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

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

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 37ºC 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 75ºC、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 65ºC、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 47ºC，且超过 44ºC 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 47ºC，且超过 44ºC 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，由外部环境与 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来进行降维转化, 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_∞	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
β	本征值
$\|M\|$	f 方阵 M 的行列式
$X(\beta_m, x)$	本征函数
$Q(x,t)$	内热源
χ	特征函数
$Goal_{L_i}$	目标函数
λ_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, 题中给定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_∞ 为环境温度;

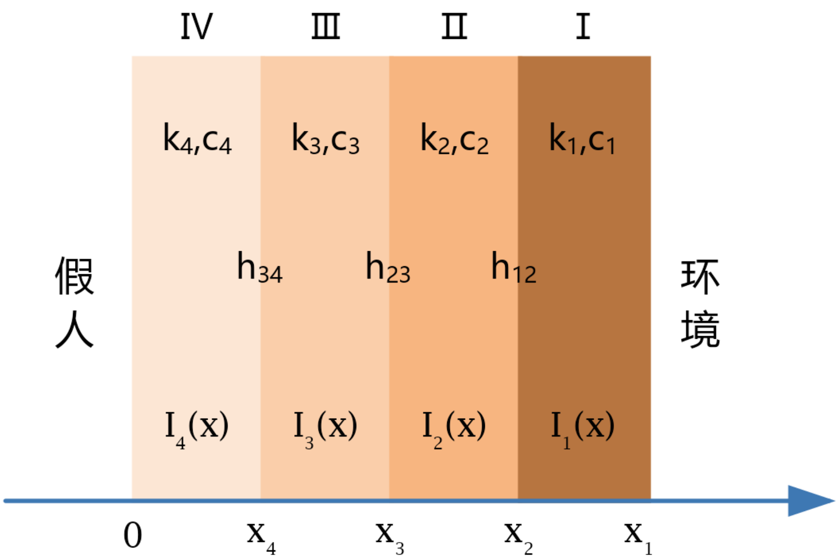

图 **1** 四层复合介质的热传导

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

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

假设中, 由于室温为 75℃ 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 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

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

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

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

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

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

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

$$h_{34} = Nu \frac{k_4}{L_4}. \tag{5}$$

此时, 应有热量交换值相等, 即

$$k_3 \frac{\partial u_3}{\partial x}\bigg|_{x=x_4} = k_3 \frac{\partial u_3}{\partial x}\bigg|_{x=x_4}. \tag{6}$$

同理可以推得 I 层与外界环境之间存在关系

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

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

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

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

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

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

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

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

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

于是结合式 (2) – (10) 可得温度分布的数学模型为

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

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

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

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

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

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

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

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

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

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

$$\begin{cases} X''+\dfrac{\beta^2}{\alpha_i}=0, \quad x_{i+1}<x<x_i, \quad i=1,2,3,4. \\ \begin{cases} -k_iX_i'\Big|_{x=x_{i+1}}=h_{i,i+1}(X_i-X_{i+1})\Big|_{x=x_{i+1}}, \\ k_iX_i'\Big|_{x=x_{i+1}}=k_{i+1}X_{i+1}'\Big|_{x=x_{i+1}}, \end{cases} \quad i=2,3,4. \\ (-k_*X_4'+h_*X_4)\Big|_{x=0}=0, \\ (-k_1X_1'+h_{1\infty}X_1)\Big|_{x=x_1}=0, \end{cases} \tag{19}$$

由式 (19) 可以确定本征值 $\beta=\beta_m, m=1,2,\cdots$ 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:

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

式中, 模为

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

于是简化的齐次模型的解为

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

此时利用初始条件 (10) 和正交性即可确定系数

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

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:

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

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 β_m 和系数 $A_{i,m}, B_{i,m}, i=1,2,3,4$, 令向量 $\eta=(A_{1,m},B_{1,m},\cdots,A_{4,m},B_{4,m})\prime$, 对应的系数矩阵记为 $M_{8\times8}$, 此时实际上是解齐次方程组

$$M\eta=0, \tag{25}$$

要使该方程组具有非零解, 必须使行列式

$$|M|=0, \tag{26}$$

由此方程解出无穷个本征值 $\beta_m, m=1,2,\cdots$; 之后再取出 (25) 一组合适的解 η_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:

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

- 积分变换:

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

则可得

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

与复合介质的温度分布

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

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

式中

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

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

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

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 β, 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:

$$u_1(x) = u_p(x) + u_h(x), \tag{34}$$

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:

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

式中 γ_i 为待求系数, $u_i^*(x) = u^*(\|x - x_i\|)$ 是修正的 Helmhohz 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:

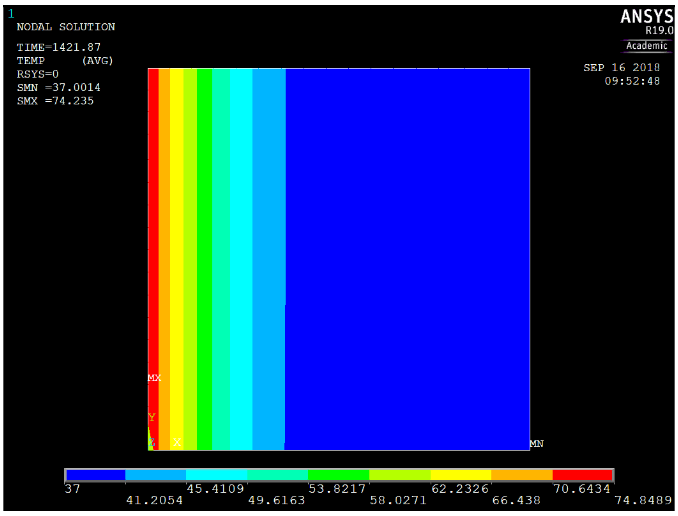

图 2　**ANSYS 模拟边界受热情况**

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:

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

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

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

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:

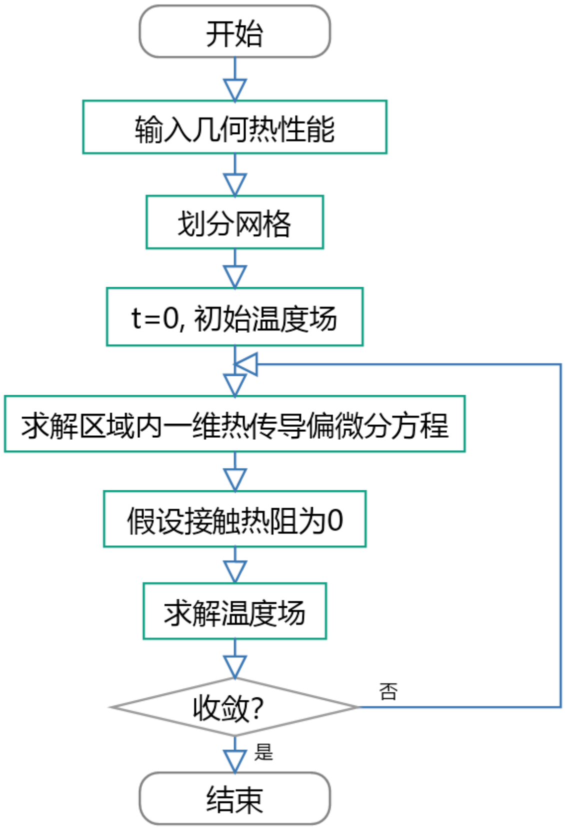

图 **3**　有限差分迭代流程图

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 specifyCofficients 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:

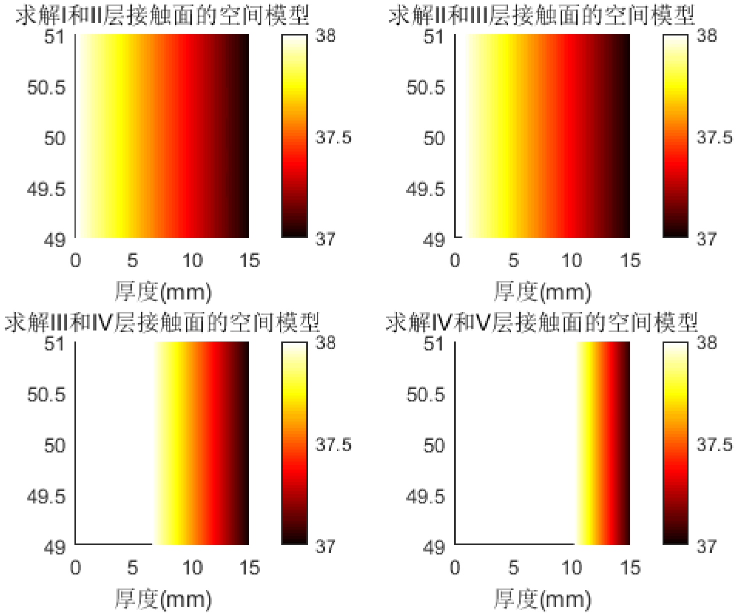

图 **4**　求解各接触面的空间模型

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:

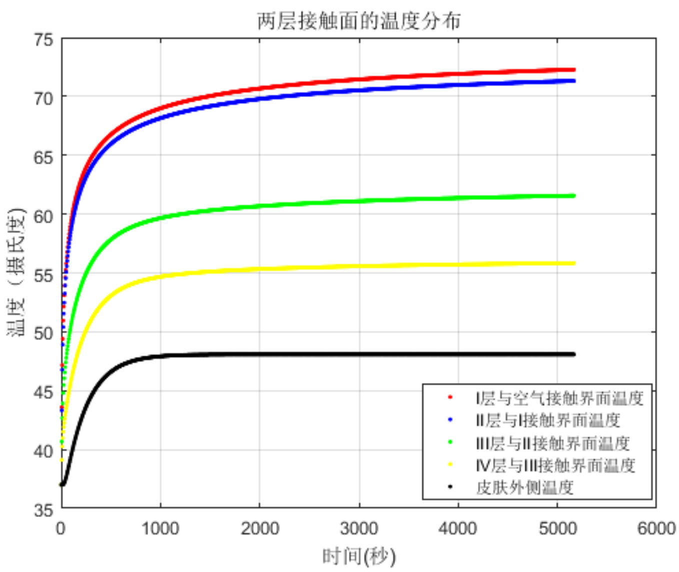

图 **5**　复合介质接触面温度分布图

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 72.27ºC, 71.31ºC, 61.56ºC, 55.83ºC, 48.08ºC, 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 65ºC, 而 IV 层的厚度改为 5.5 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 47ºC，且超过 44ºC 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, 从某一程度上面来说, 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

$$0.6\,\mathrm{mm} \leqslant L_2 \leqslant 25\,\mathrm{mm}, \tag{39}$$

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 47ºC, 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:

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

考虑第二个时间约束. 要求超过 44ºC 的时间不超过 5 分钟, 从连续的角度看, 若令此情形的集合

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

则应有

$$\int_{E_t} \chi_{E_t}(t)\,\mathrm{d}t \leqslant 300. \tag{42}$$

式中 χ 是特征函数, 含义是

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

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

$$Goal_{L_2} = \min L_2. \tag{44}$$

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

$$Goal_{L_2} = \min L_2, \tag{45}$$

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

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 ºC，这里需要对 47.1 ºC 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 $Goal_{L_2} = 6.372\,\mathrm{mm}$.

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 80ºC 时, 仍然要满足工作 30 分钟时，假人皮肤外侧温度不超过 47ºC，且超过 44ºC 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

$$0.6\,\mathrm{mm} \leqslant L_2 \leqslant 25\,\mathrm{mm}, \tag{47}$$

$$0.6\,\mathrm{mm} \leqslant L_4 \leqslant 6.4\,\mathrm{mm}, \tag{48}$$

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 47ºC, 应有

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

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

$$\int_{E_t} \chi_{E_t}(t)\,\mathrm{d}t \leqslant 300.$$

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

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

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

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

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

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, λ_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:

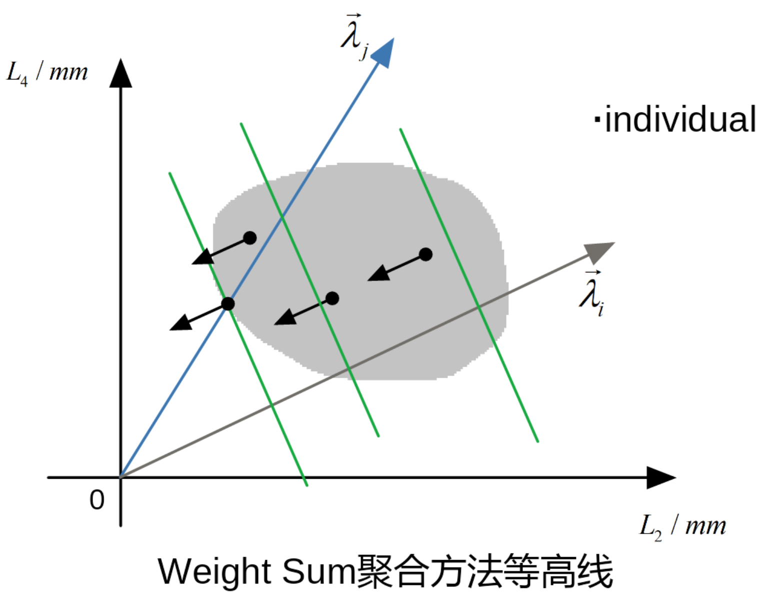

图 6　**Weighted Sum** 方法示意图

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℃ 的情况进行可行域的划分，并利用超过 44℃ 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:

$$Goal_{L_2} = 13.15\,\mathrm{mm}, \quad Goal_{L_4} = 5.40\,\mathrm{mm}, \tag{53}$$

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:

```
clc,close all,clear all;
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
numberOfPDE = 1;
pdem1 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem2 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem3 = createpde(numberOfPDE);
```

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

rho2 = 862; % 密度
Cp2 = 2100; % 比热
k2 = 0.37; % 热导率
h2 = 11;%设置的厚度为0.1 5 10 15 20 25

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

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

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]';
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]';

rat1 = h1/(h1+h2+h3+h4)
rat2 = h2/(h1+h2+h3+h4)
rat3 = h3/(h1+h2+h3+h4)
rat4 = h4/(h1+h2+h3+h4)

rate1 = rat1
rate2 = rate1 + rat2
rate3 = rate2 + rat3
rate4 = rate3 + rat4

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

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

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

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

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


%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
hmax = .2; % element size
msh1=generateMesh(pdem1,'Hmax',hmax);
%figure
%pdeplot(pdem1);
%axis([-.1 .7 5 6]);

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

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

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



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

```
temperature23 = 37
temperature34 = 37


temperature12list = ones(1,1000)
temperature23list = ones(1,1000)
temperature34list = ones(1,1000)
temperature45list = ones(1,1000)
temperature45list(1) = 37


time = 1;
for i2 = 1:1000
  if time == 1
    a2 = 1
    b1 = 1
    b2 = 1
    c1 = 1
    c2 = 1
    d1 = 1
    d2 = 1
    d3 = 1
  end
  if(time>1&&time<8)
  a2 = 1
  b1 = 0.99
  b2 = 0.99
  c1 = 0.997
  c2 = 0.996
  d1 = 0.999
  d2 = 0.99975
  d3 = 0.999
  end
  if (time>7)
    a2 = 1
    b1 = 0.99
    b2 = 0.9875
    c1 = 0.997
    c2 = 0.996
    d1 = 0.997
    d2 = 0.997
    d3 = 0.9985
    end
    if(time>160)
        a2=1;
        b1=0.99;
        b2=0.9875;
```

```
        c1=0.9965;
        c2=0.995;
        d1=0.9965;
        d2=0.996;
        d3=0.9985;
    end
  if (temperature01list(time+1) - temperature01list(time) >0.1)
    %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
    applyBoundaryCondition(pdem1,'dirichlet','Edtimege',4,'u',temperature01);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
    c = k1;
    a = 0;
    f = 0;
    d = rho1*Cp1;
    specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem1, 0);
    R = solvepde(pdem1,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
    %figure
    %pdeplot(pdem1,'XYData',u(:,1),'Contour','off','ColorMap','hot');
    %axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    for i = 1:num2
      if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature12 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature12 = temperature12 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
```

```
    temperature12 = temperature12/num3;

    temperature12list(time) = temperature12*a2;

    %第二层
    applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',b1*temperature12);
    applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
    c = k2;
    a = 0;
    f = 0;
    d = rho2*Cp2;
    specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem2, 0);
    R = solvepde(pdem2,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
    %figure
    %pdeplot(pdem2,'XYData',u(:,1),'Contour','off','ColorMap','hot');
    %axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    for i = 1:num2
      if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature23 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature23 = temperature23 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature23 = temperature23/num3;
    temperature23list(time) = temperature23*b2;
  %temperature23

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

```
    applyBoundaryCondition(pdem3,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',[1,3],'u',37);
    c = k3;
    a = 0;
    f = 0;
    d = rho3*Cp3;
    specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem3, 0);
    R = solvepde(pdem3,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
%figure
%pdeplot(pdem3,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    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)
          )
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature34 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature34 = temperature34 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature34 = temperature34/num3;
    temperature34list(time) = temperature34*c2
%temperature34
%if(time>5)
        %chazhi1 = temperature01list(time-1)-temperature12list(time-1);
        %chazhi2 = temperature12list(time-1)-temperature23list(time-1);
        %chazhi3 = temperature23list(time-1)-temperature34list(time-1);
        %chazhi4 = temperature34list(time-1)-temperature45;
        %sumchazhi = chazhi1+chazhi2+chazhi3+chazhi4;
        %temperature12list(time-1) = temperature01list(time-1) + sumchazhi*rate1
        %temperature23list(time-1) = temperature01list(time-1) + sumchazhi*rate2
```

```
      %temperature34list(time-1) = temperature01list(time-1) + sumchazhi*rate3
      %temperature45list(time) = temperature01list(time) + sumchazhi*rate4


      %chazhi2 = rat2*chazhi1/rat1;
      %chazhi3 = rat3*chazhi1/rat1;
      %chazhi4 = rat4*chazhi1/rat1;
      %temperature23list(time) = temperature12list(time)-chazhi2;
      %if(temperature23list(time)<temperature23list(time-1))
      % temperature23list(time) = temperature23;
      %end
      %temperature34list(time) = temperature23list(time)-chazhi3;
      %if(temperature34list(time)<temperature34list(time-1))
      % temperature34list(time) = temperature34;
      %end
      %temperature45list(time) = temperature34list(time)-chazhi4;
      %if(temperature45list(time)<temperature45list(time-1))
      % temperature45list(time) = temperature45;
      %end


    %end



%第四层
   applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',d1*temperature34);
   applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',d2*temperature45);
   applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
   c = k4;
   a = 0;
   f = 0;
   d = rho4*Cp4;
   specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
   tlist = 0:.1:5;
   setInitialConditions(pdem4, 0);
   R = solvepde(pdem4,tlist);
   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
   x = p(1,:);
   y = p(2,:);
   num1 = 1;
%figure
%pdeplot(pdem4,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-.1 15 49 51]);
   nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
   num2 = length(x)
```

```
        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))
            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
```

codes/best.m

```
clc,close all,clear all;
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
numberOfPDE = 1;
pdem1 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem2 = createpde(numberOfPDE);
numberOfPDE = 1;
```

```
pdem3 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem4 = createpde(numberOfPDE);
rho1 = 300; % 密度
Cp1 = 1377; % 比热
k1 = 0.082; % 热导率
h1 = 0.6;

rho2 = 862; % 密度
Cp2 = 2100; % 比热
k2 = 0.37; % 热导率
h2 = 11;%设置的厚度为0.1 5 10 15 20 25

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

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

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]';
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]';

rat1 = h1/(h1+h2+h3+h4)
rat2 = h2/(h1+h2+h3+h4)
rat3 = h3/(h1+h2+h3+h4)
rat4 = h4/(h1+h2+h3+h4)

rate1 = rat1
rate2 = rate1 + rat2
rate3 = rate2 + rat3
rate4 = rate3 + rat4

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

g2 = decsg(R2);
geometryFromEdges(pdem2 ,g2);
%figure(2)
```

```
%pdegplot(pdem2,'EdgeLabels','on');
%axis([-.1 15.3 5 6]);

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

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


%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
hmax = .2; % element size
msh1=generateMesh(pdem1,'Hmax',hmax);
%figure
%pdeplot(pdem1);
%axis([-.1 .7 5 6]);

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

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

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



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

```
temperature12 = 37
temperature23 = 37
temperature34 = 37


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


time = 1;
for i2 = 1:1000
  if time == 1
    a2 = 1
    b1 = 1
    b2 = 1
    c1 = 1
    c2 = 1
    d1 = 1
    d2 = 1
    d3 = 1
  end
  if(time>1&&time<11)
  a2 = 1
  b1 = 0.99
  b2 = 0.99
  c1 = 0.998
  c2 = 0.998
  d1 = 0.999
  d2 = 0.9995
  d3 = 0.999
  end
  if (time>7)
    a2 = 1
    b1 = 0.99
    b2 = 0.9875
    c1 = 0.997
    c2 = 0.996
    d1 = 0.998
    d2 = 0.995
    d3 = 0.998
  end
  if (temperature01list(time+1) - temperature01list(time) >0.1)
    %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
    applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
    c = k1;
    a = 0;
    f = 0;
    d = rho1*Cp1;
    specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem1, 0);
    R = solvepde(pdem1,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
    %figure
    %pdeplot(pdem1,'XYData',u(:,1),'Contour','off','ColorMap','hot');
    %axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    for i = 1:num2
      if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature12 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature12 = temperature12 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature12 = temperature12/num3;

    temperature12list(time) = temperature12*a2;

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

```
    a = 0;
    f = 0;
    d = rho2*Cp2;
    specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem2, 0);
    R = solvepde(pdem2,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
    %figure
    %pdeplot(pdem2,'XYData',u(:,1),'Contour','off','ColorMap','hot');
    %axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    for i = 1:num2
      if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature23 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature23 = temperature23 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature23 = temperature23/num3;
    temperature23list(time) = temperature23*b2;
  %temperature23

  %第三层
    applyBoundaryCondition(pdem3,'dirichlet','Edge',4,'u',c1*temperature23);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',[1,3],'u',37);
    c = k3;
    a = 0;
    f = 0;
    d = rho3*Cp3;
    specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem3, 0);
```

```matlab
    R = solvepde(pdem3, tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
%figure
%pdeplot(pdem3,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    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)
          )
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature34 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature34 = temperature34 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature34 = temperature34/num3;
    temperature34list(time) = temperature34*c2
%temperature34
%if(time>5)
        %chazhi1 = temperature01list(time-1)-temperature12list(time-1);
        %chazhi2 = temperature12list(time-1)-temperature23list(time-1);
        %chazhi3 = temperature23list(time-1)-temperature34list(time-1);
        %chazhi4 = temperature34list(time-1)-temperature45;
        %sumchazhi = chazhi1+chazhi2+chazhi3+chazhi4;
        %temperature12list(time-1) = temperature01list(time-1) + sumchazhi*rate1
        %temperature23list(time-1) = temperature01list(time-1) + sumchazhi*rate2
        %temperature34list(time-1) = temperature01list(time-1) + sumchazhi*rate3
        %temperature45list(time) = temperature01list(time) + sumchazhi*rate4


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

```
        % temperature23list(time) = temperature23;
        %end
        %temperature34list(time) = temperature23list(time)-chazhi3;
        %if(temperature34list(time)<temperature34list(time-1))
        % temperature34list(time) = temperature34;
        %end
        %temperature45list(time) = temperature34list(time)-chazhi4;
        %if(temperature45list(time)<temperature45list(time-1))
        % temperature45list(time) = temperature45;
        %end


    %end



%第四层
  applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',d1*temperature34);
  applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',d2*temperature45);
  applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
  c = k4;
  a = 0;
  f = 0;
  d = rho4*Cp4;
  specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
  tlist = 0:.1:5;
  setInitialConditions(pdem4, 0);
  R = solvepde(pdem4,tlist);
  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
  x = p(1,:);
  y = p(2,:);
  num1 = 1;
%figure
%pdeplot(pdem4,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-.1 15 49 51]);
  nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
  num2 = length(x)
  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))
      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
```

codes/best21.m

```
clc
clear
close all

% 原图像
subplot(1,2,1)
skintem=xlsread('mydata.xlsx','附件2','A3:B5403');
[h1,h2]=deal(skintem(:,1),skintem(:,2));
plot(h1,h2)

a=37;
b=75;
mn=0:5400;
subplot(1,2,2)
plot(mn,log(100+mn)*37/4.5)

% 所需
```

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

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

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

codes/bound_tem.m

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

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

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

rho4 = 1.18; % 密度
Cp4 = 1005; % 比热
```

```
k4 = 0.028; % 热导率
h4 = 5.264;

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]';
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]';

rat1 = h1/(h1+h2+h3+h4)
rat2 = h2/(h1+h2+h3+h4)
rat3 = h3/(h1+h2+h3+h4)
rat4 = h4/(h1+h2+h3+h4)

rate1 = rat1
rate2 = rate1 + rat2
rate3 = rate2 + rat3
rate4 = rate3 + rat4

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

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

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

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


%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
hmax = .2; % element size
```

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

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

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

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



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


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

judge4 = 0
judge5 = 0
time = 1;
for i2 = 1:1000
  if time == 1
    a2 = 1
    b1 = 1
    b2 = 1
    c1 = 1
```

```
    c2 = 1
    d1 = 1
    d2 = 1
    d3 = 1
  end
  if(time>1&&time<8)
  a2 = 1
  b1 = 0.99
  b2 = 0.99
  c1 = 0.997
  c2 = 0.996
  d1 = 0.999
  d2 = 0.99975
  d3 = 0.999
  end
  if (time>7)
    a2 = 1
    b1 = 0.99
    b2 = 0.9875
    c1 = 0.997
    c2 = 0.9975
    d1 = 0.99725
    d2 = 0.99775
    d3 = 0.9985
  end
  if (time>120)
    a2 = 1
    b1 = 0.99
    b2 = 0.9875
    c1 = 0.99675
    c2 = 0.99575
    d1 = 0.99675
    d2 = 0.99675
    d3 = 0.9985
  end
  if (temperature01list(time+1) - temperature01list(time) >0)
    %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
    applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
    c = k1;
    a = 0;
    f = 0;
    d = rho1*Cp1;
```

```
specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
tlist = 0:.1:5;
setInitialConditions(pdem1, 0);
R = solvepde(pdem1,tlist);
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
x = p(1,:);
y = p(2,:);
num1 = 1;
%figure
%pdeplot(pdem1,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-.1 15 49 51]);
nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
num2 = length(x)
for i = 1:num2
  if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
    nodechoose(num1) = i;
    num1 = num1 + 1;
  end
end
num3 = 0;
temperature12 = 0
nodechoose(1)
for i = 1:1000
  if((nodechoose(i)) ~=0)
    temperature12 = temperature12 + u(nodechoose(i));
    num3 = num3 +1;
  end
end
temperature12 = temperature12/num3;

temperature12list(time) = temperature12*a2;

%第二层
applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',b1*temperature12);
applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
c = k2;
a = 0;
f = 0;
d = rho2*Cp2;
specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
tlist = 0:.1:5;
setInitialConditions(pdem2, 0);
R = solvepde(pdem2,tlist);
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
```

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

  %第三层
    applyBoundaryCondition(pdem3,'dirichlet','Edge',4,'u',c1*temperature23);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',[1,3],'u',37);
    c = k3;
    a = 0;
    f = 0;
    d = rho3*Cp3;
    specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem3, 0);
    R = solvepde(pdem3,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
  %figure
  %pdeplot(pdem3,'XYData',u(:,1),'Contour','off','ColorMap','hot');
  %axis([-.1 15 49 51]);
```

```
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    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))
            nodechoose(num1) = i;
            num1 = num1 + 1;
        end
    end
    num3 = 0;
    temperature34 = 0
    nodechoose(1)
    for i = 1:1000
        if((nodechoose(i)) ~=0)
            temperature34 = temperature34 + u(nodechoose(i));
            num3 = num3 +1;
        end
    end
    temperature34 = temperature34/num3;
    temperature34list(time) = temperature34*c2
%temperature34
%if(time>5)
        %chazhi1 = temperature01list(time-1)-temperature12list(time-1);
        %chazhi2 = temperature12list(time-1)-temperature23list(time-1);
        %chazhi3 = temperature23list(time-1)-temperature34list(time-1);
        %chazhi4 = temperature34list(time-1)-temperature45;
        %sumchazhi = chazhi1+chazhi2+chazhi3+chazhi4;
        %temperature12list(time-1) = temperature01list(time-1) + sumchazhi*rate1
        %temperature23list(time-1) = temperature01list(time-1) + sumchazhi*rate2
        %temperature34list(time-1) = temperature01list(time-1) + sumchazhi*rate3
        %temperature45list(time) = temperature01list(time) + sumchazhi*rate4


        %chazhi2 = rat2*chazhi1/rat1;
        %chazhi3 = rat3*chazhi1/rat1;
        %chazhi4 = rat4*chazhi1/rat1;
        %temperature23list(time) = temperature12list(time)-chazhi2;
        %if(temperature23list(time)<temperature23list(time-1))
        % temperature23list(time) = temperature23;
        %end
        %temperature34list(time) = temperature23list(time)-chazhi3;
        %if(temperature34list(time)<temperature34list(time-1))
        % temperature34list(time) = temperature34;
        %end
        %temperature45list(time) = temperature34list(time)-chazhi4;
        %if(temperature45list(time)<temperature45list(time-1))
        % temperature45list(time) = temperature45;
```

```
      %end

    %end



  %第四层
    applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',d1*temperature34);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',d2*temperature45);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
    c = k4;
    a = 0;
    f = 0;
    d = rho4*Cp4;
    specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem4, 0);
    R = solvepde(pdem4,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
  %figure
  %pdeplot(pdem4,'XYData',u(:,1),'Contour','off','ColorMap','hot');
  %axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    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))
        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

    judge1 = 0%对于皮肤温度场在极限温度下的变化情况模拟
    judge2 = 0
    judge3 = 0
    if(temperature45>47.11)
      judge1 = 1
    end
    if(temperature45>47.9)
      judge2 = 1
    end
    if(temperature45>48)
      judge3 = 1
    end

    time = time+1
    %temperature45list(time) = temperature45*d3
    if (judge1 == 0 && judge2 == 0 && judge3 == 0)
      temperature45list(time) = temperature45*d3
    end
    if (judge1 == 1 && judge2 == 0 && judge3 == 0)
      temperature45list(time) = temperature45list(time)+0.01;
    end
    if (judge1 == 1 && judge2 == 1 && judge3 == 0 && judge4>4)
      temperature45list(time) = temperature45list(time)+0.01;
      judge4 = 0
    end
    judge4 = judge4 + 1
    if (judge1 == 1 && judge2 == 1 && judge3 == 1 && judge5>18)
      temperature45list(time) = temperature45list(time)+0.01;
      judge5 = 0
    end
    judge5 = judge5 + 1
    if temperature45list(time)>48.08
      temperature45list(time) = 48.08;
    end
    if temperature45list(time)<37
      temperature45list(time) = 37;
    end
    %temperature45
```

```
  else
    i2 = 1000;
  end
end
```

codes/diedai3.m

```
clc
close all
clear

x=xlsread('mydata.xlsx','附件2','A3:B5403');
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
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;
pdem1 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem2 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem3 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem4 = createpde(numberOfPDE);
rho1 = 300; % 密度
Cp1 = 1377; % 比热
k1 = 0.082; % 热导率
h1 = 0.6;

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

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

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

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]';
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]';

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

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

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

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


%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
hmax = .2; % element size
msh1=generateMesh(pdem1,'Hmax',hmax);
%figure
%pdeplot(pdem1);
%axis([-.1 .7 5 6]);

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

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

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


temperature = 75;%环境温度已经在另一个模型中应用
temperature01 = 37;
temperature12 = 37;
temperature23 = 37;
temperature34 = 37;
time = 1;
temperature12list = ones(1,1000);
temperature23list = ones(1,1000);
temperature34list = ones(1,1000);

for i2 = 1:1000

  if (temperature01list(time+1) - temperature01list(time) >0.038)
    %第一层
    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
    applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
    c = k1;
    a = 0;
    f = 0;
    d = rho1*Cp1;
    specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem1, 0);
    R = solvepde(pdem1,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
    %figure
    %pdeplot(pdem1,'XYData',u(:,1),'Contour','off','ColorMap','hot');
    %axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000);%选取的作为该界面的坐标值
    num2 = length(x);
```

```
for i = 1:num2
  if ((x(i)>0.5) && (x(i)<0.7) && (y(i)>35) && (y(i) <65))
    nodechoose(num1) = i;
    num1 = num1 + 1;
  end
end
num3 = 0;
temperature12 = 0;
nodechoose(1);
for i = 1:1000
  if((nodechoose(i)) ~=0)
    temperature12 = temperature12 + u(nodechoose(i));
    num3 = num3 +1;
  end
end
temperature12 = temperature12/num3;
temperature12list(time) = temperature12;

%第二层
applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',temperature12);
applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
c = k2;
a = 0;
f = 0;
d = rho2*Cp2;
specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
tlist = 0:.1:5;
setInitialConditions(pdem2, 0);
R = solvepde(pdem2,tlist);
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
x = p(1,:);
y = p(2,:);
num1 = 1;
%figure
%pdeplot(pdem2,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-.1 15 49 51]);
nodechoose =zeros(1,1000);%选取的作为该界面的坐标值
num2 = length(x);
for i = 1:num2
  if ((x(i)>6) && (x(i)<7.5) && (y(i)>35) && (y(i) <65))
    nodechoose(num1) = i;
    num1 = num1 + 1;
  end
end
num3 = 0;
```

```
    temperature23 = 0;
    nodechoose(1);
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature23 = temperature23 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature23 = temperature23/num3;
    temperature23list(time) = temperature23;
%temperature23

%第三层
    applyBoundaryCondition(pdem3,'dirichlet','Edge',4,'u',temperature23);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',[1,3],'u',37);
    c = k3;
    a = 0;
    f = 0;
    d = rho3*Cp3;
    specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem3, 0);
    R = solvepde(pdem3,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
%figure
%pdeplot(pdem3,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000);%选取的作为该界面的坐标值
    num2 = length(x);
    for i = 1:num2
      if ((x(i)>9.5) && (x(i)<11) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature34 = 0;
    nodechoose(1);
    for i = 1:1000
      if nodechoose(i) ~=0
        temperature34 = temperature34 + u(nodechoose(i));
        num3 = num3 +1;
```

```
        end
    end
    temperature34 = temperature34/num3;
    temperature34list(time) = temperature34;
%temperature34

%第四层
    applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',temperature34);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
    c = k4;
    a = 0;
    f = 0;
    d = rho4*Cp4;
    specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem4, 0);
    R = solvepde(pdem4,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
%figure
%pdeplot(pdem4,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000);%选取的作为该界面的坐标值
    num2 = length(x);
    for i = 1:num2
        if ((x(i)>14.5) && (x(i)<15.2) && (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;
    %temperature45


```

```
        time = time+1;


    else
        i2 = 1000;
    end
end
```

codes/tem_suit.m

```
% 计算温度分布
clc
clear
close all

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

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

%% 求解 beta 的行列式
syms beta
gamma=suit(:,3)./sqrt(alpha).*beta;
eta=x./sqrt(alpha).*beta;
% 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
    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))
    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
    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))
    0 0 0 0 0 0 0 1
    ];

% 令行列式为0, 求 beta
% det_A=det(A);
solve(det(A)==0,beta)

%% 解方程 A
beta=0;
null(eval(A))

%% 画出图像
% [x0,y0]=meshgrid(0:5400,linspace(0,x(1)*10^3,5401));
% mesh(x0,y0,temdistrib(x0,y0))
%
% % 这个函数是设出来的
% function s=temdistrib(x,t)
% % 温度分布函数
%
% s=exp(-t.^2).*sin(x);
%
% end
```

codes/temsuit.m

```
clc,close all,clear all;
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
numberOfPDE = 1;
pdem1 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem2 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem3 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem4 = createpde(numberOfPDE);
```

```
rho1 = 300; % 密度
Cp1 = 1377; % 比热
k1 = 0.082; % 热导率
h1 = 0.6;

rho2 = 862; % 密度
Cp2 = 2100; % 比热
k2 = 0.37; % 热导率
h2 = 10.295;%设置的厚度为0.1 5 10 15 20 25

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

rho4 = 1.18; % 密度
Cp4 = 1005; % 比热
k4 = 0.028; % 热导率
h4 = 5.5;

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]';
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]';

rat1 = h1/(h1+h2+h3+h4)
rat2 = h2/(h1+h2+h3+h4)
rat3 = h3/(h1+h2+h3+h4)
rat4 = h4/(h1+h2+h3+h4)

rate1 = rat1
rate2 = rate1 + rat2
rate3 = rate2 + rat3
rate4 = rate3 + rat4

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

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

```

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

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


%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
hmax = .2; % element size
msh1=generateMesh(pdem1,'Hmax',hmax);
%figure
%pdeplot(pdem1);
%axis([-.1 .7 5 6]);

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

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

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



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

```
temperature12list = ones(1,1100)
temperature23list = ones(1,1100)
temperature34list = ones(1,1100)
temperature45list = ones(1,1100)
temperature45list(1) = 37

judge4 = 0
judge5 = 0
time = 1;
for i2 = 1:1000
  if time == 1
     a2 = 1
     b1 = 1
     b2 = 1
     c1 = 1
     c2 = 1
     d1 = 1
     d2 = 1
     d3 = 1
  end
  if(time>1&&time<8)
  a2 = 1
  b1 = 0.99
  b2 = 0.99
  c1 = 0.997
  c2 = 0.996
  d1 = 0.999
  d2 = 0.99975
  d3 = 0.999
  end
  if (time>7)
     a2 = 1
     b1 = 0.99
     b2 = 0.9875
     c1 = 0.997
     c2 = 0.9975
     d1 = 0.99725
     d2 = 0.99775
     d3 = 0.9985
  end
  if (time>120)
     a2 = 1
     b1 = 0.99
     b2 = 0.9875
     c1 = 0.99675
```

```
    c2 = 0.99575
    d1 = 0.99675
    d2 = 0.99675
    d3 = 0.9985
end
if (temperature01list(time+1) - temperature01list(time) >0)
  %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
    applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
    c = k1;
    a = 0;
    f = 0;
    d = rho1*Cp1;
    specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem1, 0);
    R = solvepde(pdem1,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    for i = 1:num2
      if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature12 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature12 = temperature12 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature12 = temperature12/num3;

    temperature12list(time) = temperature12*a2;
```

```
    %第二层
    applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',b1*temperature12);
    applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
    c = k2;
    a = 0;
    f = 0;
    d = rho2*Cp2;
    specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem2, 0);
    R = solvepde(pdem2,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
    %figure
    %pdeplot(pdem2,'XYData',u(:,1),'Contour','off','ColorMap','hot');
    %axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    for i = 1:num2
      if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature23 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature23 = temperature23 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature23 = temperature23/num3;
    temperature23list(time) = temperature23*b2;
  %temperature23

  %第三层
    applyBoundaryCondition(pdem3,'dirichlet','Edge',4,'u',c1*temperature23);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',[1,3],'u',37);
    c = k3;
    a = 0;
```

```
    f = 0;
    d = rho3*Cp3;
    specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem3, 0);
    R = solvepde(pdem3,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
%figure
%pdeplot(pdem3,'XYData',u(:,1),'Contour','off','ColorMap','hot');
%axis([-.1 15 49 51]);
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    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)
          )
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature34 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature34 = temperature34 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature34 = temperature34/num3;
    temperature34list(time) = temperature34*c2


%第四层
    applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',d1*temperature34);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',d2*temperature45);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
    c = k4;
    a = 0;
    f = 0;
    d = rho4*Cp4;
    specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem4, 0);
```

```
R = solvepde(pdem4,tlist);
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
x = p(1,:);
y = p(2,:);
num1 = 1;
nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
num2 = length(x)
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))
    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

judge1 = 0%对于皮肤温度场在极限温度下的变化情况模拟
judge2 = 0
judge3 = 0
if(temperature45>47.11)
  judge1 = 1
end
if(temperature45>47.9)
  judge2 = 1
end
if(temperature45>48)
  judge3 = 1
end

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

```
        temperature45list(time) = temperature45*d3
    end
    if (judge1 == 1 && judge2 == 0 && judge3 == 0)
        temperature45list(time) = temperature45list(time)+0.01;
    end
    if (judge1 == 1 && judge2 == 1 && judge3 == 0 && judge4>4)
        temperature45list(time) = temperature45list(time)+0.01;
        judge4 = 0
    end
    judge4 = judge4 + 1
    if (judge1 == 1 && judge2 == 1 && judge3 == 1 && judge5>18)
        temperature45list(time) = temperature45list(time)+0.01;
        judge5 = 0
    end
    judge5 = judge5 + 1
    if temperature45list(time)>48.08
        temperature45list(time) = 48.08;
    end
    if temperature45list(time)<37
        temperature45list(time) = 37;
    end
    %temperature45





  else
    i2 = 1000;
  end
end
```

codes/prom2.m

```
clc,close all,clear all;
x = xlsread('data2.xlsx','A1:B1081')
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;
pdem1 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem2 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem3 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem4 = createpde(numberOfPDE);
rho1 = 300; % 密度
Cp1 = 1377; % 比热
```

```
k1 = 0.082; % 热导率
h1 = 0.6;

rho2 = 862; % 密度
Cp2 = 2100; % 比热
k2 = 0.37; % 热导率
h2 = 6;%设置的厚度为0.1 5 10 15 20 25

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

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

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]';
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]';

rat1 = h1/(h1+h2+h3+h4)
rat2 = h2/(h1+h2+h3+h4)
rat3 = h3/(h1+h2+h3+h4)
rat4 = h4/(h1+h2+h3+h4)

rate1 = rat1
rate2 = rate1 + rat2
rate3 = rate2 + rat3
rate4 = rate3 + rat4

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

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

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

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

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


%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
hmax = .2; % element size
msh1=generateMesh(pdem1,'Hmax',hmax);
%figure
%pdeplot(pdem1);
%axis([-.1 .7 5 6]);

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


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


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




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


temperature12list = ones(1,1100)
temperature23list = ones(1,1100)
temperature34list = ones(1,1100)
temperature45list = ones(1,1100)
temperature45list(1) = 37
```

```
judge4 = 0
judge5 = 0
time = 1;
for i2 = 1:1000

%对边界热阻、织物孔隙等因素进行参数模拟
  if time == 1
    a2 = 1
    b1 = 1
    b2 = 1
    c1 = 1
    c2 = 1
    d1 = 1
    d2 = 1
    d3 = 1
  end
  if(time>1&&time<8)
  a2 = 1
  b1 = 0.99
  b2 = 0.99
  c1 = 0.997
  c2 = 0.996
  d1 = 0.999
  d2 = 0.99975
  d3 = 0.999
  end
  if (time>7)
    a2 = 1
    b1 = 0.99
    b2 = 0.9875
    c1 = 0.997
    c2 = 0.996
    d1 = 0.997
    d2 = 0.997
    d3 = 0.9985
  end
  if (time>120)
    a2 = 1
    b1 = 0.99
    b2 = 0.9875
    c1 = 0.99675
    c2 = 0.99575
    d1 = 0.99675
    d2 = 0.99675
    d3 = 0.9985
  end
  if (temperature01list(time+1) - temperature01list(time) >0)
```

```
%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
applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
c = k1;
a = 0;
f = 0;
d = rho1*Cp1;
specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
tlist = 0:.1:5;
setInitialConditions(pdem1, 0);
R = solvepde(pdem1,tlist);
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
x = p(1,:);
y = p(2,:);
num1 = 1;

nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
num2 = length(x)
for i = 1:num2
   if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
      nodechoose(num1) = i;
      num1 = num1 + 1;
   end
end
num3 = 0;
temperature12 = 0
nodechoose(1)
for i = 1:1000
   if((nodechoose(i)) ~=0)
      temperature12 = temperature12 + u(nodechoose(i));
      num3 = num3 +1;
   end
end
temperature12 = temperature12/num3;

temperature12list(time) = temperature12*a2;

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

```
    a = 0;
    f = 0;
    d = rho2*Cp2;
    specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem2, 0);
    R = solvepde(pdem2,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;

    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    for i = 1:num2
      if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature23 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature23 = temperature23 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature23 = temperature23/num3;
    temperature23list(time) = temperature23*b2;
  %temperature23

  %第三层
    applyBoundaryCondition(pdem3,'dirichlet','Edge',4,'u',c1*temperature23);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',[1,3],'u',37);
    c = k3;
    a = 0;
    f = 0;
    d = rho3*Cp3;
    specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem3, 0);
    R = solvepde(pdem3,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;

    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    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))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature34 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature34 = temperature34 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature34 = temperature34/num3;
    temperature34list(time) = temperature34*c2




  %第四层
    applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',d1*temperature34);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',d2*temperature45);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
    c = k4;
    a = 0;
    f = 0;
    d = rho4*Cp4;
    specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem4, 0);
    R = solvepde(pdem4,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
```

```
num2 = length(x)
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))
    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

judge1 = 0%对于皮肤温度场在极限温度下的变化情况模拟
judge2 = 0
judge3 = 0
if(temperature45>47.11)
  judge1 = 1
end
if(temperature45>47.9)
  judge2 = 1
end
if(temperature45>48)
  judge3 = 1
end
time = time+1%对皮肤外侧温度在极限温度下升温行为的模拟
if (judge1 == 0 && judge2 == 0 && judge3 == 0)
  temperature45list(time) = temperature45*d3
end
if (judge1 == 1 && judge2 == 0 && judge3 == 0)
  temperature45list(time) = temperature45list(time-1)+0.01;
end
if (judge1 == 1 && judge2 == 1 && judge3 == 0 && judge4>4)
  temperature45list(time) = temperature45list(time-1)+0.01;
  judge4 = 0;
end
```

```
    judge4 = judge4 + 1
    if (judge1 == 1 && judge2 == 1 && judge3 == 1 && judge5>18)
      temperature45list(time) = temperature45list(time-1)+0.01;
      judge5 = 0
    end
    judge5 = judge5 + 1
    if temperature45list(time)>48.08 && time>250
      temperature45list(time) = 48.08;
    end
    %temperature45




  else
    i2 = 1000;
  end
end
```

codes/problem1.m

```
clc,close all,clear all;
x=xlsread('data1.xlsx', 'A1:B5401');
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
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;
pdem1 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem2 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem3 = createpde(numberOfPDE);
numberOfPDE = 1;
pdem4 = createpde(numberOfPDE);
rho1 = 300; % 密度
Cp1 = 1377; % 比热
k1 = 0.082; % 热导率
h1 = 0.6;

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

rho3 = 74.2; % 密度
Cp3 = 1726; % 比热
```

```
k3 = 0.045; % 热导率
h3 = 3.6;

rho4 = 1.18; % 密度
Cp4 = 1005; % 比热
k4 = 0.028; % 热导率
h4 = 5;
%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]';
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]';
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
g1 = decsg(R1);
geometryFromEdges(pdem1 ,g1);


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


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

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




%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
hmax = .2; % element size
msh1=generateMesh(pdem1,'Hmax',hmax);


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


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


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

```

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

for i2 = 1:1100

  if (temperature01list(time+1) - temperature01list(time) >0.001)
   %第一层
    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
    applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
    c = k1;
    a = 0;
    f = 0;
    d = rho1*Cp1;
    specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem1, 0);
    R = solvepde(pdem1,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
   %figure
    pdeplot(pdem1,'XYData',u(:,1),'Contour','off','ColorMap','hot');
    xlabel('厚度(mm)');
    axis([-.1 15 49 51]);
    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
    num2 = length(x)
    for i = 1:num2
      if ((x(i)>0.5) && (x(i)<0.7) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
```

```
    end
  end
  num3 = 0;
  temperature12 = 0
  nodechoose(1)
  for i = 1:1000
    if((nodechoose(i)) ~=0)
      temperature12 = temperature12 + u(nodechoose(i));
      num3 = num3 +1;
    end
  end
  temperature12 = temperature12/num3;
  temperature12list(time) = temperature12;

  %第二层
  applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',temperature12);
  applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
  applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
  c = k2;
  a = 0;
  f = 0;
  d = rho2*Cp2;
  specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
  tlist = 0:.1:5;
  setInitialConditions(pdem2, 0);
  R = solvepde(pdem2,tlist);
  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
  x = p(1,:);
  y = p(2,:);
  num1 = 1;
  figure
  pdeplot(pdem2,'XYData',u(:,1),'Contour','off','ColorMap','hot');
  xlabel('厚度(mm)');
  axis([-.1 15 49 51]);
  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
  num2 = length(x)
  for i = 1:num2
    if ((x(i)>6) && (x(i)<7.5) && (y(i)>35) && (y(i) <65))
      nodechoose(num1) = i;
      num1 = num1 + 1;
    end
  end
  num3 = 0;
  temperature23 = 0
  nodechoose(1)
```

```
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature23 = temperature23 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature23 = temperature23/num3;
    temperature23list(time) = temperature23;
%temperature23

%第三层
    applyBoundaryCondition(pdem3,'dirichlet','Edge',4,'u',temperature23);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',[1,3],'u',37);
    c = k3;
    a = 0;
    f = 0;
    d = rho3*Cp3;
    specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem3, 0);
    R = solvepde(pdem3,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
 figure
 pdeplot(pdem3,'XYData',u(:,1),'Contour','off','ColorMap','hot');
 xlabel('厚度(mm)');
 axis([-.1 15 49 51]);
 title('求解III和IV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
    num2 = length(x)
    for i = 1:num2
      if ((x(i)>9.5) && (x(i)<11) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature34 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature34 = temperature34 + u(nodechoose(i));
        num3 = num3 +1;
```

```
        end
    end
    temperature34 = temperature34/num3;
    temperature34list(time) = temperature34
%temperature34

%第四层
    applyBoundaryCondition(pdem4,'dirichlet','Edge',4,'u',38);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem4,'dirichlet','Edge',[1,3],'u',37);
    c = k4;
    a = 0;
    f = 0;
    d = rho4*Cp4;
    specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem4, 0);
    R = solvepde(pdem4,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
 figure
 pdeplot(pdem4,'XYData',u(:,1),'Contour','off','ColorMap','hot');
 xlabel('厚度(mm)');
 axis([-.1 15 49 51]);
 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
    num2 = length(x)
    for i = 1:num2
        if ((x(i)>14.5) && (x(i)<15.2) && (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;
    %temperature45
```

```
      time = time+1


   else
      i2 = 1100;
   end
end
```

codes/prom11.m

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

rho2 = 862; % 密度
Cp2 = 2100; % 比热
k2 = 0.37; % 热导率
h2 = 13.806;%设置的厚度为0.1 5 10 15 20 25

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

rho4 = 1.18; % 密度
Cp4 = 1005; % 比热
k4 = 0.028; % 热导率
h4 = 6.218;

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]';
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]';
```

```
rat1 = h1/(h1+h2+h3+h4)
rat2 = h2/(h1+h2+h3+h4)
rat3 = h3/(h1+h2+h3+h4)
rat4 = h4/(h1+h2+h3+h4)

rate1 = rat1
rate2 = rate1 + rat2
rate3 = rate2 + rat3
rate4 = rate3 + rat4

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

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

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

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



%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
hmax = .2; % element size
msh1=generateMesh(pdem1,'Hmax',hmax);

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


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

hmax = .5; % element size
```

```
msh4=generateMesh(pdem4, 'Hmax' ,hmax);



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


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

judge4 = 0
judge5 = 0
time = 1;
for i2 = 1:1000
   if time == 1
      a2 = 1
      b1 = 1
      b2 = 1
      c1 = 1
      c2 = 1
      d1 = 1
      d2 = 1
      d3 = 1
   end
   if(time>1&&time<8)
   a2 = 1
   b1 = 0.99
   b2 = 0.99
   c1 = 0.997
   c2 = 0.996
   d1 = 0.999
   d2 = 0.99975
   d3 = 0.999
   end
   if (time>7)
      a2 = 1
      b1 = 0.99
      b2 = 0.9875
      c1 = 0.997
      c2 = 0.9975
```

```
    d1 = 0.99725
    d2 = 0.99775
    d3 = 0.9985
  end
  if (time>120)
    a2 = 1
    b1 = 0.99
    b2 = 0.9875
    c1 = 0.99675
    c2 = 0.99575
    d1 = 0.99675
    d2 = 0.99675
    d3 = 0.9985
  end
  if (temperature01list(time+1) - temperature01list(time) >0)
    %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
    applyBoundaryCondition(pdem1,'dirichlet','Edge',4,'u',temperature01);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem1,'dirichlet','Edge',[1,3],'u',37);
    c = k1;
    a = 0;
    f = 0;
    d = rho1*Cp1;
    specifyCoefficients(pdem1,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem1, 0);
    R = solvepde(pdem1,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    for i = 1:num2
      if ((x(i)>h1-0.1) && (x(i)<h1+0.1) && (y(i)>35) && (y(i) <65))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature12 = 0
    nodechoose(1)
    for i = 1:1000
```

```
    if((nodechoose(i)) ~=0)
      temperature12 = temperature12 + u(nodechoose(i));
      num3 = num3 +1;
    end
  end
  temperature12 = temperature12/num3;

  temperature12list(time) = temperature12*a2;

  %第二层
  applyBoundaryCondition(pdem2,'dirichlet','Edge',4,'u',b1*temperature12);
  applyBoundaryCondition(pdem2,'dirichlet','Edge',2,'u',temperature45);
  applyBoundaryCondition(pdem2,'dirichlet','Edge',[1,3],'u',37);
  c = k2;
  a = 0;
  f = 0;
  d = rho2*Cp2;
  specifyCoefficients(pdem2,'m',0,'d',0,'c',c,'a',a,'f',f);
  tlist = 0:.1:5;
  setInitialConditions(pdem2, 0);
  R = solvepde(pdem2,tlist);
  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
  x = p(1,:);
  y = p(2,:);
  num1 = 1;
  %figure
  %pdeplot(pdem2,'XYData',u(:,1),'Contour','off','ColorMap','hot');
  %axis([-.1 15 49 51]);
  nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
  num2 = length(x)
  for i = 1:num2
    if ((x(i)>(h1+h2-0.6)) && (x(i)<(h1+h2+0.6)) && (y(i)>35) && (y(i) <65))
      nodechoose(num1) = i;
      num1 = num1 + 1;
    end
  end
  num3 = 0;
  temperature23 = 0
  nodechoose(1)
  for i = 1:1000
    if((nodechoose(i)) ~=0)
      temperature23 = temperature23 + u(nodechoose(i));
      num3 = num3 +1;
    end
  end
  temperature23 = temperature23/num3;
```

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

%第三层
    applyBoundaryCondition(pdem3,'dirichlet','Edge',4,'u',c1*temperature23);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',2,'u',temperature45);
    applyBoundaryCondition(pdem3,'dirichlet','Edge',[1,3],'u',37);
    c = k3;
    a = 0;
    f = 0;
    d = rho3*Cp3;
    specifyCoefficients(pdem3,'m',0,'d',0,'c',c,'a',a,'f',f);
    tlist = 0:.1:5;
    setInitialConditions(pdem3, 0);
    R = solvepde(pdem3,tlist);
    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
    x = p(1,:);
    y = p(2,:);
    num1 = 1;
    nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
    num2 = length(x)
    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))
        nodechoose(num1) = i;
        num1 = num1 + 1;
      end
    end
    num3 = 0;
    temperature34 = 0
    nodechoose(1)
    for i = 1:1000
      if((nodechoose(i)) ~=0)
        temperature34 = temperature34 + u(nodechoose(i));
        num3 = num3 +1;
      end
    end
    temperature34 = temperature34/num3;
    temperature34list(time) = temperature34*c2


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

```
a = 0;
f = 0;
d = rho4*Cp4;
specifyCoefficients(pdem4,'m',0,'d',0,'c',c,'a',a,'f',f);
tlist = 0:.1:5;
setInitialConditions(pdem4, 0);
R = solvepde(pdem4,tlist);
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
x = p(1,:);
y = p(2,:);
num1 = 1;
nodechoose =zeros(1,1000)%选取的作为该界面的坐标值
num2 = length(x)
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))
    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

judge1 = 0%对于皮肤温度场在极限温度下的变化情况模拟
judge2 = 0
judge3 = 0
if(temperature45>47.11)
  judge1 = 1
end
if(temperature45>47.9)
  judge2 = 1
end
if(temperature45>48)
```

```
      judge3 = 1
    end

    time = time+1
    %temperature45list(time) = temperature45*d3
    if (judge1 == 0 && judge2 == 0 && judge3 == 0)
      temperature45list(time) = temperature45*d3
    end
    if (judge1 == 1 && judge2 == 0 && judge3 == 0)
      temperature45list(time) = temperature45list(time)+0.01;
    end
    if (judge1 == 1 && judge2 == 1 && judge3 == 0 && judge4 >4)
      temperature45list(time) = temperature45list(time)+0.01;
      judge4 = 0
    end
    judge4 = judge4 + 1
    if (judge1 == 1 && judge2 == 1 && judge3 == 1 && judge5 >18)
      temperature45list(time) = temperature45list(time)+0.01;
      judge5 = 0
    end
    judge5 = judge5 + 1
    if temperature45list(time)>48.08
      temperature45list(time) = 48.08;
    end
    if temperature45list(time)<37
      temperature45list(time) = 37;
    end
    %temperature45




  else
    i2 = 1000;
  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℃

9. Main menu->Preprocessor->Solution->Define Loads->Apply->Initial Condit’n->Define 选择 pick all，设置初始温度为 37℃

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