rate4 = rate3 + rat4
45
g1 = decsg(R1);
47 geometryFromEdges(pdem1 ,g1);
%figure(1)
49 %pdegplot(pdem1,'EdgeLabels','on');
%axis([-1 15.3 49 51]);
51
g2 = decsg(R2);
53 geometryFromEdges(pdem2 ,g2);
%figure(2)
55 %pdegplot(pdem2,'EdgeLabels','on');
%axis([-1 15.3 5 6]);
57
g3 = decsg(R3);
59 geometryFromEdges(pdem3 ,g3);
%figure(3)
61 %pdegplot(pdem3,'EdgeLabels','on');
%axis([-1 15.3 5 6]);
63
g4 = decsg(R4);
65 geometryFromEdges(pdem4 ,g4);
%figure(4)
67 %pdegplot(pdem4,'EdgeLabels','on');
%axis([-1 15.3 5 6]);
69

71 %虽然希望三角网格的划分越精细越好，但是由于上下边界无穷远的设定，导致这部分无用网格
    太多，
    %所以注意大小
73 hmax = .2; % element size

```

```

msh1=generateMesh(pdem1,'Hmax',hmax);
75 %figure
    %pdeplot(pdem1);
77 %axis([-1 .7 5 6]);

79 hmax = .5; % element size
    msh2=generateMesh(pdem2,'Hmax',hmax);
81 %figure
    %pdeplot(pdem2);
83 %axis([.5 6.7 2 8]);

85 hmax = .5; % element size
    msh3=generateMesh(pdem3,'Hmax',hmax);
87 %figure
    %pdeplot(pdem3);
89 %axis([6.5 10.3 3 7]);

91 hmax = .5; % element size
    msh4=generateMesh(pdem4,'Hmax',hmax);
93 %figure
    %pdeplot(pdem4);
95 %axis([10.1 15.3 2 8]);

97

99 temperature = 65;%环境温度已经在另一个模型中应用
    temperature01 = 37
101 temperature12 = 37
    temperature23 = 37
103 temperature34 = 37

105
    temperature12list = ones(1,1100)
107 temperature23list = ones(1,1100)
    temperature34list = ones(1,1100)
109 temperature45list = ones(1,1100)
    temperature45list(1) = 37
111

    judge4 = 0
113 judge5 = 0
    time = 1;
115 for i2 = 1:1000
        if time == 1
117             a2 = 1
                b1 = 1
119             b2 = 1
                c1 = 1

```

```

121     c2 = 1
122     d1 = 1
123     d2 = 1
124     d3 = 1
125 end
126 if(time>1&&time<8)
127     a2 = 1
128     b1 = 0.99
129     b2 = 0.99
130     c1 = 0.997
131     c2 = 0.996
132     d1 = 0.999
133     d2 = 0.99975
134     d3 = 0.999
135 end
136 if (time>7)
137     a2 = 1
138     b1 = 0.99
139     b2 = 0.9875
140     c1 = 0.997
141     c2 = 0.9975
142     d1 = 0.99725
143     d2 = 0.99775
144     d3 = 0.9985
145 end
146 if (time>120)
147     a2 = 1
148     b1 = 0.99
149     b2 = 0.9875
150     c1 = 0.99675
151     c2 = 0.99575
152     d1 = 0.99675
153     d2 = 0.99675
154     d3 = 0.9985
155 end
156 if (temperature01list(time+1) - temperature01list(time) >0)
157     %第一层
158     temperature01 = temperature01list(time,1);
159     temperature45 = temperature45list(time);%每隔5秒作为一次迭代，所以选取5秒后的皮肤外侧温度
160     applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
161     applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
162     applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
163     c = k1;
164     a = 0;
165     f = 0;
166     d = rho1*Cp1;

```

```

167 specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
169 setInitialConditions(pdem1, 0);
R = solvepde(pdem1,tlist);
171 u = R.NodalSolution;%反解每个节点的温度
p = pdem1.Mesh.Nodes;%得出每个mesh后的节点坐标
173 x = p(1,:);
    y = p(2,:);
175 num1 = 1;
%figure
177 %pdeplot(pdem1,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-1 15 49 51]);
179 nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
num2 = length(x)
181 for i = 1:num2
    if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
183         nodechoose(num1) = i;
        num1 = num1 + 1;
185     end
end
187 num3 = 0;
    temperature12 = 0
189 nodechoose(1)
    for i = 1:1000
191         if((nodechoose(i)) ~=0)
            temperature12 = temperature12 + u(nodechoose(i));
193             num3 = num3 +1;
        end
195    end
    temperature12 = temperature12/num3;

197
    temperature12list(time) = temperature12*a2;
199
%第二层
201 applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',b1*temperature12);
    applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
203 applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
    c = k2;
205    a = 0;
    f = 0;
207    d = rho2*Cp2;
    specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
209    tlist = 0:.1:5;
    setInitialConditions(pdem2, 0);
211 R = solvepde(pdem2,tlist);
    u = R.NodalSolution;%反解每个节点的温度
213 p = pdem2.Mesh.Nodes;%得出每个mesh后的节点坐标

```

```

215 x = p(1,:);
y = p(2,:);
num1 = 1;
217 %figure
%pdeplot(pdem2,'XYData',u(:,1),'Contour','off','ColorMap','hot');
219 %axis([-1 15 49 51]);
nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
221 num2 = length(x)
for i = 1:num2
223     if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
225         num1 = num1 + 1;
    end
227 end
num3 = 0;
229 temperature23 = 0
nodechoose(1)
231 for i = 1:1000
    if((nodechoose(i)) ~=0)
233         temperature23 = temperature23 + u(nodechoose(i));
        num3 = num3 +1;
235     end
end
237 temperature23 = temperature23/num3;
temperature23list(time) = temperature23*b2;
239 %temperature23

241 %第三层
    applyBoundaryCondition(pdem3,'dirichlet','Edge',4,'u',c1*temperature23);
243     applyBoundaryCondition(pdem3,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',[1,3],'u',37);
245     c = k3;
    a = 0;
247     f = 0;
    d = rho3*Cp3;
249     specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:1:5;
251     setInitialConditions(pdem3, 0);
    R = solvepde(pdem3,tlist);
253     u = R.NodalSolution;%反解每个节点的温度
    p = pdem3.Mesh.Nodes;%得出每个mesh后的节点坐标
255     x = p(1,:);
    y = p(2,:);
257     num1 = 1;
%figure
259 %pdeplot(pdem3,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-1 15 49 51]);

```

```

261 nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
num2 = length(x)
263 for i = 1:num2
    if ((x(i)>(h1+h2+h3-0.6)) && (x(i)<(h1+h2+h3+0.6)) && (y(i)>35) && (y(i) <65)
        )
265         nodechoose(num1) = i;
        num1 = num1 + 1;
267     end
end
269 num3 = 0;
temperature34 = 0
271 nodechoose(1)
for i = 1:1000
273     if((nodechoose(i)) ~=0)
        temperature34 = temperature34 + u(nodechoose(i));
275         num3 = num3 +1;
        end
277 end
temperature34 = temperature34/num3;
279 temperature34list(time) = temperature34*c2
%temperature34
281 %if( time>5)
    %chazhi1 = temperature01list(time-1)-temperature12list(time-1);
283     %chazhi2 = temperature12list(time-1)-temperature23list(time-1);
    %chazhi3 = temperature23list(time-1)-temperature34list(time-1);
285     %chazhi4 = temperature34list(time-1)-temperature45;
    %sumchazhi = chazhi1+chazhi2+chazhi3+chazhi4;
287     %temperature12list(time-1) = temperature01list(time-1) + sumchazhi*rate1
    %temperature23list(time-1) = temperature01list(time-1) + sumchazhi*rate2
289     %temperature34list(time-1) = temperature01list(time-1) + sumchazhi*rate3
    %temperature45list(time) = temperature01list(time) + sumchazhi*rate4
291
    %chazhi2 = rat2*chazhi1/rat1;
    %chazhi3 = rat3*chazhi1/rat1;
295     %chazhi4 = rat4*chazhi1/rat1;
    %temperature23list(time) = temperature12list(time)-chazhi2;
297     %if( temperature23list(time)<temperature23list(time-1))
    % temperature23list(time) = temperature23;
299     %end
    %temperature34list(time) = temperature23list(time)-chazhi3;
301     %if( temperature34list(time)<temperature34list(time-1))
    % temperature34list(time) = temperature34;
303     %end
    %temperature45list(time) = temperature34list(time)-chazhi4;
305     %if( temperature45list(time)<temperature45list(time-1))
    % temperature45list(time) = temperature45;

```



```

307     %end

309

311     %end

313

315     %第四层
    applyBoundaryCondition(pdem4, 'dirichlet', 'Edge', 4, 'u', d1*temperature34);
    applyBoundaryCondition(pdem4, 'dirichlet', 'Edge', 2, 'u', d2*temperature45);
317    applyBoundaryCondition(pdem4, 'dirichlet', 'Edge', [1,3], 'u', 37);
    c = k4;
319    a = 0;
    f = 0;
321    d = rho4*Cp4;
    specifyCoefficients(pdem4, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
323    tlist = 0:.1:5;
    setInitialConditions(pdem4, 0);
325    R = solvepde(pdem4, tlist);
    u = R.NodalSolution;%反解每个节点的温度
327    p = pdem4.Mesh.Nodes;%得出每个mesh后的节点坐标
    x = p(1,:);
329    y = p(2,:);
    num1 = 1;
331    %figure
    %pdeplot(pdem4, 'XYData', u(:,1), 'Contour', 'off', 'ColorMap', 'hot');
333    %axis([-1 15 49 51]);
    nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
335    num2 = length(x)
    for i = 1:num2
337        if ((x(i)>(h1+h2+h3+h4-0.5)) && (x(i)<(h1+h2+h3+h4+0.5)) && (y(i)>35) && (y(i)
            ) <65))
            nodechoose(num1) = i;
339            num1 = num1 + 1;
        end
341    end
    num3 = 0;
343    temperature45 = 0
    nodechoose(1)
345    for i = 1:1000
        if((nodechoose(i)) ~=0)
347            temperature45 = temperature45 + u(nodechoose(i));
            num3 = num3 +1;
349        end
    end
351    temperature45 = temperature45/num3;

```

```

353     if(time<3)
354         temperature45 = 37;
355         d2=1;
356     end
357
358     judge1 = 0%对于皮肤温度场在极限温度下的变化情况模拟
359     judge2 = 0
360     judge3 = 0
361     if(temperature45>47.11)
362         judge1 = 1
363     end
364     if(temperature45>47.9)
365         judge2 = 1
366     end
367     if(temperature45>48)
368         judge3 = 1
369     end
370
371     time = time+1
372     %temperature45list(time) = temperature45*d3
373     if (judge1 == 0 && judge2 == 0 && judge3 == 0)
374         temperature45list(time) = temperature45*d3
375     end
376     if (judge1 == 1 && judge2 == 0 && judge3 == 0)
377         temperature45list(time) = temperature45list(time)+0.01;
378     end
379     if (judge1 == 1 && judge2 == 1 && judge3 == 0 && judge4>4)
380         temperature45list(time) = temperature45list(time)+0.01;
381         judge4 = 0
382     end
383     judge4 = judge4 + 1
384     if (judge1 == 1 && judge2 == 1 && judge3 == 1 && judge5>18)
385         temperature45list(time) = temperature45list(time)+0.01;
386         judge5 = 0
387     end
388     judge5 = judge5 + 1
389     if temperature45list(time)>48.08
390         temperature45list(time) = 48.08;
391     end
392     if temperature45list(time)<37
393         temperature45list(time) = 37;
394     end
395     %temperature45
396
397
398
399

```

```

401     else
        i2 = 1000;
403     end
end

```

codes/diedai3.m

```

clc
2 close all
clear
4
x=xlsread('mydata.xlsx','附件2','A3:B5403');
6 xx = xlsread('temp_bound.xlsx','A1:B201');
    temperature45list = x(:,2);%读取皮肤外侧数据，作为模型另一边的温度情况
8 temperature01list = xx(:,2);%读取I层靠近环境数据，作为模型另一边的温度情况
    numberOfPDE = 1;
10 pdem1 = createpde(numberOfPDE);
    numberOfPDE = 1;
12 pdem2 = createpde(numberOfPDE);
    numberOfPDE = 1;
14 pdem3 = createpde(numberOfPDE);
    numberOfPDE = 1;
16 pdem4 = createpde(numberOfPDE);
    rho1 = 300; % 密度
18 Cp1 = 1377; % 比热
    k1 = 0.082; % 热导率
20 h1 = 0.6;

22 rho2 = 862; % 密度
    Cp2 = 2100; % 比热
24 k2 = 0.37; % 热导率
    h2 = 6;

26
    rho3 = 74.2; % 密度
28 Cp3 = 1726; % 比热
    k3 = 0.045; % 热导率
30 h3 = 3.6;

32 rho4 = 1.18; % 密度
    Cp4 = 1005; % 比热
34 k4 = 0.028; % 热导率
    h4 = 5;

36
R1 = [3 4 0 h1+h2+h3+h4 h1+h2+h3+h4 0 0 0 100 100]';
38 R2 = [3 4 h1 h1+h2+h3+h4 h1+h2+h3+h4 h1 0 0 100 100]';
R3 = [3 4 h1+h2 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2 0 0 100 100]';

```

```

40 R4 = [3 4 h1+h2+h3 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2+h3 0 0 100 100]';

42 g1 = decsg(R1);
    geometryFromEdges(pdem1 ,g1);
44 %figure(1)
    %pdegplot(pdem1,'EdgeLabels','on');
46 %axis([-1 15.3 49 51]);

48 g2 = decsg(R2);
    geometryFromEdges(pdem2 ,g2);
50 %figure(2)
    %pdegplot(pdem2,'EdgeLabels','on');
52 %axis([-1 15.3 5 6]);

54 g3 = decsg(R3);
    geometryFromEdges(pdem3 ,g3);
56 %figure(3)
    %pdegplot(pdem3,'EdgeLabels','on');
58 %axis([-1 15.3 5 6]);

60 g4 = decsg(R4);
    geometryFromEdges(pdem4 ,g4);
62 %figure(4)
    %pdegplot(pdem4,'EdgeLabels','on');
64 %axis([-1 15.3 5 6]);

66
    %虽然希望三角网格的划分越精细越好，但是由于上下边界无穷远的设定，导致这部分无用网格
    太多，
68 %所以注意大小
    hmax = .2; % element size
70 msh1=generateMesh(pdem1,'Hmax',hmax);
    %figure
72 %pdeplot(pdem1);
    %axis([-1 .7 5 6]);

74
    hmax = .5; % element size
76 msh2=generateMesh(pdem2,'Hmax',hmax);
    %figure
78 %pdeplot(pdem2);
    %axis([.5 6.7 2 8]);

80
    hmax = .5; % element size
82 msh3=generateMesh(pdem3,'Hmax',hmax);
    %figure
84 %pdeplot(pdem3);
    %axis([6.5 10.3 3 7]);

```

```

86     hmax = .5; % element size
87     msh4=generateMesh(pdem4,'Hmax',hmax);
88     %figure
89     %pdplot(pdem4);
90     %axis([10.1 15.3 2 8]);
91
92
93
94     temperature = 75;%环境温度已经在另一个模型中应用
95     temperature01 = 37;
96     temperature12 = 37;
97     temperature23 = 37;
98     temperature34 = 37;
99     time = 1;
100     temperature12list = ones(1,1000);
101     temperature23list = ones(1,1000);
102     temperature34list = ones(1,1000);
103
104     for i2 = 1:1000
105
106         if (temperature01list(time+1) - temperature01list(time) > 0.038)
107             %第一层
108             temperature01 = temperature01list(time,1);
109             temperature45 = temperature45list(time*5,1);%每隔5秒作为一次迭代，所以选取5秒后
110                 的皮肤外侧温度
111             applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
112             applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
113             applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
114             c = k1;
115             a = 0;
116             f = 0;
117             d = rho1*Cp1;
118             specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
119             tlist = 0:1:5;
120             setInitialConditions(pdem1, 0);
121             R = solvepde(pdem1,tlist);
122             u = R.NodalSolution;%反解每个节点的温度
123             p = pdem1.Mesh.Nodes;%得出每个mesh后的节点坐标
124             x = p(1,:);
125             y = p(2,:);
126             num1 = 1;
127             %figure
128             %pdplot(pdem1,'XYData',u(:,1),'Contour','off','ColorMap','hot');
129             %axis([-1 15 49 51]);
130             nodechoose = zeros(1,1000);%选取的作为该界面的坐标值
131             num2 = length(x);

```

```

132     for i = 1:num2
133         if ((x(i)>0.5) && (x(i)<0.7) && (y(i)>35) && (y(i) <65))
134             nodechoose(num1) = i;
135             num1 = num1 + 1;
136         end
137     end
138     num3 = 0;
139     temperature12 = 0;
140     nodechoose(1);
141     for i = 1:1000
142         if((nodechoose(i)) ~=0)
143             temperature12 = temperature12 + u(nodechoose(i));
144             num3 = num3 +1;
145         end
146     end
147     temperature12 = temperature12/num3;
148     temperature12list(time) = temperature12;

150 %第二层
151     applyBoundaryCondition(pdem2, 'dirichlet', 'Edge', 4, 'u', temperature12);
152     applyBoundaryCondition(pdem2, 'dirichlet', 'Edge', 2, 'u', temperature45);
153     applyBoundaryCondition(pdem2, 'dirichlet', 'Edge', [1,3], 'u', 37);
154     c = k2;
155     a = 0;
156     f = 0;
157     d = rho2*Cp2;
158     specifyCoefficients(pdem2, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
159     tlist = 0:1:5;
160     setInitialConditions(pdem2, 0);
161     R = solvepde(pdem2, tlist);
162     u = R.NodalSolution;%反解每个节点的温度
163     p = pdem2.Mesh.Nodes;%得出每个mesh后的节点坐标
164     x = p(1,:);
165     y = p(2,:);
166     num1 = 1;
167     %figure
168     %pdeplot(pdem2, 'XYData', u(:,1), 'Contour', 'off', 'ColorMap', 'hot');
169     %axis([-1 15 49 51]);
170     nodechoose = zeros(1,1000);%选取的作为该界面的坐标值
171     num2 = length(x);
172     for i = 1:num2
173         if ((x(i)>6) && (x(i)<7.5) && (y(i)>35) && (y(i) <65))
174             nodechoose(num1) = i;
175             num1 = num1 + 1;
176         end
177     end
178     num3 = 0;

```

```

180     temperature23 = 0;
181     nodechoose(1);
182     for i = 1:1000
183         if((nodechoose(i)) ~=0)
184             temperature23 = temperature23 + u(nodechoose(i));
185             num3 = num3 +1;
186         end
187     end
188     temperature23 = temperature23/num3;
189     temperature23list(time) = temperature23;
190     %temperature23
191
192     %第三层
193     applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 4, 'u', temperature23);
194     applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 2, 'u', temperature45);
195     applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', [1,3], 'u', 37);
196     c = k3;
197     a = 0;
198     f = 0;
199     d = rho3*Cp3;
200     specifyCoefficients(pdem3, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
201     tlist = 0:.1:5;
202     setInitialConditions(pdem3, 0);
203     R = solvepde(pdem3, tlist);
204     u = R.NodalSolution;%反解每个节点的温度
205     p = pdem3.Mesh.Nodes;%得出每个mesh后的节点坐标
206     x = p(1,:);
207     y = p(2,:);
208     num1 = 1;
209     %figure
210     %pdeplot(pdem3, 'XYData', u(:,1), 'Contour', 'off', 'ColorMap', 'hot');
211     %axis([-1 15 49 51]);
212     nodechoose = zeros(1,1000);%选取的作为该界面的坐标值
213     num2 = length(x);
214     for i = 1:num2
215         if ((x(i)>9.5) && (x(i)<11) && (y(i)>35) && (y(i) <65))
216             nodechoose(num1) = i;
217             num1 = num1 + 1;
218         end
219     end
220     num3 = 0;
221     temperature34 = 0;
222     nodechoose(1);
223     for i = 1:1000
224         if nodechoose(i) ~=0
225             temperature34 = temperature34 + u(nodechoose(i));
226             num3 = num3 +1;

```

```

226     end
227     end
228     temperature34 = temperature34/num3;
229     temperature34list(time) = temperature34;
230 %temperature34
231
232 %第四层
233     applyBoundaryCondition(pdem4, 'dirichlet', 'Edge', 4, 'u', temperature34);
234     applyBoundaryCondition(pdem4, 'dirichlet', 'Edge', 2, 'u', temperature45);
235     applyBoundaryCondition(pdem4, 'dirichlet', 'Edge', [1,3], 'u', 37);
236     c = k4;
237     a = 0;
238     f = 0;
239     d = rho4*Cp4;
240     specifyCoefficients(pdem4, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
241     tlist = 0:1:5;
242     setInitialConditions(pdem4, 0);
243     R = solvepde(pdem4, tlist);
244     u = R.NodalSolution;%反解每个节点的温度
245     p = pdem4.Mesh.Nodes;%得出每个mesh后的节点坐标
246     x = p(1,:);
247     y = p(2,:);
248     num1 = 1;
249 %figure
250 %pdeplot(pdem4, 'XYData', u(:,1), 'Contour', 'off', 'ColorMap', 'hot');
251 %axis([-1 15 49 51]);
252     nodechoose = zeros(1,1000);%选取的作为该界面的坐标值
253     num2 = length(x);
254     for i = 1:num2
255         if ((x(i)>14.5) && (x(i)<15.2) && (y(i)>35) && (y(i) <65))
256             nodechoose(num1) = i;
257             num1 = num1 + 1;
258         end
259     end
260     num3 = 0;
261     temperature45 = 0;
262     nodechoose(1);
263     for i = 1:1000
264         if((nodechoose(i)) ~=0)
265             temperature45 = temperature45 + u(nodechoose(i));
266             num3 = num3 +1;
267         end
268     end
269     temperature45 = temperature45/num3;
270 %temperature45
271

```



```

274     time = time+1;

276     else

278         i2 = 1000;

end
end

```

codes/tem\_suit.m

```

% 计算温度分布
2 clc
clear
4 close all

6 % 数据准备
% IV 左边界条件
8 skintem=xlsread('mydata.xlsx','附件2','A3:B5403');
% plot(skintem(:,1),skintem(:,2))
10 % 服装设计参数
suit=xlsread('mydata.xlsx','附件1','B3:D6');
12

%PDE方程参数
14 % 5个边界坐标
x(4)=5*10^(-3);
16 x(3)=(5+3.6)*10^(-3);
x(2)=(5+3.6+6)*10^(-3);
18 x(1)=(5+3.6+6+0.6)*10^(-3);
% 努塞尔数
20 Nu=4.336;
% I层与环境换热系数
22 h_1=10;
% IV层与III层换热系数
24 h_34=Nu*suit(4,3)/x(4);
% I层与II层, II层与III层 换热系数
26 [h_12,h_23]=deal(10^10);
% 化简的系数
28 alpha=suit(:,3)./suit(:,1)./suit(:,2);

30 %% 求解 beta 的行列式
syms beta
32 gamma=suit(:,3)./sqrt(alpha).*beta;
eta=x./sqrt(alpha).*beta;
34 % 系数矩阵方程
A=[-gamma(1)*cos(eta(1))-h_12*sin(eta(2)) gamma(1)*sin(eta(1))-h_12*cos(eta(2))
    h_12*sin(x(1)/x(2)*eta(2)) h_12*cos(x(1)/x(2)*eta(2)) 0 0 0 0
36    0 0 -gamma(2)*cos(eta(2))-h_23*sin(eta(3)) gamma(3)*sin(eta(2))-h_23*cos(eta(3))

```

```

        ) h_12*sin(x(2)/x(3)*eta(2)) h_23*cos(x(2)/x(3)*eta(3)) 0 0
    0 0 0 0 -gamma(3)*cos(eta(3))-h_34*sin(eta(4)) gamma(3)*sin(eta(3))-h_34*cos(
        eta(4)) h_34*sin(x(3)/x(4)*eta(4)) h_34*cos(x(3)/x(4)*eta(4))
38 gamma(1)*cos(eta(1))+h_1*sin(eta(2)) -gamma(1)*sin(eta(1))+h_1*cos(eta(2)) 0 0
    0 0 0 0
    gamma(1)*cos(eta(1)) -gamma(1)*sin(eta(1)) -gamma(2)*cos(x(1)/x(2)*eta(2))
        gamma(2)*sin(x(1)/x(2)*eta(2)) 0 0 0 0
40 0 0 gamma(2)*cos(eta(2)) -gamma(2)*sin(eta(2)) -gamma(3)*cos(x(2)/x(3)*eta(3))
        gamma(3)*sin(x(2)/x(3)*eta(3)) 0 0
    0 0 0 0 gamma(3)*cos(eta(3)) -gamma(3)*sin(eta(3)) -gamma(4)*cos(x(3)/x(4)*eta
        (4)) gamma(4)*sin(x(3)/x(4)*eta(4))
42 0 0 0 0 0 0 0 1
    ];
44
% 令行列式为0, 求 beta
46 % det_A=det(A);
    solve(det(A)==0,beta)
48
%% 解方程 A
50 beta=0;
    null(eval(A))
52
%% 画出图像
54 % [x0,y0]=meshgrid(0:5400,linspace(0,x(1)*10^3,5401));
    % mesh(x0,y0,temdistrib(x0,y0))
56 %
    %% 这个函数是设出来的
58 % function s=temdistrib(x,t)
    %% 温度分布函数
60 %
    % s=exp(-t.^2).*sin(x);
62 %
    % end

```

codes/temsuit.m

```

clc,close all,clear all;
2 x = xlsread('data4.xlsx','A1:B721')
    temperature01list = x(:,2);%读取I层靠近环境数据, 作为模型另一边的温度情况
4 numberOfPDE = 1;
    pdem1 = createpde(numberOfPDE);
6 numberOfPDE = 1;
    pdem2 = createpde(numberOfPDE);
8 numberOfPDE = 1;
    pdem3 = createpde(numberOfPDE);
10 numberOfPDE = 1;
    pdem4 = createpde(numberOfPDE);

```

```

12 rho1 = 300; % 密度
    Cp1 = 1377; % 比热
14 k1 = 0.082; % 热导率
    h1 = 0.6;
16
    rho2 = 862; % 密度
18 Cp2 = 2100; % 比热
    k2 = 0.37; % 热导率
20 h2 = 10.295;%设置的厚度为0.1 5 10 15 20 25

22 rho3 = 74.2; % 密度
    Cp3 = 1726; % 比热
24 k3 = 0.045; % 热导率
    h3 = 3.6;
26
    rho4 = 1.18; % 密度
28 Cp4 = 1005; % 比热
    k4 = 0.028; % 热导率
30 h4 = 5.5;

32 R1 = [3 4 0 h1+h2+h3+h4 h1+h2+h3+h4 0 0 0 100 100]';
    R2 = [3 4 h1 h1+h2+h3+h4 h1+h2+h3+h4 h1 0 0 100 100]';
34 R3 = [3 4 h1+h2 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2 0 0 100 100]';
    R4 = [3 4 h1+h2+h3 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2+h3 0 0 100 100]';
36
    rat1 = h1/(h1+h2+h3+h4)
38 rat2 = h2/(h1+h2+h3+h4)
    rat3 = h3/(h1+h2+h3+h4)
40 rat4 = h4/(h1+h2+h3+h4)

42 rate1 = rat1
    rate2 = rate1 + rat2
44 rate3 = rate2 + rat3
    rate4 = rate3 + rat4
46
    g1 = decsg(R1);
48 geometryFromEdges(pdem1 ,g1);
    %figure(1)
50 %pdegplot(pdem1 , 'EdgeLabels' , 'on');
    %axis([-1 15.3 49 51]);
52
    g2 = decsg(R2);
54 geometryFromEdges(pdem2 ,g2);
    %figure(2)
56 %pdegplot(pdem2 , 'EdgeLabels' , 'on');
    %axis([-1 15.3 5 6]);
58

```

```

g3 = decsg(R3);
60 geometryFromEdges(pdem3 ,g3);
%figure(3)
62 %pdegplot(pdem3,'EdgeLabels','on');
%axis([-1 15.3 5 6]);
64
g4 = decsg(R4);
66 geometryFromEdges(pdem4 ,g4);
%figure(4)
68 %pdegplot(pdem4,'EdgeLabels','on');
%axis([-1 15.3 5 6]);
70

72 %虽然希望三角网格的划分越精细越好，但是由于上下边界无穷远的设定，导致这部分无用网格
    太多，
    %所以注意大小
74 hmax = .2; % element size
    msh1=generateMesh(pdem1,'Hmax',hmax);
76 %figure
    %pdeplot(pdem1);
78 %axis([-1 .7 5 6]);

80 hmax = .5; % element size
    msh2=generateMesh(pdem2,'Hmax',hmax);
82 %figure
    %pdeplot(pdem2);
84 %axis([.5 6.7 2 8]);

86 hmax = .5; % element size
    msh3=generateMesh(pdem3,'Hmax',hmax);
88 %figure
    %pdeplot(pdem3);
90 %axis([6.5 10.3 3 7]);

92 hmax = .5; % element size
    msh4=generateMesh(pdem4,'Hmax',hmax);
94 %figure
    %pdeplot(pdem4);
96 %axis([10.1 15.3 2 8]);

98

100 temperature = 65%环境温度已经在另一个模型中应用
    temperature01 = 37
102 temperature12 = 37
    temperature23 = 37
104 temperature34 = 37

```

```

106 temperature12list = ones(1,1100)
108 temperature23list = ones(1,1100)
    temperature34list = ones(1,1100)
110 temperature45list = ones(1,1100)
    temperature45list(1) = 37
112
    judge4 = 0
114 judge5 = 0
    time = 1;
116 for i2 = 1:1000
    if time == 1
118         a2 = 1
            b1 = 1
120         b2 = 1
            c1 = 1
122         c2 = 1
            d1 = 1
124         d2 = 1
            d3 = 1
126     end
        if (time>1&&time<8)
128             a2 = 1
                b1 = 0.99
130             b2 = 0.99
                c1 = 0.997
132             c2 = 0.996
                d1 = 0.999
134             d2 = 0.99975
                d3 = 0.999
136         end
            if (time>7)
138                 a2 = 1
                    b1 = 0.99
140                 b2 = 0.9875
                    c1 = 0.997
142                 c2 = 0.9975
                    d1 = 0.99725
144                 d2 = 0.99775
                    d3 = 0.9985
146             end
                if (time>120)
148                     a2 = 1
                        b1 = 0.99
150                     b2 = 0.9875
                        c1 = 0.99675

```

```

152     c2 = 0.99575
153     d1 = 0.99675
154     d2 = 0.99675
155     d3 = 0.9985
156 end
157 if (temperature01list(time+1) - temperature01list(time) > 0)
158     %第一层
159     temperature01 = temperature01list(time,1);
160     temperature45 = temperature45list(time);%每隔5秒作为一次迭代，所以选取5秒后的皮肤外侧温度
161     applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
162     applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
163     applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
164     c = k1;
165     a = 0;
166     f = 0;
167     d = rho1*Cp1;
168     specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
169     tlist = 0:.1:5;
170     setInitialConditions(pdem1, 0);
171     R = solvepde(pdem1, tlist);
172     u = R.NodalSolution;%反解每个节点的温度
173     p = pdem1.Mesh.Nodes;%得出每个mesh后的节点坐标
174     x = p(1,:);
175     y = p(2,:);
176     num1 = 1;
177     nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
178     num2 = length(x)
179     for i = 1:num2
180         if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
181             nodechoose(num1) = i;
182             num1 = num1 + 1;
183         end
184     end
185     num3 = 0;
186     temperature12 = 0
187     nodechoose(1)
188     for i = 1:1000
189         if((nodechoose(i)) ~=0)
190             temperature12 = temperature12 + u(nodechoose(i));
191             num3 = num3 +1;
192         end
193     end
194     temperature12 = temperature12/num3;
195
196     temperature12list(time) = temperature12*a2;

```

```

198 %第二层
    applyBoundaryCondition(pdem2, 'dirichlet', 'Edge', 4, 'u', b1*temperature12);
200 applyBoundaryCondition(pdem2, 'dirichlet', 'Edge', 2, 'u', temperature45);
    applyBoundaryCondition(pdem2, 'dirichlet', 'Edge', [1,3], 'u', 37);
202 c = k2;
    a = 0;
204 f = 0;
    d = rho2*Cp2;
206 specifyCoefficients(pdem2, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
    tlist = 0:1:5;
208 setInitialConditions(pdem2, 0);
    R = solvepde(pdem2, tlist);
210 u = R.NodalSolution;%反解每个节点的温度
    p = pdem2.Mesh.Nodes;%得出每个mesh后的节点坐标
212 x = p(1,:);
    y = p(2,:);
214 num1 = 1;
    %figure
216 %pdeplot(pdem2, 'XYData', u(:,1), 'Contour', 'off', 'ColorMap', 'hot');
    %axis([-1 15 49 51]);
218 nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
220 for i = 1:num2
        if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
222             nodechoose(num1) = i;
                num1 = num1 + 1;
224         end
    end
226 num3 = 0;
    temperature23 = 0
228 nodechoose(1)
    for i = 1:1000
230         if((nodechoose(i)) ~=0)
                temperature23 = temperature23 + u(nodechoose(i));
232             num3 = num3 +1;
        end
234    end
    temperature23 = temperature23/num3;
236 temperature23list(time) = temperature23*b2;
    %temperature23
238
239 %第三层
240 applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 4, 'u', c1*temperature23);
    applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 2, 'u', temperature45);
242 applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', [1,3], 'u', 37);
    c = k3;
244 a = 0;

```

```

f = 0;
246 d = rho3*Cp3;
specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
248 tlist = 0:1:5;
setInitialConditions(pdem3, 0);
250 R = solvepde(pdem3,tlist);
u = R.NodalSolution;%反解每个节点的温度
252 p = pdem3.Mesh.Nodes;%得出每个mesh后的节点坐标
x = p(1,:);
254 y = p(2,:);
num1 = 1;
256 %figure
%pdeplot(pdem3,'XYData',u(:,1),'Contour','off','ColorMap','hot');
258 %axis([-1 15 49 51]);
nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
260 num2 = length(x)
for i = 1:num2
262     if ((x(i)>(h1+h2+h3-0.6)) && (x(i)<(h1+h2+h3+0.6)) && (y(i)>35) && (y(i) <65)
        )
        nodechoose(num1) = i;
264         num1 = num1 + 1;
    end
266 end
num3 = 0;
268 temperature34 = 0
nodechoose(1)
270 for i = 1:1000
    if((nodechoose(i)) ~=0)
272         temperature34 = temperature34 + u(nodechoose(i));
        num3 = num3 +1;
274     end
end
276 temperature34 = temperature34/num3;
temperature34list(time) = temperature34*c2
278
280 %第四层
applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',d1*temperature34);
282 applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',d2*temperature45);
applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
284 c = k4;
a = 0;
286 f = 0;
d = rho4*Cp4;
288 specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
tlist = 0:1:5;
290 setInitialConditions(pdem4, 0);

```



```

R = solvepde(pdem4,tlist);
292 u = R.NodalSolution;%反解每个节点的温度
p = pdem4.Mesh.Nodes;%得出每个mesh后的节点坐标
294 x = p(1,:);
y = p(2,:);
296 num1 = 1;
nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
298 num2 = length(x)
for i = 1:num2
300     if ((x(i)>(h1+h2+h3+h4-0.5)) && (x(i)<(h1+h2+h3+h4+0.5)) && (y(i)>35) && (y(i)
        ) <65))
        nodechoose(num1) = i;
302     num1 = num1 + 1;
    end
304 end
num3 = 0;
306 temperature45 = 0
nodechoose(1)
308 for i = 1:1000
    if((nodechoose(i)) ~=0)
310         temperature45 = temperature45 + u(nodechoose(i));
        num3 = num3 +1;
312     end
    end
314 temperature45 = temperature45/num3;

316 if(time<3)
    temperature45 = 37;
318     d2=1;
    end
320
judge1 = 0;%对于皮肤温度场在极限温度下的变化情况模拟
322 judge2 = 0
judge3 = 0
324 if(temperature45>47.11)
    judge1 = 1
326 end
if(temperature45>47.9)
328     judge2 = 1
    end
330 if(temperature45>48)
    judge3 = 1
332 end

334 time = time+1
%temperature45list(time) = temperature45*d3
336 if (judge1 == 0 && judge2 == 0 && judge3 == 0)

```

```

    temperature45list(time) = temperature45*d3
338 end
    if (judge1 == 1 && judge2 == 0 && judge3 == 0)
340     temperature45list(time) = temperature45list(time)+0.01;
    end
342     if (judge1 == 1 && judge2 == 1 && judge3 == 0 && judge4>4)
        temperature45list(time) = temperature45list(time)+0.01;
344     judge4 = 0
    end
346     judge4 = judge4 + 1
    if (judge1 == 1 && judge2 == 1 && judge3 == 1 && judge5>18)
348     temperature45list(time) = temperature45list(time)+0.01;
        judge5 = 0
350    end
    judge5 = judge5 + 1
352    if temperature45list(time)>48.08
        temperature45list(time) = 48.08;
354    end
    if temperature45list(time)<37
356     temperature45list(time) = 37;
    end
358    %temperature45
360
362
364 else
    i2 = 1000;
366 end
end

```

codes/prom2.m

```

1 clc ,close all ,clear all;
  x = xlsread('data2.xlsx','A1:B1081')
3 temperature01list = x(:,2);%读取I层靠近环境数据，作为模型另一边的温度情况
  numberOfPDE = 1;
5 pdem1 = createpde(numberOfPDE);
  numberOfPDE = 1;
7 pdem2 = createpde(numberOfPDE);
  numberOfPDE = 1;
9 pdem3 = createpde(numberOfPDE);
  numberOfPDE = 1;
11 pdem4 = createpde(numberOfPDE);
    rho1 = 300; % 密度
13 Cp1 = 1377; % 比热

```

```

k1 = 0.082; % 热导率
15 h1 = 0.6;

17 rho2 = 862; % 密度
Cp2 = 2100; % 比热
19 k2 = 0.37; % 热导率
h2 = 6;%设置的厚度为0.1 5 10 15 20 25
21
rho3 = 74.2; % 密度
23 Cp3 = 1726; % 比热
k3 = 0.045; % 热导率
25 h3 = 3.6;

27 rho4 = 1.18; % 密度
Cp4 = 1005; % 比热
29 k4 = 0.028; % 热导率
h4 = 5;
31
R1 = [3 4 0 h1+h2+h3+h4 h1+h2+h3+h4 0 0 0 100 100]';
33 R2 = [3 4 h1 h1+h2+h3+h4 h1+h2+h3+h4 h1 0 0 100 100]';
R3 = [3 4 h1+h2 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2 0 0 100 100]';
35 R4 = [3 4 h1+h2+h3 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2+h3 0 0 100 100]';

37 rat1 = h1/(h1+h2+h3+h4)
rat2 = h2/(h1+h2+h3+h4)
39 rat3 = h3/(h1+h2+h3+h4)
rat4 = h4/(h1+h2+h3+h4)
41
rate1 = rat1
43 rate2 = rate1 + rat2
rate3 = rate2 + rat3
45 rate4 = rate3 + rat4

47 g1 = decsg(R1);
geometryFromEdges(pdem1 ,g1);
49 %figure(1)
%pddegplot(pdem1 , 'EdgeLabels ', 'on');
51 %axis([-0.1 15.3 49 51]);

53 g2 = decsg(R2);
geometryFromEdges(pdem2 ,g2);
55 %figure(2)
%pddegplot(pdem2 , 'EdgeLabels ', 'on');
57 %axis([-0.1 15.3 5 6]);

59 g3 = decsg(R3);
geometryFromEdges(pdem3 ,g3);

```

```

61 %figure (3)
    %pdegplot(pdem3,'EdgeLabels','on');
63 %axis([-1 15.3 5 6]);

65 g4 = decsg(R4);
    geometryFromEdges(pdem4 ,g4);
67 %figure (4)
    %pdegplot(pdem4,'EdgeLabels','on');
69 %axis([-1 15.3 5 6]);

71
    %虽然希望三角网格的划分越精细越好，但是由于上下边界无穷远的设定，导致这部分无用网格
    太多，
73 %所以注意大小
    hmax = .2; % element size
75 msh1=generateMesh(pdem1,'Hmax',hmax);
    %figure
77 %pdeplot(pdem1);
    %axis([-1 .7 5 6]);
79
    hmax = .5; % element size
81 msh2=generateMesh(pdem2,'Hmax',hmax);

83
    hmax = .5; % element size
85 msh3=generateMesh(pdem3,'Hmax',hmax);

87
    hmax = .5; % element size
89 msh4=generateMesh(pdem4,'Hmax',hmax);

91

93
    temperature = 75%环境温度已经在另一个模型中应用
95 temperature01 = 37
    temperature12 = 37
97 temperature23 = 37
    temperature34 = 37
99

101 temperature12list = ones(1,1100)
    temperature23list = ones(1,1100)
103 temperature34list = ones(1,1100)
    temperature45list = ones(1,1100)
105 temperature45list(1) = 37

```

```

107 judge4 = 0
    judge5 = 0
109 time = 1;
    for i2 = 1:1000
111
112 %对边界热阻、织物孔隙等因素进行参数模拟
113     if time == 1
114         a2 = 1
115         b1 = 1
116         b2 = 1
117         c1 = 1
118         c2 = 1
119         d1 = 1
120         d2 = 1
121         d3 = 1
122     end
123     if (time>1&&time<8)
124         a2 = 1
125         b1 = 0.99
126         b2 = 0.99
127         c1 = 0.997
128         c2 = 0.996
129         d1 = 0.999
130         d2 = 0.99975
131         d3 = 0.999
132     end
133     if (time>7)
134         a2 = 1
135         b1 = 0.99
136         b2 = 0.9875
137         c1 = 0.997
138         c2 = 0.996
139         d1 = 0.997
140         d2 = 0.997
141         d3 = 0.9985
142     end
143     if (time>120)
144         a2 = 1
145         b1 = 0.99
146         b2 = 0.9875
147         c1 = 0.99675
148         c2 = 0.99575
149         d1 = 0.99675
150         d2 = 0.99675
151         d3 = 0.9985
152     end
153     if (temperature01list(time+1) - temperature01list(time) >0)

```

```

155 %第一层
    temperature01 = temperature01list(time,1);
    temperature45 = temperature45list(time);%每隔5秒作为一次迭代，所以选取5秒后的皮肤外侧温度
157 applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
159 applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
    c = k1;
161 a = 0;
    f = 0;
163 d = rho1*Cp1;
    specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
165 tlist = 0:.1:5;
    setInitialConditions(pdem1, 0);
167 R = solvepde(pdem1,tlist);
    u = R.NodalSolution;%反解每个节点的温度
169 p = pdem1.Mesh.Nodes;%得出每个mesh后的节点坐标
    x = p(1,:);
171 y = p(2,:);
    num1 = 1;
173
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
175 num2 = length(x)
    for i = 1:num2
177         if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
                nodechoose(num1) = i;
179         num1 = num1 + 1;
        end
181    end
    num3 = 0;
183    temperature12 = 0
    nodechoose(1)
185    for i = 1:1000
        if((nodechoose(i)) ~=0)
187            temperature12 = temperature12 + u(nodechoose(i));
            num3 = num3 +1;
189        end
    end
191    temperature12 = temperature12/num3;

193    temperature12list(time) = temperature12*a2;

195 %第二层
    applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',b1*temperature12);
197    applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
199    c = k2;

```

```

201     a = 0;
202     f = 0;
203     d = rho2*Cp2;
204     specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
205     tlist = 0:1:5;
206     setInitialConditions(pdem2, 0);
207     R = solvepde(pdem2,tlist);
208     u = R.NodalSolution;%反解每个节点的温度
209     p = pdem2.Mesh.Nodes;%得出每个mesh后的节点坐标
210     x = p(1,:);
211     y = p(2,:);
212     num1 = 1;

213     nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
214     num2 = length(x)
215     for i = 1:num2
216         if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
217             nodechoose(num1) = i;
218             num1 = num1 + 1;
219         end
220     end
221     num3 = 0;
222     temperature23 = 0
223     nodechoose(1)
224     for i = 1:1000
225         if((nodechoose(i)) ~=0)
226             temperature23 = temperature23 + u(nodechoose(i));
227             num3 = num3 +1;
228         end
229     end
230     temperature23 = temperature23/num3;
231     temperature23list(time) = temperature23*b2;
232     %temperature23
233
234     %第三层
235     applyBoundaryCondition(pdem3,'dirichlet','Edge',4,'u',c1*temperature23);
236     applyBoundaryCondition(pdem3,'dirichlet','Edge',2,'u',temperature45);
237     applyBoundaryCondition(pdem3,'dirichlet','Edge',[1,3],'u',37);
238     c = k3;
239     a = 0;
240     f = 0;
241     d = rho3*Cp3;
242     specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
243     tlist = 0:1:5;
244     setInitialConditions(pdem3, 0);
245     R = solvepde(pdem3,tlist);
246     u = R.NodalSolution;%反解每个节点的温度

```

```

247 p = pdem3.Mesh.Nodes;%得出每个mesh后的节点坐标
    x = p(1,:);
249 y = p(2,:);
    num1 = 1;
251
    nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
253 num2 = length(x)
    for i = 1:num2
255         if ((x(i)>(h1+h2+h3-0.6)) && (x(i)<(h1+h2+h3+0.6)) && (y(i)>35) && (y(i) <65)
            )
                nodechoose(num1) = i;
257         num1 = num1 + 1;
        end
259    end
    num3 = 0;
261    temperature34 = 0
    nodechoose(1)
263    for i = 1:1000
        if((nodechoose(i)) ~=0)
265            temperature34 = temperature34 + u(nodechoose(i));
            num3 = num3 +1;
267        end
    end
269    temperature34 = temperature34/num3;
    temperature34list(time) = temperature34*c2
271
273
275 %第四层
    applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',d1*temperature34);
277    applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',d2*temperature45);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
279    c = k4;
    a = 0;
281    f = 0;
    d = rho4*Cp4;
283    specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:1:5;
285    setInitialConditions(pdem4, 0);
    R = solvepde(pdem4,tlist);
287    u = R.NodalSolution;%反解每个节点的温度
    p = pdem4.Mesh.Nodes;%得出每个mesh后的节点坐标
289    x = p(1,:);
    y = p(2,:);
291    num1 = 1;

```



```

293 num2 = length(x)
    for i = 1:num2
295         if ((x(i)>(h1+h2+h3+h4-0.5)) && (x(i)<(h1+h2+h3+h4+0.5)) && (y(i)>35) && (y(i)
                ) <65))
                nodechoose(num1) = i;
297         num1 = num1 + 1;
        end
299     end
    num3 = 0;
301     temperature45 = 0
    nodechoose(1)
303     for i = 1:1000
        if((nodechoose(i)) ~=0)
305             temperature45 = temperature45 + u(nodechoose(i));
            num3 = num3 +1;
307         end
        end
309     temperature45 = temperature45 /num3;

311     if(time<3)
        temperature45 = 37;
313         d2=1;
        end
315
    judge1 = 0%对于皮肤温度场在极限温度下的变化情况模拟
317     judge2 = 0
    judge3 = 0
319     if(temperature45>47.11)
        judge1 = 1
321     end
    if(temperature45>47.9)
323         judge2 = 1
        end
325     if(temperature45>48)
        judge3 = 1
327     end
    time = time+1%对皮肤外侧温度在极限温度下升温行为的模拟
329     if (judge1 == 0 && judge2 == 0 && judge3 == 0)
        temperature45list(time) = temperature45*d3
331     end
    if (judge1 == 1 && judge2 == 0 && judge3 == 0)
333         temperature45list(time) = temperature45list(time-1)+0.01;
        end
335     if (judge1 == 1 && judge2 == 1 && judge3 == 0 && judge4>4)
        temperature45list(time) = temperature45list(time-1)+0.01;
337         judge4 = 0;
        end

```

```

339 judge4 = judge4 + 1
    if (judge1 == 1 && judge2 == 1 && judge3 == 1 && judge5 > 18)
341         temperature45list(time) = temperature45list(time-1)+0.01;
        judge5 = 0
343     end
    judge5 = judge5 + 1
345     if temperature45list(time) > 48.08 && time > 250
        temperature45list(time) = 48.08;
347     end
    %temperature45
349
351
353
    else
355         i2 = 1000;
    end
357 end

```

codes/problem1.m

```

1  clc,close all,clear all;
   x=xlsread('data1.xlsx','A1:B5401');
3  xx = xlsread('data2.xlsx','A1:B1081')
   temperature45list = x(:,2);%读取皮肤外侧数据，作为模型另一边的温度情况
5  temperature01list = xx(:,2);%读取I层靠近环境数据，作为模型另一边的温度情况
   numberOfPDE = 1;
7  pdem1 = createpde(numberOfPDE);
   numberOfPDE = 1;
9  pdem2 = createpde(numberOfPDE);
   numberOfPDE = 1;
11 pdem3 = createpde(numberOfPDE);
   numberOfPDE = 1;
13 pdem4 = createpde(numberOfPDE);
   rho1 = 300; % 密度
15 Cp1 = 1377; % 比热
   k1 = 0.082; % 热导率
17 h1 = 0.6;

19 rho2 = 862; % 密度
   Cp2 = 2100; % 比热
21 k2 = 0.37; % 热导率
   h2 = 6;
23
   rho3 = 74.2; % 密度
25 Cp3 = 1726; % 比热

```

```

k3 = 0.045; % 热导率
27 h3 = 3.6;

rho4 = 1.18; % 密度
Cp4 = 1005; % 比热
31 k4 = 0.028; % 热导率
h4 = 5;
33 %PDE区域内几何模型选定
R1 = [3 4 0 h1+h2+h3+h4 h1+h2+h3+h4 0 0 0 100 100]';
35 R2 = [3 4 h1 h1+h2+h3+h4 h1+h2+h3+h4 h1 0 0 100 100]';
R3 = [3 4 h1+h2 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2 0 0 100 100]';
37 R4 = [3 4 h1+h2+h3 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2+h3 0 0 100 100]';
%将模型放入PDE空间
39 g1 = decsg(R1);
geometryFromEdges(pdem1 ,g1);
41

43 g2 = decsg(R2);
geometryFromEdges(pdem2 ,g2);
45

47 g3 = decsg(R3);
geometryFromEdges(pdem3 ,g3);
49

g4 = decsg(R4);
51 geometryFromEdges(pdem4 ,g4);

53

55 %虽然希望三角网格的划分越精细越好，但是由于上下边界无穷远的设定，导致这部分无用网格
    太多，
    %所以注意大小
57 hmax = .2; % element size
msh1=generateMesh(pdem1 , 'Hmax' ,hmax);
59

61 hmax = .5; % element size
msh2=generateMesh(pdem2 , 'Hmax' ,hmax);
63

65 hmax = .5; % element size
msh3=generateMesh(pdem3 , 'Hmax' ,hmax);
67

69 hmax = .5; % element size
msh4=generateMesh(pdem4 , 'Hmax' ,hmax);
71

```

```

73
75 temperature = 75%环境温度已经在另一个模型中应用
   temperature01 = 37
77 temperature12 = 37
   temperature23 = 37
79 temperature34 = 37
   time = 1;
81 temperature12list = ones(1,1200)
   temperature23list = ones(1,1200)
83 temperature34list = ones(1,1200)

85 for i2 = 1:1100

87     if (temperature01list(time+1) - temperature01list(time) > 0.001)
           %第一层
89         temperature01 = temperature01list(time,1);
           temperature45 = temperature45list(time*5,1);%每隔5秒作为一次迭代，所以选取5秒后
               的皮肤外侧温度
91         applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
           applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
93         applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
           c = k1;
95         a = 0;
           f = 0;
97         d = rho1*Cp1;
           specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
99         tlist = 0:.1:5;
           setInitialConditions(pdem1, 0);
101        R = solvepde(pdem1,tlist);
           u = R.NodalSolution;%反解每个节点的温度
103        p = pdem1.Mesh.Nodes;%得出每个mesh后的节点坐标
           x = p(1,:);
105        y = p(2,:);
           num1 = 1;
107        %figure
           pdeplot(pdem1,'XYData',u(:,1),'Contour','off','ColorMap','hot');
109        xlabel('厚度(mm)');
           axis([-1 15 49 51]);
111        title('求解I和II层接触面的空间模型')
           nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
113        num2 = length(x)
           for i = 1:num2
115                if ((x(i)>0.5) && (x(i)<0.7) && (y(i)>35) && (y(i) <65))
                   nodechoose(num1) = i;
117                num1 = num1 + 1;

```

```

    end
119 end
    num3 = 0;
121 temperature12 = 0
    nodechoose(1)
123 for i = 1:1000
    if((nodechoose(i)) ~=0)
125         temperature12 = temperature12 + u(nodechoose(i));
        num3 = num3 +1;
127     end
    end
129 temperature12 = temperature12/num3;
    temperature12list(time) = temperature12;
131

%第二层
133 applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',temperature12);
    applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
135 applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
    c = k2;
137 a = 0;
    f = 0;
139 d = rho2*Cp2;
    specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
141 tlist = 0:.1:5;
    setInitialConditions(pdem2, 0);
143 R = solvepde(pdem2,tlist);
    u = R.NodalSolution;%反解每个节点的温度
145 p = pdem2.Mesh.Nodes;%得出每个mesh后的节点坐标
    x = p(1,:);
147 y = p(2,:);
    num1 = 1;
149 figure
    pdeplot(pdem2,'XYData',u(:,1),'Contour','off','ColorMap','hot');
151 xlabel('厚度(mm)');
    axis([-1 15 49 51]);
153 title('求解II和III层接触面的空间模型')
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
155 num2 = length(x)
    for i = 1:num2
157         if ((x(i)>6) && (x(i)<7.5) && (y(i)>35) && (y(i) <65))
            nodechoose(num1) = i;
159             num1 = num1 + 1;
        end
    end
161 end
    num3 = 0;
163 temperature23 = 0
    nodechoose(1)

```

```

165     for i = 1:1000
166         if((nodechoose(i)) ~=0)
167             temperature23 = temperature23 + u(nodechoose(i));
168             num3 = num3 +1;
169         end
170     end
171     temperature23 = temperature23 /num3;
172     temperature23list(time) = temperature23;
173 %temperature23
174
175 %第三层
176     applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 4, 'u', temperature23);
177     applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 2, 'u', temperature45);
178     applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', [1,3], 'u', 37);
179     c = k3;
180     a = 0;
181     f = 0;
182     d = rho3*Cp3;
183     specifyCoefficients(pdem3, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
184     tlist = 0:.1:5;
185     setInitialConditions(pdem3, 0);
186     R = solvepde(pdem3, tlist);
187     u = R.NodalSolution;%反解每个节点的温度
188     p = pdem3.Mesh.Nodes;%得出每个mesh后的节点坐标
189     x = p(1,:);
190     y = p(2,:);
191     num1 = 1;
192
193 figure
194 pdeplot(pdem3, 'XYData', u(:,1), 'Contour', 'off', 'ColorMap', 'hot');
195 xlabel('厚度(mm)');
196 axis([-1 15 49 51]);
197 title('求解 III 和 IV 层接触面的空间模型')
198     nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
199     num2 = length(x)
200     for i = 1:num2
201         if ((x(i)>9.5) && (x(i)<11) && (y(i)>35) && (y(i) <65))
202             nodechoose(num1) = i;
203             num1 = num1 + 1;
204         end
205     end
206     num3 = 0;
207     temperature34 = 0
208     nodechoose(1)
209     for i = 1:1000
210         if((nodechoose(i)) ~=0)
211             temperature34 = temperature34 + u(nodechoose(i));
212             num3 = num3 +1;

```

```

        end
213     end
        temperature34 = temperature34/num3;
215     temperature34list(time) = temperature34
%temperature34
217
%第四层
219     applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',38);
        applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',temperature45);
221     applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
        c = k4;
223     a = 0;
        f = 0;
225     d = rho4*Cp4;
        specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
227     tlist = 0:1:5;
        setInitialConditions(pdem4, 0);
229     R = solvepde(pdem4,tlist);
        u = R.NodalSolution;%反解每个节点的温度
231     p = pdem4.Mesh.Nodes;%得出每个mesh后的节点坐标
        x = p(1,:);
233     y = p(2,:);
        num1 = 1;
235     figure
        pdeplot(pdem4,'XYData',u(:,1),'Contour','off','ColorMap','hot');
237     xlabel('厚度(mm)');
        axis([-1 15 49 51]);
239     title('求解IV和V层接触面的空间模型')
        nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
241     num2 = length(x)
        for i = 1:num2
243         if ((x(i)>14.5) && (x(i)<15.2) && (y(i)>35) && (y(i) <65))
            nodechoose(num1) = i;
245             num1 = num1 + 1;
        end
247     end
        num3 = 0;
249     temperature45 = 0
        nodechoose(1)
251     for i = 1:1000
        if((nodechoose(i)) ~=0)
253         temperature45 = temperature45 + u(nodechoose(i));
            num3 = num3 +1;
255     end
        end
257     temperature45 = temperature45/num3;
%temperature45

```

```

259
261     time = time+1
263
265     else
267         i2 = 1100;
267     end
267 end

```

codes/prom11.m

```

1  clc ,close all ,clear all;
2  x = xlsread('data5.xlsx','A1:B361')
3  temperature01list = x(:,2);
   numberOfPDE = 1;
5  pdem1 = createpde(numberOfPDE);
   numberOfPDE = 1;
7  pdem2 = createpde(numberOfPDE);
   numberOfPDE = 1;
9  pdem3 = createpde(numberOfPDE);
   numberOfPDE = 1;
11 pdem4 = createpde(numberOfPDE);
    rho1 = 300; % 密度
13 Cp1 = 1377; % 比热
    k1 = 0.082; % 热导率
15 h1 = 0.6;

17 rho2 = 862; % 密度
    Cp2 = 2100; % 比热
19 k2 = 0.37; % 热导率
    h2 = 13.806;%设置的厚度为0.1 5 10 15 20 25
21
    rho3 = 74.2; % 密度
23 Cp3 = 1726; % 比热
    k3 = 0.045; % 热导率
25 h3 = 3.6;

27 rho4 = 1.18; % 密度
    Cp4 = 1005; % 比热
29 k4 = 0.028; % 热导率
    h4 = 6.218;
31
    R1 = [3 4 0 h1+h2+h3+h4 h1+h2+h3+h4 0 0 0 100 100]';
33 R2 = [3 4 h1 h1+h2+h3+h4 h1+h2+h3+h4 h1 0 0 100 100]';
    R3 = [3 4 h1+h2 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2 0 0 100 100]';
35 R4 = [3 4 h1+h2+h3 h1+h2+h3+h4 h1+h2+h3+h4 h1+h2+h3 0 0 100 100]';

```



```

37 rat1 = h1/(h1+h2+h3+h4)
   rat2 = h2/(h1+h2+h3+h4)
39 rat3 = h3/(h1+h2+h3+h4)
   rat4 = h4/(h1+h2+h3+h4)
41
   rate1 = rat1
43 rate2 = rate1 + rat2
   rate3 = rate2 + rat3
45 rate4 = rate3 + rat4

47 g1 = decsg(R1);
   geometryFromEdges(pdem1 ,g1);
49 %figure(1)
   %pdegplot(pdem1,'EdgeLabels','on');
51 %axis([-1 15.3 49 51]);

53 g2 = decsg(R2);
   geometryFromEdges(pdem2 ,g2);
55 %figure(2)
   %pdegplot(pdem2,'EdgeLabels','on');
57 %axis([-1 15.3 5 6]);

59 g3 = decsg(R3);
   geometryFromEdges(pdem3 ,g3);
61 %figure(3)
   %pdegplot(pdem3,'EdgeLabels','on');
63 %axis([-1 15.3 5 6]);

65 g4 = decsg(R4);
   geometryFromEdges(pdem4 ,g4);
67

69 %虽然希望三角网格的划分越精细越好，但是由于上下边界无穷远的设定，导致这部分无用网格
   太多，
   %所以注意大小
71 hmax = .2; % element size
   msh1=generateMesh(pdem1 , 'Hmax' ,hmax);
73
   hmax = .5; % element size
75 msh2=generateMesh(pdem2 , 'Hmax' ,hmax);

77
   hmax = .5; % element size
79 msh3=generateMesh(pdem3 , 'Hmax' ,hmax);

81 hmax = .5; % element size

```

```

msh4=generateMesh(pdem4,'Hmax',hmax);
83
85
temperature = 65%环境温度已经在另一个模型中应用
87 temperature01 = 37
temperature12 = 37
89 temperature23 = 37
temperature34 = 37
91
93 temperature12list = ones(1,1100)
temperature23list = ones(1,1100)
95 temperature34list = ones(1,1100)
temperature45list = ones(1,1100)
97 temperature45list(1) = 37
99 judge4 = 0
judge5 = 0
101 time = 1;
for i2 = 1:1000
103     if time == 1
a2 = 1
105     b1 = 1
b2 = 1
107     c1 = 1
c2 = 1
109     d1 = 1
d2 = 1
111     d3 = 1
end
113     if (time>1&&time<8)
a2 = 1
115     b1 = 0.99
b2 = 0.99
117     c1 = 0.997
c2 = 0.996
119     d1 = 0.999
d2 = 0.99975
121     d3 = 0.999
end
123     if (time>7)
a2 = 1
125     b1 = 0.99
b2 = 0.9875
127     c1 = 0.997
c2 = 0.9975

```

```

129     d1 = 0.99725
130     d2 = 0.99775
131     d3 = 0.9985
132 end
133 if (time>120)
134     a2 = 1
135     b1 = 0.99
136     b2 = 0.9875
137     c1 = 0.99675
138     c2 = 0.99575
139     d1 = 0.99675
140     d2 = 0.99675
141     d3 = 0.9985
142 end
143 if (temperature01list(time+1) - temperature01list(time) >0)
144     %第一层
145     temperature01 = temperature01list(time,1);
146     temperature45 = temperature45list(time);%每隔5秒作为一次迭代，所以选取5秒后的皮
147         肤外侧温度
148     applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
149     applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
150     applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
151     c = k1;
152     a = 0;
153     f = 0;
154     d = rho1*Cp1;
155     specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
156     tlist = 0:1:5;
157     setInitialConditions(pdem1, 0);
158     R = solvepde(pdem1,tlist);
159     u = R.NodalSolution;%反解每个节点的温度
160     p = pdem1.Mesh.Nodes;%得出每个mesh后的节点坐标
161     x = p(1,:);
162     y = p(2,:);
163     num1 = 1;
164     nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
165     num2 = length(x)
166     for i = 1:num2
167         if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
168             nodechoose(num1) = i;
169             num1 = num1 + 1;
170         end
171     end
172     num3 = 0;
173     temperature12 = 0
174     nodechoose(1)
175     for i = 1:1000

```

```

175     if((nodechoose(i)) ~=0)
176         temperature12 = temperature12 + u(nodechoose(i));
177         num3 = num3 +1;
178     end
179 end
180 temperature12 = temperature12/num3;
181
182 temperature12list(time) = temperature12*a2;
183
184 %第二层
185 applyBoundaryCondition(pdem2, 'dirichlet', 'Edge', 4, 'u', b1*temperature12);
186 applyBoundaryCondition(pdem2, 'dirichlet', 'Edge', 2, 'u', temperature45);
187 applyBoundaryCondition(pdem2, 'dirichlet', 'Edge', [1,3], 'u', 37);
188 c = k2;
189 a = 0;
190 f = 0;
191 d = rho2*Cp2;
192 specifyCoefficients(pdem2, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
193 tlist = 0:.1:5;
194 setInitialConditions(pdem2, 0);
195 R = solvepde(pdem2, tlist);
196 u = R.NodalSolution;%反解每个节点的温度
197 p = pdem2.Mesh.Nodes;%得出每个mesh后的节点坐标
198 x = p(1,:);
199 y = p(2,:);
200 num1 = 1;
201 %figure
202 %pdeplot(pdem2, 'XYData', u(:,1), 'Contour', 'off', 'ColorMap', 'hot');
203 %axis([-1 15 49 51]);
204 nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
205 num2 = length(x)
206 for i = 1:num2
207     if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
208         nodechoose(num1) = i;
209         num1 = num1 + 1;
210     end
211 end
212 num3 = 0;
213 temperature23 = 0
214 nodechoose(1)
215 for i = 1:1000
216     if((nodechoose(i)) ~=0)
217         temperature23 = temperature23 + u(nodechoose(i));
218         num3 = num3 +1;
219     end
220 end
221 temperature23 = temperature23/num3;

```

```

    temperature23list(time) = temperature23*b2;
223 %temperature23

225 %第三层
    applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 4, 'u', c1*temperature23);
227 applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', 2, 'u', temperature45);
    applyBoundaryCondition(pdem3, 'dirichlet', 'Edge', [1,3], 'u', 37);
229 c = k3;
    a = 0;
231 f = 0;
    d = rho3*Cp3;
233 specifyCoefficients(pdem3, 'm', 0, 'd', 0, 'c', c, 'a', a, 'f', f);
    tlist = 0:.1:5;
235 setInitialConditions(pdem3, 0);
    R = solvepde(pdem3, tlist);
237 u = R.NodalSolution;%反解每个节点的温度
    p = pdem3.Mesh.Nodes;%得出每个mesh后的节点坐标
239 x = p(1,:);
    y = p(2,:);
241 num1 = 1;
    nodechoose = zeros(1,1000)%选取的作为该界面的坐标值
243 num2 = length(x)
    for i = 1:num2
245         if ((x(i)>(h1+h2+h3-0.6)) && (x(i)<(h1+h2+h3+0.6)) && (y(i)>35) && (y(i) <65)
                )
                nodechoose(num1) = i;
247         num1 = num1 + 1;
    end
249 end
    num3 = 0;
251 temperature34 = 0
    nodechoose(1)
253 for i = 1:1000
        if((nodechoose(i)) ~=0)
255             temperature34 = temperature34 + u(nodechoose(i));
                num3 = num3 +1;
257         end
    end
259 temperature34 = temperature34/num3;
    temperature34list(time) = temperature34*c2
261

263 %第四层
    applyBoundaryCondition(pdem4, 'dirichlet', 'Edge', 4, 'u', d1*temperature34);
265 applyBoundaryCondition(pdem4, 'dirichlet', 'Edge', 2, 'u', d2*temperature45);
    applyBoundaryCondition(pdem4, 'dirichlet', 'Edge', [1,3], 'u', 37);
267 c = k4;

```

```

a = 0;
269 f = 0;
d = rho4*Cp4;
271 specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
tlist = 0:1:5;
273 setInitialConditions(pdem4, 0);
R = solvepde(pdem4,tlist);
275 u = R.NodalSolution;%反解每个节点的温度
p = pdem4.Mesh.Nodes;%得出每个mesh后的节点坐标
277 x = p(1,:);
y = p(2,:);
279 num1 = 1;
nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
281 num2 = length(x)
for i = 1:num2
283     if ((x(i)>(h1+h2+h3+h4-0.5)) && (x(i)<(h1+h2+h3+h4+0.5)) && (y(i)>35) && (y(i)
        ) <65))
        nodechoose(num1) = i;
285         num1 = num1 + 1;
    end
287 end
num3 = 0;
289 temperature45 = 0
nodechoose(1)
291 for i = 1:1000
    if((nodechoose(i)) ~=0)
293         temperature45 = temperature45 + u(nodechoose(i));
        num3 = num3 +1;
295     end
end
297 temperature45 = temperature45/num3;

299 if(time<3)
    temperature45 = 37;
301     d2=1;
end
303
judge1 = 0%对于皮肤温度场在极限温度下的变化情况模拟
305 judge2 = 0
judge3 = 0
307 if(temperature45>47.11)
    judge1 = 1
309 end
if(temperature45>47.9)
311     judge2 = 1
end
313 if(temperature45>48)

```

```

        judge3 = 1
315     end

317     time = time+1
    %temperature45list(time) = temperature45*d3
319     if (judge1 == 0 && judge2 == 0 && judge3 == 0)
        temperature45list(time) = temperature45*d3
321     end
    if (judge1 == 1 && judge2 == 0 && judge3 == 0)
323         temperature45list(time) = temperature45list(time)+0.01;
    end
325     if (judge1 == 1 && judge2 == 1 && judge3 == 0 && judge4>4)
        temperature45list(time) = temperature45list(time)+0.01;
327         judge4 = 0
    end
329     judge4 = judge4 + 1
    if (judge1 == 1 && judge2 == 1 && judge3 == 1 && judge5>18)
331         temperature45list(time) = temperature45list(time)+0.01;
        judge5 = 0
333     end
    judge5 = judge5 + 1
335     if temperature45list(time)>48.08
        temperature45list(time) = 48.08;
337     end
    if temperature45list(time)<37
339         temperature45list(time) = 37;
    end
341     %temperature45
343
345
347     else
        i2 = 1000;
349     end
end
end

```

codes/prom3.m

与 ANSYS 交互代码如下

1. Main menu->Preferences->Thermal->ok
2. Main menu->Preprocessor->Element Type->Add/Edit/Delete->Add->Solid->8node 77->ok
3. Main menu->Preprocessor->Material Props->Material Models 设置 Isotropic: 0.082,

Specific Heat: 1137, Density: 300

4. Main menu->Preprocessor->Modeling->Create->Areas->Rectangle 设置 x: 0 0.1, y: 0 0.1
5. Main menu->Preprocessor->Meshing->MeshTool 选择 Smart Size, 移动到 4, 进行 mesh, 选择 area, ok
6. Main menu->Preprocessor->Solution->Analysis Type->new Analysis 选择 Transient, ok
7. Main menu->Preprocessor->Solution->Analysis Type->Sol'n Controls 设置 Time at end of loadstep:5400, time step size: 5, Frequency: write every substep
8. Main menu->Preprocessor->Solution->Define Loads->Apply->Thermal ->Convection->On Lines 选择 area 其中的一条边后, 设置对流系数为 20, 温度为 75°C
9. Main menu->Preprocessor->Solution->Define Loads->Apply->Initial Condition->Define 选择 pick all, 设置初始温度为 37°C
10. Main menu->Preprocessor->Solution->Solve->Current LS
11. 选择 General Postproc, PlotCtrls->Animates->Over Time 设置为 1080 帧, 时间设置为 5400 秒