科技部補助專題研究計畫成果報告
期末報告

配合實驗數據之逆向熱傳導問題分析(I)

計 畫 類 別 ： 個別型計畫
計 畫 編 號 ： MOST 105-2221-E-006-127-
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執 行 單 位 ： 國立成功大學機械工程學系（所）

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報 告 附 件 ： 移地研究心得報告

中 華 民 國 106 年 10 月 29 日

中文摘要：這是一個兩年期研究計畫的第一年結案報告。本研究主要在於提出創新的熱傳導問題之逆向分析方法，本方法結合解析解（利用移位函數法求解）、實驗數據與最小均方誤差數值分析。實際的實驗範例，包括(a)雷射表面加熱問題　與(b)噴霧表面散熱問題。藉由最小均方誤差法，在比對從物體內量得到的實驗溫度，和從具猜測之時變性邊界條件之熱傳問題(在加熱表面有未知溫度)的解析解所估算的溫度數據，可求得在受熱端的溫度函數。據此，在時間和空間內任意點的溫度分佈及熱通量亦均可以求得到。最後，藉由數學和實驗的範例，說明本計畫提出方法具簡單性、準確性以及效率性。此外，亦將進行相關實驗驗證。

本計畫提出的熱傳逆運算研究方法具有無須積分轉換之優點，且計畫目的在於解決下述目前大部分逆向分析方法存在的問題：

(a)必須處理繁瑣的數值問題，如拉普拉斯轉換、數值分析的穩定度和含大量元素的矩陣運算；

(b)無法同時求得在時間和空間內任意點的溫度及熱通量；

(c)表面加熱處理的時間不可以長;

(d)無法求解逆向熱傳導分析兩端均為未知的時變性溫度函數問題；

(e)量測溫度的位置須非常接近加熱或散熱表面；

(f)加熱處理表面的溫度變化須緩慢；

(g)缺乏對多層結構的熱傳導逆向分析。

本計畫的第一年在於解決上述提到的困難(a-d)，而計畫第二年的研究內容則在於處理上述提到的困難(e-g)。

中文關鍵詞：熱傳導問題逆向分析，雷射表面加熱，噴霧表面散熱，時變性邊界條件，最小均方誤差法，移位函數法

英文摘要：This is the first-year report of a two-year term research proposal. These propose solution methods utilizes a analytic solution (using the shifting function method), experimental data and numerical analysis for the inverse analysis of heat conduction problems. Experimental data come from the previous studies on both (a) laser surface heating and (b) surface spray cooling problems. By minimizing the mean square error between the experimental temperature data obtained from inside the body and the estimated data from the derived analytical solution of the heat conduction problems with guessed time-dependent boundary conditions (at heating surface with unknown temperature), the temperature function at the heating/cooling end can be determined. Consequently, the temperature distribution and the heat flux over the entire time and space domains can also be obtained. Mathematical and experimental examples will be given to illustrate the simplicity, accuracy, and efficiency of the proposed methodology. In addition, these plans will conduct the relative experiments.

The proposed methods of these plans do not require integral transformation to solve the heat conduction problems. One expects to overcome the following existing difficulties in the existing literatures: (a) the integral transform and tedious numerical operations, (b) unable to obtain the temperature distribution over the entire time and space domains, (c) the surface heating time can’t be long, (d), unable to tackle the inverse problems with unknown temperature histories at both ends, (e) the temperature measurement point has to be very close to the heating/cooling surface, (f) the temperature variation is relatively fast, and (g) multilayer composite problems.

In the first year, the proposed solution method is to overcome the mentioned difficulties (a-d), listed above while in the second year, the proposed solution method will also overcome the mentioned difficulties the difficulties (e-g).

英文關鍵詞： inverse analysis of heat conduction problems, laser surface heating, surface spray cooling, time dependent boundary condition, mean squares error mehtod, shifting function method

科技部補助專題研究計畫成果報告

（□期中進度報告/■期末報告）

配合實驗數據之逆向熱傳導問題分析(I)

Inverse Analysis of Heat Conduction Problems with Experimental Data (I)

計畫類別：■個別型計畫　□整合型計畫
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計畫主持人：李森墉
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本計畫除繳交成果報告外，另含下列出國報告，共 _0_ 份：
□執行國際合作與移地研究心得報告
□出席國際學術會議心得報告
□出國參訪及考察心得報告

中　華　民　國　106　年　7 月　31 日

目　　　　錄

摘　要

本二年期計畫之第一年提出了一種針對兩邊時變性邊界條件均未知一維熱傳導逆向問題的解決方法。混合了移位函數法和最小均方誤差法等相關技術，來處理噴霧表面散熱之熱表面問題。之後利用假設半幅傅立葉餘弦函數擴展雙邊界未知溫度，再利用移位函數法，求得此邊界值熱傳系統的解析解。之後藉由最小均方誤差法，在比對從物體內量到的兩個實驗溫度數值和從具猜測之雙時變性邊界條件之熱傳問題解析解(在加熱和非加熱表面均有未知溫度)所估算的溫度數據,可求得在受熱端和非受熱端的邊界溫度函數。據此，在時間和空間域內任意點的溫度分佈及熱通量亦均可以求得到。最後，具實驗數值的噴霧表面散熱範例將被用來證明本逆運算法具有簡單性、準確性且有效率。

關鍵詞：熱傳導逆向問題，噴霧表面散熱，半幅擴展函數，移位函數法，最小均方誤差法，第一型時變性邊界條件

Abstract

This result of the two-year plan proposes a solution methodology for one-dimensional inverse heat conduction problems with unknown temperature histories at both ends. A hybrid technique is applied to analyze laser surface heating or spray cooling on a hot surface. The present work assumed the unknown temperature histories in half-range Fourier cosine expansion forms and used the shifting function method to generate an analytical solution. By minimizing the mean square error between the experimental temperature data obtained from two interior locations and the estimated temperature data from the derived analytical solution of the heat conduction problems with guessed time-dependent boundary conditions (with two unknown temperature histories at both surfaces), the temperature function at the laser heating end can be determined. Consequently, the temperature distribution and the heat flux over the entire time and space domains can also be obtained. Examples of spray cooling problems with experimental data will be given to illustrate the simplicity, accuracy, and efficiency of the proposed methodology.

Keywords: inverse heat conduction problems, surface spray cooling, half-range expansions, shifting function method, mean squares error method, time dependent boundary condition of the first kind

第一章　　前　言

熱傳導逆向問題 (inverse heat conduction problems, 簡稱 IHCPs) 應用於許多的工程熱傳問題上，特別是難以量測的受熱面溫度或物體表面熱通量的問題。典型的具體例子，包括：雷射表面加工、熱交換器、燃燒室、量熱式儀表、砲管內部溫度、金屬加工的快速冷卻和淬火及電子元件的冷卻。底下僅探討雷射表面加工和熱表面的噴灑冷卻問題。

首先，以雷射表面加工問題而言，在雷射表面硬化處理過程，表面溫度需要維持在臨界轉變溫度且要低於熔點。因此，在熱處理過程中，準確估算表面之溫度以及熱通量表面吸收率極其重要。但由於直接量測加熱表面的溫度和熱通量相當困難，這些物理量常利用加熱時間內物體內部的量測溫度資料估算得。具體而言，此種估算法即為典型的熱傳導逆向問題。

其次，就熱表面的噴灑冷卻問題而言，其熱表面的表面溫度測試，在淬火中為最重要的參數，常被用來定義不同熱轉換機制中的沸騰曲線。因此，在噴灑冷卻過程中，表面溫度和熱通量的估算準確度是相當重要的。但由於不易直接量測噴灑冷卻表面的溫度和熱通量，這些物理量常由在噴霧冷卻時間內物體內部的量測溫度資料估算而得。此種估算法亦是典型的熱傳導逆向問題。

第二章　計畫目的

目前有許多數值方法用來解決一維的熱傳導逆向問題，諸如有限差分法、有限元素法以及邊界元素法等，最常被用來建模，以及模擬分析熱傳導逆向問題。

本二年期計畫在於提出創新的一維熱傳導之逆向分析方法，以解決雷射表面加熱與噴霧表面散熱之工程熱傳問題。而此方法無須利用積分轉換，便可求解一維具有時變性邊界條件的熱傳導逆向問題。

據此，本二年期計畫目的在於解決下列逆向分析方法中所面臨的七大問題：

(a)必須處理繁瑣的數值問題，如拉普拉斯轉換、數值分析的穩定度和含大量元素的矩陣運算；

(b)無法同時求得在時間和空間內任意點的溫度及熱通量；

(c)表面加熱處理的時間不可以長；

(d)無法求解逆向熱傳導分析兩端均為未知的時變性溫度函數問題；

(e)量測溫度的位置須非常接近加熱或散熱表面；

(f)加熱處理表面的溫度變化須緩慢；

(g)缺乏對多層結構的熱傳導逆向分析。

其中，項次(a)至(d)為第一年之工作重點。具體而言，

(1)首先先推導具有時變性邊界條件的熱傳導問題之精確解，本方法為一種無須採用積分轉換的方法;

(2)進行實驗量測一維除端點外均為絕熱的棒材，在一端或兩端受熱時，內部三點與端點隨時間變化的溫度。加熱方法可為電阻或乙炔焰加熱;

(3)以函數(如：簡易的多項式函數、分段的多項式函數或是傅立葉函數等)來近似從物體內部所量測到的實驗數據;

(4)將具有時變性邊界條件的熱傳導問題精確解之時變性邊界函數，以上述之相似未知函數代入。

第三章　文獻探討

多數逆向熱傳導問題發生在熱傳導狀態下，其對應的邊界條件會造成其量測上的困難。因此，如何去估算表面溫度與熱通量為大多數學者研究的課題。而此問題在工程上的具體應用，包括雷射表面加熱、熱交換器、燃燒室、金屬鑄造快速冷卻與淬火、電子元件冷卻以及表面噴霧等典型例子。

對於雷射表面加熱問題，據悉雷射表面硬化過程中，其表面溫度必須維持高於臨界轉變溫度並低於熔點溫度。因此，在加熱過程中，溫度、熱通量與表面吸收率的精確估算是很重要的。由於直接量測加熱表面的溫度和熱通量相當困難，這些物理量可由在加熱時間內物體內部的量測溫度資料估算而得。此外，對於高溫表面噴霧冷卻問題。在噴霧冷卻過程中，熱表面的表面溫度測試在淬火中為最重要的參數，被用來定義不同熱轉換機制中的沸騰曲線。因此，在噴灑冷卻過程中，表面溫度與熱通量的估算準確度同是相當重要的。同樣地，直接量測噴灑冷卻表面的溫度和熱通量相當困難，而這些物理量可由在噴霧冷卻時間內物體內部的量測溫度資料估算而得。綜合言之，如何估算上述雷射加工或噴霧冷卻表面溫度，即為典型的熱傳導逆向問題。

目前有許多數值方法用來解決一維的熱傳導逆向問題。在這些方法中，有限差分法、有限元素法、邊界元素法最常被選擇用來建模，以及模擬分析熱傳導逆向問題。文獻上，Lesnic 和 Elliott [1]利用 Adomian’s 分解法來處理紊亂的輸入數據，得到一個穩定的近似解。而 Monde 和 Mitsutake [2]，Monde et al. [3]和 Woodfield et al. [4]發展一種解析的方法，利用拉普拉斯轉換和有時間延遲的半級數解來估算一維熱傳導逆向問題之熱擴散率、表面溫度和熱通量。他們建議選擇接近表面的點來量測，以求做良好的估算。此外，Hon 和 Wei [5]，Jin 和 Zheng [6]以及 Yan et al. [7]則發展一種網格和積分為架構的數值方法，利用徑向函數求解一維熱傳導逆向問題。然而其矩陣和方程式因過於複雜，導致很難得到一個準確的結果。

對於雷射表面加熱處理問題，Wang et al. [8]利用一種分析方法，包括

共軛梯度法做逆向研究，去估算靠近加熱表面的溫度。他們指出合理的方法，需藉由兩個不同位置的裝置來得到表面溫度。此外，Chen 和 Wu [9] 提出一個混合拉普拉斯轉換和有限差分的方法，並配合 Wang et al. [8]在圓柱內測得的實驗數據去預測雷射表面加熱的溫度。在他們數值的範例中與精確解比較，其估算的熱通量誤差接近 3%。2014 年，Lee 和 Huang [10]則藉由最小均方誤差法，在比對從物體內量得到的實驗溫度，和從具猜測之時變性邊界條件之熱傳問題的解析解所估算的溫度數據，來研究雷射表面加熱問題，其熱處理的過程不到 7 秒。

對於熱表面的噴霧冷卻問題，Qiao 和 Chandra [11]，Cui et al. [12]利用連續函數方法估算表面熱通量。Hsieh et al. [13]則利用暫態液晶技術和熱電偶，去求熱表面噴霧冷卻時的純水之表面溫度參數。之後，Chen 和 Lee [14]利用混合混合拉普拉斯轉換和有限差分的方法，配合實驗數據去預測噴霧冷卻表面的溫度。2016 年，Lee 和 Huang [15]提出了長時間噴霧熱處理的冷卻解決方法。他們把整個熱處理時間域劃分成多個子時間間隔，每個時間間隔均以多項式函數模擬，再藉由最小均方誤差法，在比對從物體內量得到的實驗溫度，和從具猜測之時變性邊界條件之熱傳問題的解析解所估算的溫度數據來研究噴霧散熱問題，最終每個子時間間隔的噴霧冷卻表面溫度函數均可以預測得到。

綜上所述，大多數現有的解決方法必須處理繁瑣的數值問題，如拉普拉斯轉換、數值分析的穩定度和含大量元素的矩陣運算。此外，建議的溫度測量點應接近熱處理表面。本二年期計畫提出創新的熱傳導問題之逆向分析方法，係延伸 Lee 和 Lin [16] ，Lee et al. [17]與 Chen et al. [18]的移位函數法，來分析具時變性邊界條件的熱傳導逆向問題。最近，Lee 和 Huang [10, 15]提出創新的混和方法來解具時變性邊界條件的一維逆向熱傳導問題。他們認為以多項式函數當作未知的溫度搭配移位函數的方法可以獲得解析解。而其中多項式函數的係數可以通過最小均方誤差法，在比對實驗溫度與猜測之時變性邊界條件之熱傳問題的解析解所估算的溫度來確定。在考慮整個時間域不分割的情況下，Lee 和 Yan [19]於 2017 年使用半幅擴展函數當作未知的時變性邊界條件。藉由最小均方誤差法，在比對從物體內量得到的實驗溫度，和從具猜測之時變性邊界條件之熱傳問題的解

析解所估算的溫度數據，可求得半幅擴展函數相對應的係數。據此，在時間和空間內任意點的溫度分佈及熱通量亦均可以求得到。

本二年期計畫之第一年，主要在於求解如下之逆運算問題：

(a)必須處理繁瑣的數值問題，如拉普拉斯轉換、數值分析的穩定度和含大量元素的矩陣運算；

(b)無法同時求得在時間和空間內任意點的溫度及熱通量；

(c)表面加熱處理的時間不可以長；

(d)無法求解逆向熱傳導分析兩端均為未知的時變性溫度函數問題；

底下將針對第(d)項，詳細說明整個求解方法以及數值分析結果。

第四章　研究方法

一、一維熱傳導數學模型

Consider a one-dimensional heating-conductive body with unknown temperature histories at both boundaries, as shown in Fig. 1. The unknown time-dependent temperature functions, $f_0(t)$ and $f_L(t)$, at the both ends want to be determined through two temperature measurements at the interior locations, i.e., $x = x_{m1}$ and $x = x_{m2}$. We assume that the thermal body is with isotropic and homogeneous material and without internal heat generation. The governing partial differential equation, the time-dependent boundary conditions of the first kind, and the initial condition of the one-dimensional heat conduction are given as

$$k\frac{\partial^2 T(x,t)}{\partial x^2} = \rho c \frac{\partial T(x,t)}{\partial t}, \qquad 0 < x < L, \quad t > 0, \tag{1}$$

$$T(x,t) = f_0(t) = ?, \qquad \text{at} \quad x = 0, \qquad 0 \le t \le t_f, \tag{2}$$

$$T(x,t) = f_L(t) = ?, \qquad \text{at} \quad x = L, \qquad 0 \le t \le t_f, \tag{3}$$

$$T(x,0) = T_0, \qquad 0 \le x \le L, \qquad t = 0, \tag{4}$$

where $T(x,t)$ is the temperature field over the whole domain. x and t respectively denote the spatial-domain and the time variables. k, ρ, and c are the thermal conductivity, the density, and the specific heat, respectively. Moreover, L is the length of the body, T_0 is an initial surrounding temperature, and t_f stands for the final time on the heating application. It should be mentioned that the relationship $f_0(0) = f_L(0) = T_0$ must be met at the initial time.

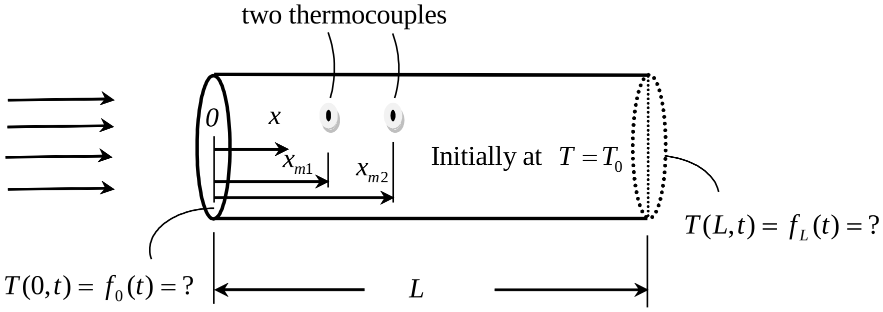


Figure 1: Schematic diagram of the inverse heat conduction problem with unknown temperature histories at both ends.

二、一維熱傳導之解析解

Assume that the two unknown time-dependent functions $f_0(t)$ and $f_L(t)$ have been given first and then $T(x,t)$ want to be determined. Therefore, the one-dimensional thermophysical system can be regarded as a direct problem. The shifting function method will be utilized to generate a closed solution of the heat conduction problem as described in Eqs. (1) - (4).

1. 變數變換

We first separate the temperature function $T(x,t)$ as

$$T(x,t) = U(x,t) + g_0(x) f_0(t) + g_L(x) f_L(t), \tag{5}$$

where $U(x,t)$ is the transformed function, and in which, $g_0(x)$ and $g_L(x)$ are two shifting functions to be determined.

After substituting Eq. (5) back into Eqs. (1) - (4), one has the following partial differential equation

$$\alpha\left[\frac{\partial^2 U(x,t)}{\partial x^2} + g_0''(x) f_0(t) + g_L''(x) f_L(t)\right] = \frac{\partial U(x,t)}{\partial t} + g_0(x)\dot{f}_0(t) + g_L(x)\dot{f}_L(t). \tag{6}$$

Note that the double primes and the dot have been respectively used to denote twice differentiation with respect to x and differentiation with respect to t. In addition, the parameter $\alpha = \frac{k}{\rho c}$ has been introduced and with the meaning 'thermal diffusivity'. The boundary conditions and the initial condition now become:

$$U(0,t) + g_0(0) f_0(t) + g_L(0) f_L(t) = f_0(t), \tag{7}$$

$$U(L,t) + g_0(L) f_0(t) + g_L(L) f_L(t) = f_L(t), \tag{8}$$

$$U(x,0) + g_0(x) f_0(0) + g_L(x) f_L(0) = T_0. \tag{9}$$

2. 移位函數法

For later convenience, one lets $g_0(x)$ and $g_L(x)$ to satisfy the following ordinary differential equation and the boundary conditions:

$$g_0''(x) = 0, \qquad g_L''(x) = 0, \tag{10}$$

$$g_0(0) = 1, \qquad g_L(0) = 0, \qquad g_0(L) = 0, \qquad g_L(L) = 1. \tag{11}$$

Solving the above equations simultaneously, we determine the shifting functions as

$$g_0(x) = \frac{L - x}{L}, \qquad g_L(x) = \frac{x}{L}. \tag{12}$$

The governing equation, Eq. (6), thus, is in terms of the function variable, $U(x,t)$:

$$\frac{\partial U(x,t)}{\partial t} - \alpha \frac{\partial^2 U(x,t)}{\partial x^2} = -g_0(x)\dot{f}_0(t) - g_L(x)\dot{f}_L(t). \tag{13}$$

The associated boundary conditions, Eqs. (7) - (8), turn to be homogeneous ones as follows:

$$U(0,t) = 0, \qquad U(L,t) = 0. \tag{14}$$

The associated initial condition, Eq. (9), is read as

$$U(x,0) = T_0 - g_0(x) f_0(0) - g_L(x) f_L(0) = 0. \tag{15}$$

3. 轉換函數之解

The transformed function $U(x,t)$ can easily be specified by using the theorem of eigenfunction expansions. To meet the homogeneous boundary conditions, the associated n-th eigenfunction $\phi_n(x)$ are given as

$$\phi_n(x) = \sin(\lambda_n x), \qquad n = 1, 2, 3, \cdots\cdots. \tag{16}$$

Here, the characteristic values λ_n are the roots of the following transcendental equation:

$$\sin(\lambda_n L) = 0. \tag{17}$$

In this case, $\lambda_n = \dfrac{n\pi}{L}$ $(n = 1, 2, 3, \cdots)$ and the inner products of two trial functions are

$$\int_0^L \phi_m(x)\phi_n(x)dx = \begin{cases} 0 & \text{for} \quad m \neq n \\ N_n = \dfrac{L}{2} & \text{for} \quad m = n \end{cases}, \tag{18}$$

where N_n is the norm of these trial functions.

To solve Eq. (13), we expand $U(x,t)$ in the series form as:

$$U(x,t)=\sum_{n=1}^{\infty}\phi_n(x)q_n(t), \tag{19}$$

where $q_n(t)(n=1,2,3,\cdots)$ are undetermined time-dependent generalized coordinates. Substituting solution form Eq. (19) back into the Eq. (13) will reach at

$$\sum_{n=1}^{\infty}\{\phi_n(x)\dot{q}_n(t)-\alpha\phi_n''(x)q_n(t)\}=-g_0(x)\dot{f}_0(t)-g_L(x)\dot{f}_L(t). \tag{20}$$

Moreover, expanding $g_0(x)$ and $g_L(x)$ on the right hand side of the above equation in series forms, one can transform Eq. (20) to

$$\sum_{n=1}^{\infty}\{\phi_n(x)\dot{q}_n(t)-\alpha\phi_n''(x)q_n(t)\}=\sum_{n=1}^{\infty}[-\gamma_n\phi_n(x)\dot{f}_0(t)-\bar{\gamma}_n\phi_n(x)\dot{f}_L(t)], \tag{21}$$

where γ_n and $\bar{\gamma}_n$ are given as

$$\gamma_n=\frac{\int_0^L g_0(x)\phi_n(x)dx}{N_n}=\frac{2}{n\pi}, \tag{22}$$

$$\bar{\gamma}_n=\frac{\int_0^L g_L(x)\phi_n(x)dx}{N_n}=\begin{cases}\dfrac{2}{n\pi} & n=1,3,5,\cdots\\ -\dfrac{2}{n\pi} & n=2,4,6,\cdots\end{cases}. \tag{23}$$

From observing Eq. (21), one can let

$$\phi_n(x)\dot{q}_n(t)-\alpha\phi_n''(x)q_n(t)=[-\gamma_n\dot{f}_0(t)-\bar{\gamma}_n\dot{f}_L(t)]\phi_n(x). \tag{24}$$

After taking the inner product in Eq. (24) with $\phi_n(x)$ term by term and integrating over the domain, one will obtain the resulting differential equation as

$$\dot{q}_n(t)+\alpha\lambda_n^2q_n(t)=\xi_n(t), \tag{25}$$

where $\xi_n(t)$ is defined as

$$\xi_n(t) = -\gamma_n \dot{f}_0(t) - \bar{\gamma}_n \dot{f}_L(t)\,. \tag{26}$$

As a consequence, with the zero initial condition $q_n(0)$, the complete solution of Eq. (25) will be

$$q_n(t) = \int_0^t \xi_n(\varphi) \cdot e^{-\alpha\lambda_n^2 (t-\varphi)} d\varphi\,. \tag{27}$$

After substituting Eqs. (12), (16), (19), and Eq. (27), back into Eq. (5), one obtains the analytical solution for the one-dimensional heat conduction with two unknown temperature histories at both ends as follows:

$$T(x,t) = \sum_{n=1}^{\infty} \left[\sin(\lambda_n x) q_n(t)\right] + \frac{L-x}{L} f_0(t) + \frac{x}{L} f_L(t)\,. \tag{28}$$

Differentiating the above equation with respect to x and multiplying by ($-k$), one can get the heat flux function as below:

$$q(x,t) = -k\{\sum_{n=1}^{\infty} \left[\lambda_n \cos(\lambda_n x) q_n(t)\right] - \frac{1}{L}[f_0(t) - f_L(t)]\}\,. \tag{29}$$

三、最小均方誤差法及逆向分析

The solutions obtained in Eqs. (28) and (29) can be utilized to any one-dimensional IHCP with time-dependent boundary conditions of the first kind. Nevertheless, we will choose the spray cooling of the surface of a copper cylinder with experimental data [11-12] to be the numerical examples. Because the time of the spray cooling process is usually long, the time-dependent temperature functions at both ends are assumed as periodic functions and expressed in half-range Fourier cosine series, as follows:

$$f_0(t) = A_0 + \sum_{p=1}^{M} A_p \cos(\frac{p\pi}{t_f} t)\,, \qquad f_L(t) = A_{N+1} + \sum_{q=M+1}^{N} A_q \cos(\frac{\bar{q}\pi}{t_f} t)\,, \tag{30}$$

where $\bar{q}$ is defined as the difference between q and M. In addition, $A_p\,(p = 1, 2, \cdots, M)$ and $A_q\,(q = M+1, M+2, \cdots, N)$ denote the unknown coefficients of these cosine functions. We can determine them by using the least squares method in conjunction with the temperature measurements at two sensor locations, $x = x_{m1}$ and $x = x_{m2}$ (Fig. 1), within the time interval t_f under spray cooling. Using the initial temperature condition $f_0(0) = f_L(0) = T_0$, one has the following relationships:

$$A_0 = T_0 - \sum_{p=1}^{M} A_p \quad , \qquad A_{N+1} = T_0 - \sum_{q=M+1}^{N} A_q \ . \tag{31}$$

After substituting Eq. (30) back into Eqs. (26), (27), and (28), the analytical solution of one-dimensional heat conduction will be written as

$$T(x_m, t) = T_0 + \sum_{p=1}^{M} b_p(x_m, t) A_p + \sum_{q=M+1}^{N} b_q(x_m, t) A_q \,, \qquad 0 < t < t_f \,, \tag{32}$$

where $b_p(x_m, t)$, and $b_q(x_m, t)$ are derived as

$$b_p(x_m, t) = \frac{p\pi}{t_f} \sum_{n=1}^{\infty} [\gamma_n D_{pn}(t) \sin(\lambda_n x_m)] + \frac{L - x_m}{L} [\cos(\frac{p\pi}{t_f} t) - 1] \,, \tag{33}$$

$$b_q(x_m, t) = \frac{\bar{q}\pi}{t_f} \sum_{n=1}^{\infty} [\bar{\gamma}_n D_{\bar{q}n}(t) \sin(\lambda_n x_m)] + \frac{x_m}{L} [\cos(\frac{\bar{q}\pi}{t_f} t) - 1] . \tag{34}$$

Here $D_{pn}(t)$ and $D_{\bar{q}n}(t)$ are defined as

$$D_{pn}(t) = \int_0^t \sin(\frac{p\pi}{t_f} \varphi) \cdot e^{-\alpha\lambda_n^2 (t-\varphi)} d\varphi = \frac{\alpha\lambda_n^2 \sin(\frac{p\pi}{t_f} t) - (\frac{p\pi}{t_f})[\cos(\frac{p\pi}{t_f} t) - e^{-\alpha\lambda_n^2 t}]}{\alpha^2 \lambda_n^4 + (\frac{p\pi}{t_f})^2} \,, \tag{35}$$

$$D_{\bar{q}n}(t) = \int_0^t \sin(\frac{\bar{q}\pi}{t_f} \varphi) \cdot e^{-\alpha\lambda_n^2 (t-\varphi)} d\varphi = \frac{\alpha\lambda_n^2 \sin(\frac{\bar{q}\pi}{t_f} t) - (\frac{\bar{q}\pi}{t_f})[\cos(\frac{\bar{q}\pi}{t_f} t) - e^{-\alpha\lambda_n^2 t}]}{\alpha^2 \lambda_n^4 + (\frac{\bar{q}\pi}{t_f})^2} \ . \tag{36}$$

To minimize the mean squares error among the measured temperatures, $T^{meas}(x_{m1}, t_r)$ and $T^{meas}(x_{m2}, t_r)$, together with the computed temperatures from Eq. (32), $T(x_{m1}, t_r)$ and $T(x_{m2}, t_r)$, one defines an objective function as

$$E(A_1, A_2, \cdots, A_N) = \sum_{l=1}^{2} \sum_{r=1}^{S} [T(x_{ml}, t_r) - T^{meas}(x_{ml}, t_r)]^2 \,, \tag{37}$$

where the discrete measured times $t_r, r = 1 \sim S$, are within the time interval of the spray cooling process, and the number of measured time, S, must be equal to or greater than N. When the objective function is minimized, these N unknown coefficients can be determined by

$$\frac{\partial E}{\partial A_p} = 0, \qquad p = 1, 2, \cdots, N \ . \tag{38}$$

Through some mathematical operation, one generates the matrix equation as below:

$$\mathbf{Z}_{N\times N} \mathbf{A}_{N\times 1} = \mathbf{R}_{N\times 1} \,, \tag{39}$$

where the elements of the matrix $\mathbf{Z}$ along with the elements of the vector $\mathbf{R}$ are given as

$$z_{ij} = \sum_{l=1}^{2}\sum_{r=1}^{S} b_{ir} b_{jr} , \quad r_i = \sum_{l=1}^{2}\sum_{r=1}^{S} [T^{meas}(x_{ml}, t_r) - T_0] b_{ir} , \; i = 1 \sim N, \; j = 1 \sim N . \tag{40}$$

Here b_{ir} stands for the abbreviation of $b_i(x_{ml}, t_r)$, $i = 1 \sim N$, $l = 1 \sim 2$, $r = 1 \sim S$.

With these N coefficients given, both the time-dependent temperature functions at two ends can be determined from the two parts in Eq. (30). Simultaneously, the temperature and the heat flux functions over the entire time and space domains can be directly developed from Eqs. (28) and (29), respectively.

第五章　結果與討論

To verify the accuracy, the efficiency, and the reliability of the proposed inverse methodology, we consider the spray cooling of the surface of a copper cylinder with a $D = 25.4mm$ diameter which experimentally conducted by Qiao and Chandra [11] along with Cui et al. [12], as shown in Fig. 2. The lower end of the circular cylinder was bolted to a copper heater block that housed two 500W cartridge heaters which were regulated by a temperature controller, keeping constant surface temperature before pure water was sprayed on it. To prevent the heater block and the sides of the cylindrical surface from heat loss, they are enclosed with mineral wool. In addition, four chromel-alumel thermocouples of K-type with 0.5 mm diameter were used to measure the temperatures of the test cylinder at different locations (i.e., $x_1 = 0.4mm$, $x_2 = 6.75mm$, $x_3 = 13.1mm$, and $x_4 = 19.45mm$) [11]. We assumed constant thermophysical quantities of the cylinder with $k = 385.1\text{W}(\text{m}^0\text{C})^{-1}$, $\rho = 8933\text{kg.m}^{-3}$, and $c = 412.66\text{J}(\text{kg}^0\text{C})^{-1}$ [14]. Also, the other parameter values used in the following examples are $t_f = 115s$ and $T_0 = 240^0C$. The aim of the present study is to apply experimental temperature data at different sensor locations to estimate the unknown temperature histories at both ends during spray cooling.

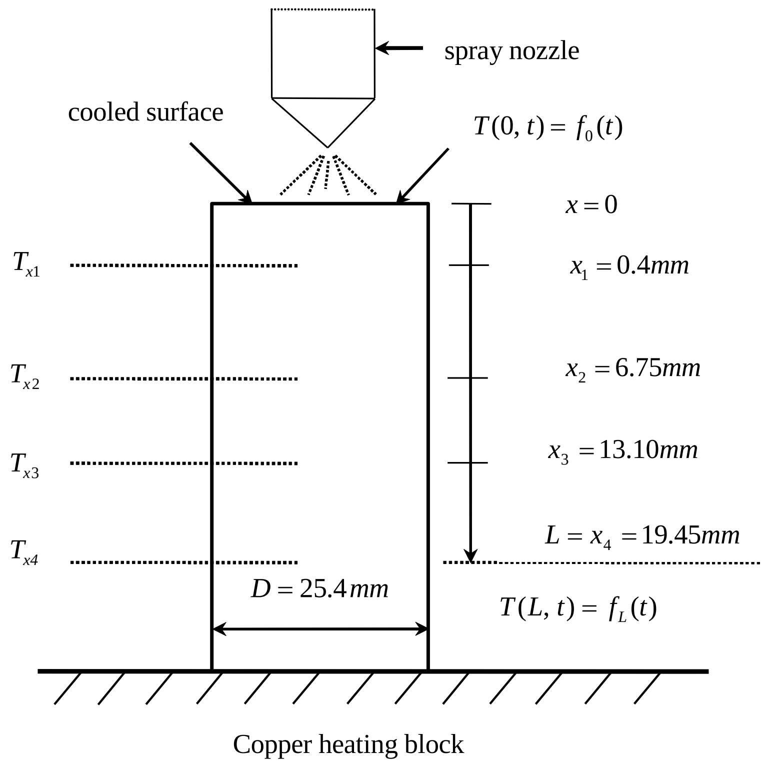


Figure 2: Schematic diagram of the inverse problem of spray cooling.

一、噴霧散熱單邊待求實驗數據範例

In the case, the temperature history at $x_4 = 19.45mm$ of the spray cooling problem shown in Fig. 2 is considered as the known time-dependent boundary condition $f_L(t)$, and has been expressed by Lee and Huang [15] in four polynomial functions $f_{sL}(t)\,(s=1-4)$ of the third degree as

$$f_{sL}(t) = c_{1s} + c_{2s}(t - t_s) + c_{3s}(t - t_s)^2 + c_{4s}(t - t_s)^3, \tag{41}$$

where s denotes the number of the sub-time intervals and t_s is equal to the time length from the initial time to the upper time of the s-th time interval. In addition, the coefficients $c_{js}\,(j = 1\text{-}4,\ s = 1\text{-}4)$ have been given for different measurement locations [15].

First, we will expand the time-dependent temperature function $f_L(t)$ in half-range Fourier cosine form as

$$f_L(t) = a_0 + \sum_{p=1}^{N} [a_p \cos(\frac{p\pi}{t_f} t)], \tag{42}$$

where $a_p\,(p = 0, 1, 2, \cdots, N)$ are the $(N+1)$ coefficients to be determined and N denotes the number of unknown coefficients a_p. a_0 is then given as

$$a_0 = \frac{1}{t_f}\int_0^{t_f} f_L(t)dt = \frac{1}{t_f}\{\sum_{s=1}^{4}[c_{1s}(t_s - t_{s-1}) - \frac{c_{2s}}{2}(t_s - t_{s\text{-}1})^2 + \frac{c_{3s}}{3}(t_s - t_{s\text{-}1})^3 - \frac{c_{4s}}{4}(t_s - t_{s\text{-}1})^4]\}, \tag{43}$$

where we have defined $t_0 = 0$ and $t_4 = t_f$. Moreover, if we use the initial condition $f_L(0) = T_0$, we can also get another expression of a_0 as

$$a_0 = T_0 - \sum_{p=1}^{N} a_p\ . \tag{44}$$

Likewise, $a_p\,(p = 1, 2, \cdots, N)$ are now given as

$$
\begin{aligned}
a_p &= \frac{2}{t_f}\int_0^{t_f} f_L(t)\cos(\frac{p\pi}{t_f}t)dt \\
&= \frac{2}{t_f}\{\sum_{s=1}^{4}[c_{1s}\frac{\sin(\frac{p\pi t_s}{t_f})-\sin(\frac{p\pi t_{s-1}}{t_f})}{(\frac{p\pi}{t_f})} + c_{2s}\frac{\cos(\frac{p\pi t_s}{t_f})-\cos(\frac{p\pi t_{s-1}}{t_f})+(\frac{p\pi}{t_f})(t_s-t_{s-1})\sin(\frac{p\pi t_{s-1}}{t_f})}{(\frac{p\pi}{t_f})^2} \\
&+ c_{3s}\frac{2(\frac{p\pi}{t_f})(t_s-t_{s-1})\cos(\frac{p\pi t_{s-1}}{t_f})-[(\frac{p\pi}{t_f})^2(t_s-t_{s-1})^2-2]\sin(\frac{p\pi t_{s-1}}{t_f})-2\sin(\frac{p\pi t_s}{t_f})}{(\frac{p\pi}{t_f})^3} \\
&+ c_{4s}\frac{3\{-2\cos(\frac{p\pi t_s}{t_f})-[(\frac{p\pi}{t_f})^2(t_s-t_{s-1})^2-2]\cos(\frac{p\pi t_{s-1}}{t_f})\}+(\frac{p\pi}{t_f})(t_s-t_{s-1})[(\frac{p\pi}{t_f})^2(t_s-t_{s-1})^2-6]\sin(\frac{p\pi t_{s-1}}{t_f})}{(\frac{p\pi}{t_f})^4}]\} .
\end{aligned}
\quad (45)
$$

Using Eqs. (44) and (45), we compare the present estimates for $N=6$ and $N=10$ of $f_L(t)$ with the temperature function $f_{sL}(t)(s=1-4)$ of Lee and Huang [15] in Fig. 3. We found that the estimates for $N=10$ agrees very well with that of Ref. [15]. Accordingly, we will take $N=10$ in performing the following numerical analyses.

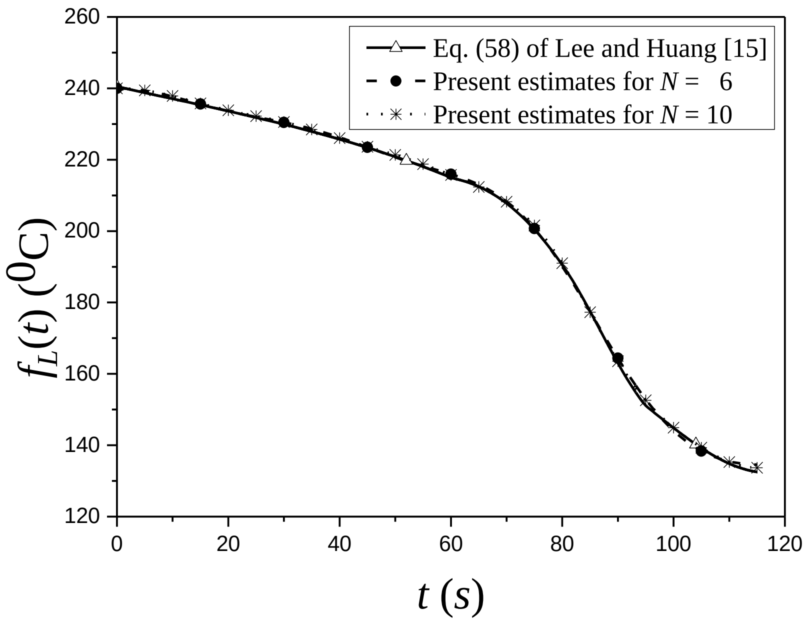


Figure 3 : Comparison of $f_L(t)$ between the estimates given in this study and those given by Lee and Huang [15] at the boundary L.

Next, the unknown time-dependent temperature $f_0(t)$ at the cooled end need to be determined in this example, while the measured temperatures $T^{meas}(x_m, t_r)$ are adopted from the experimental data [11]. The inverse methodology is used to estimate the temperature history of $f_0(t)$ from the knowledge of the temperature measurement at the interior location .

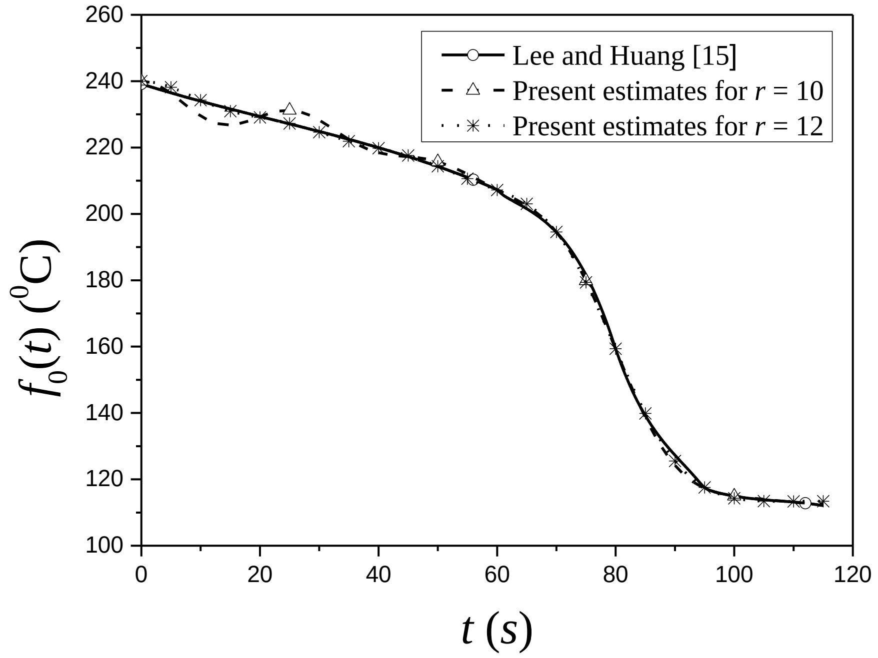


Figure 4 : Comparison of $f_0(t)$ between the estimates given in this study and those given by Lee and Huang [15] at the cooled end ($N=10$).

Considering three discrete measurement times (see below), the present estimates of $f_0(t)$ during spray cooling for different number r of measurement times t_r is shown in Fig. 4 . [t_{fA} : ($t_1=5$, $t_2=20$, $t_3=35$, $t_4=45$, $t_5=60$, $t_6=70$, $t_7=80$, $t_8=95$, $t_9=100$, $t_{10}=110$); t_{fB} : ($t_1=5$, $t_2=15$, $t_3=25$, $t_4=40$, $t_5=50$, $t_6=60$, $t_7=70$, $t_8=80$, $t_9=87$, $t_{10}=95$, $t_{11}=105$, $t_{12}=110$); t_{fC} : ($t_1=5$, $t_2=10$, $t_3=20$, $t_4=30$, $t_5=40$, $t_6=50$, $t_7=60$, $t_8=70$, $t_9=80$, $t_{10}=85$, $t_{11}=90$, $t_{12}=95$, $t_{13}=100$, $t_{14}=110$)]. From the figure, we found that $r=12$ could be consistent with the result of Ref. [15]. We thus take $r=12$ (i.e., t_{fB} set) below. Table 1 depicts the estimated coefficients, $A_1 \sim A_{10}$, of the spray cooling temperature function $f_0(t)$ for the measurement location x_{m1} and discrete measurement times t_r with respect to the iteration number n of

$T(x,t)$ (Eq. (28)). From this table, we found that the convergence rate is very fast, and $n=5$ will be taken below.

Table 1: Estimated coefficients, ($A_1 \sim A_{10}$), of the spray cooling temperature function $f_0(t)$ for measurement location x_{m1} and measurement times $t_r(r=1\sim 12)$ ($t_1=5$, $t_2=15$, $t_3=25$, $t_4=40$, $t_5=50$, $t_6=60$, $t_7=70$, $t_8=80$, $t_9=87$, $t_{10}=95$, $t_{11}=105$, $t_{12}=110$)

	$n=2$	$n=5$	$n=10$	$n=20$
A_1	61.4964	61.4997	61.5004	61.5008
A_2	-19.1375	-19.1354	-19.1346	-19.1342
A_3	4.5224	4.5183	4.5170	4.5163
A_4	6.1274	6.1306	6.1313	6.1318
A_5	-4.5624	-4.5625	-4.5624	-4.5624
A_6	2.5342	2.5330	2.5326	2.5324
A_7	1.0783	1.0801	1.0807	1.0810
A_8	-0.8700	-0.8701	-0.8701	-0.8701
A_9	0.7633	0.7630	0.7628	0.7627
A_{10}	0.5208	0.5208	0.5208	0.5207

Table 2 depicts the comparison of estimated surface temperature $f_0(t)\,({}^0C)$ at $x=0$ of the copper cylinder for various measurement locations $x_m(m=1,2,3)$ and various discrete measurement times with those of Lee and Huang [15]. We found that the results of either of $x_m(m=1,2,3)$ are nearly the same as those of Ref. [15].

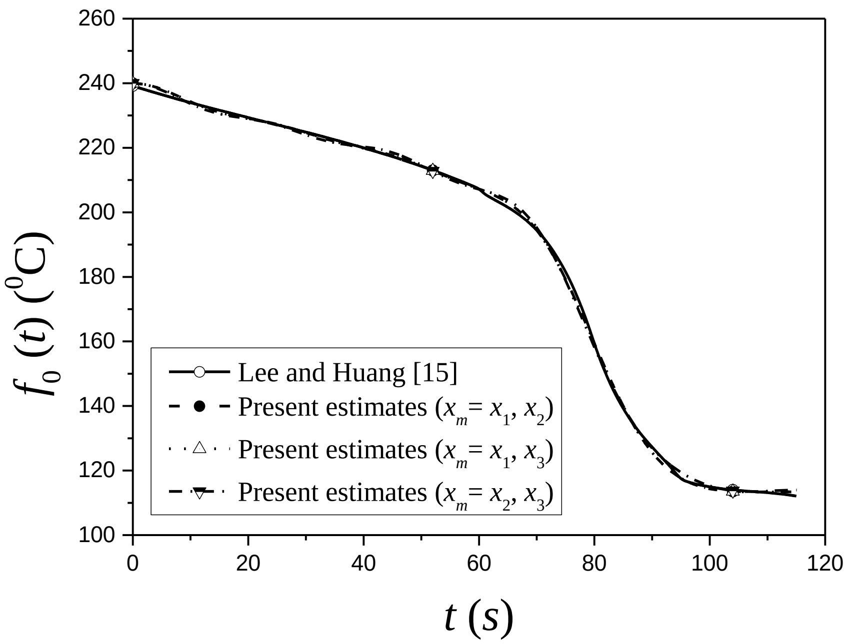
Table 2: Estimated surface temperature $f_0(t)\,(^0C)$ at $x=0$ of the copper cylinder for various measurement locations $x_m(m=1,2,3)$ and discrete measurement times

$t(s)$ \ x_m	$x_1=0.4mm$	$x_2=6.75mm$	$x_3=13.1mm$	Lee and Huang [15]
0	240.0000	240.0000	240.0000	239.5617
10	234.2658	233.4067	232.8275	233.9811
30	224.6349	223.3863	221.6315	224.8422
50	214.3821	213.7723	211.1753	214.2886
60	207.2193	206.6757	205.2325	206.5586
70	194.5490	195.1403	194.4420	194.4876
80	159.3727	157.2191	154.2058	159.1861
90	125.5464	125.4263	120.9869	127.2741
95	117.5807	117.8452	113.4677	117.1316
105	113.4233	112.6956	110.4101	113.8456
115	113.4029	113.8992	113.7383	112.0796

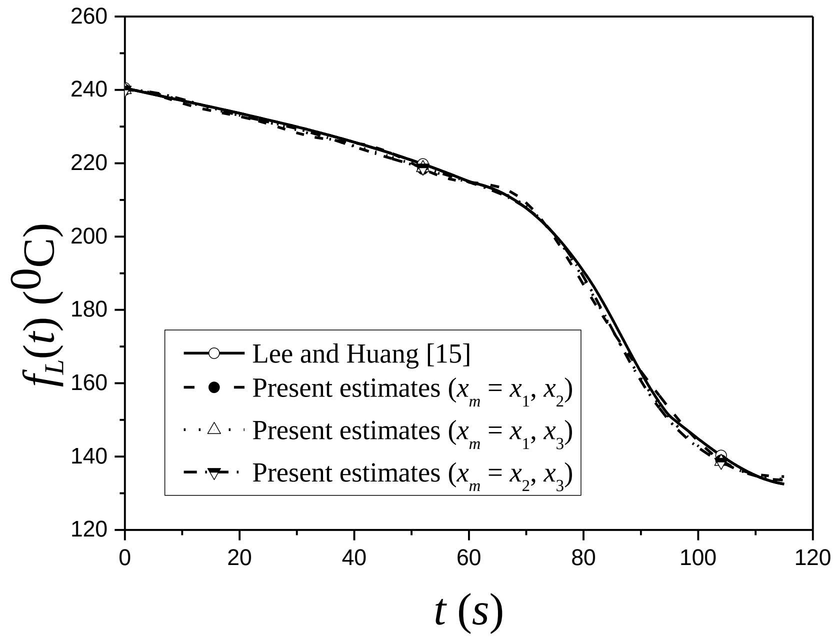
二、噴霧散熱雙邊待求實驗數據範例

In this example, the unknown time-dependent temperatures $f_0(t)$ and $f_L(t)$ need to be determined, while the measured temperatures, $T^{meas}(x_{m1},t_r)$ and $T^{meas}(x_{m2},t_r)$ which are generated from the experimental solutions [11]. The inverse methodology is used to predict the temperature histories at the both ends from the knowledge of the temperature measurement at the two interior locations.

Fig. 5 depicts the estimation of $f_0(t)$ and $f_L(t)$ at both ends of the inverse spray cooling problem with respect to different measurement locations used ($x_m=x_1,x_2$; $x_m=x_1,x_3$; $x_m=x_2,x_3$). Note that $N=10$, $n=5$, and $r=12$ have been used in the case. It can be observed from Fig. 5a and Fig. 5b that the present estimates regardless of the measurement locations used agree with those of Ref. [15] over the whole time domain. This implies that the present inverse scheme can obtain good estimates which is independent of the measurement positions.



(a) Estimation of $f_0(t)$



(b) Estimation of $f_L(t)$

Figure 5: Estimation of $f_0(t)$ and $f_L(t)$ at both ends of the inverse spray cooling problem ($N = 10$, $n = 5$, $r = 12$).

第六章　結論

本二年期計畫將對雷射表面加熱與噴霧散熱之逆向熱傳導問題提出了新的混和解決方法。多項式函數與半範圍擴展函數當作單邊未知溫度以及利用移位函數法，則此熱傳系統的解析解可以獲知。再藉由最小均方誤差法，在比對從物體內量得到的實驗溫度，和從具猜測之時變性邊界之熱傳問題的解析解所估算的溫度數據，可求得在受熱端的溫度函數。本計畫估算結果與實驗數據相當符合。

本二年期計畫之第一年對雷射表面加熱與噴霧散熱問題，考慮其受熱表面的溫度為隨時間變動的函數，已解決現有逆向分析方法大多面臨的問題：

(1)本研究不須處理繁瑣的數值問題，如拉普拉斯轉換、數值分析的穩定度和含大量元素的矩陣運算；

(2)本研究容易同時求得在時間與空間內任意點的溫度及熱通量；

(3)過往量測位置要非常接近加熱或散熱表面，而本研究量測溫度的位置可以不靠近加熱或散熱表面；

(4)過往表面熱處理時間不宜過長問題，而本研究可以處理長時間的熱處理問題。

(5)過往均需假設單邊邊界條件為已知，而本研究可以處理雙邊邊界條件均未知的熱處理問題。

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1.因個人動心臟手術，未使用出國經費
2.部分出國經費(按規定比例)已挪為業務費使用

105年度專題研究計畫成果彙整表

計畫主持人：李森墉　　**計畫編號：**105-2221-E-006-127-

計畫名稱：配合實驗數據之逆向熱傳導問題分析(I)

成果項目					量化	單位	質化（說明：各成果項目請附佐證資料或細項說明，如期刊名稱、年份、卷期、起訖頁數、證號...等）
國內	學術性論文	期刊論文			0	篇	
		研討會論文			0		
		專書			0	本	
		專書論文			0	章	
		技術報告			0	篇	
		其他			0	篇	
	智慧財產權及成果	專利權	發明專利	申請中	0	件	
				已獲得	0		
			新型/設計專利		0		
		商標權			0		
		營業秘密			0		
		積體電路電路布局權			0		
		著作權			0		
		品種權			0		
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	技術移轉	件數			0	件	
		收入			0	千元	
國外	學術性論文	期刊論文			2	篇	1. S. Y. Lee and Q. Z. Yan: Inverse analysis of heat conduction problems with relatively long heat treatment, International Journal of Heat and Mass Transfer (2017), vol.105, pp. 401-410. 2. Te Wen Tu and Sen Yung Lee (2017): “Exact Temperature Field in a Slab with Time Varying Ambient Temperature and Time-Dependent Heat Transfer Coefficient”, International Journal of Thermal Sciences. vol. 116, pp. 82－90.
		研討會論文			0		
		專書			0	本	
		專書論文			0	章	
		技術報告			0	篇	
		其他			0	篇	

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科技部補助專題研究計畫成果自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現（簡要敘述成果是否具有政策應用參考價值及具影響公共利益之重大發現）或其他有關價值等，作一綜合評估。

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1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估
■達成目標
□未達成目標（請說明，以100字為限）
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說明：
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2. 研究成果在學術期刊發表或申請專利等情形（請於其他欄註明專利及技轉之證號、合約、申請及洽談等詳細資訊）
論文：■已發表 □未發表之文稿 □撰寫中 □無
專利：□已獲得 □申請中 ■無
技轉：□已技轉 □洽談中 ■無
其他：（以200字為限）
1. International Journal of Heat and Mass Transfer (2017), vol.105, pp. 401-410.
2. International Journal of Thermal Sciences (2017). vol. 116, pp. 82–90.
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<tr><td>
3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性，以500字為限）
在學術上本二年期計畫提出創新的熱傳導問題之逆向分析方法，求解一維具有時變性邊界條件的熱傳導之逆向問題。此方法主要結合了解析解（利用移位函數法求解）、物體內部量測到的實驗數據，以及利用最小均方誤差數值分析法，以解決因受熱面溫度或是物體表面熱通量在量測上的困難，典型工程實例，計有：雷 射表面加工、熱交換器、燃燒室、量熱式儀表、砲管內部溫度、金屬加工的快速冷卻和淬火及電子元件的冷卻等。其中，(1)雷射表面加工問題：在雷射表面硬化處理下，表面溫度會維持在臨界變形溫度並低於熔點。因此在熱處理過程中，準確估算出加熱表面之溫度以及熱通量表面吸收率極其重要。不過，由於直接量測加熱表面的溫度和熱通量相當困難，這些物理量可由在加熱時間內物體內部的量 測溫度資料估算而得；　(2)熱表面的噴灑冷卻問題：熱表面的表面溫度測試在淬火中是最重要的參數，被用來定義不同熱轉換機制中的沸騰曲線。因此，在噴灑冷卻過程中，表面溫度和熱通量的估算準確度非常重要。同樣地，由於不易直接量測噴灑冷卻表面的溫度和熱通量，這些物理量需要在噴霧冷卻時間內量測物體內部的溫度資料，再利用逆運算分析估算求得。
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4. 主要發現

本研究具有政策應用參考價值：■否　□是，建議提供機關

（勾選「是」者，請列舉建議可提供施政參考之業務主管機關）

本研究具影響公共利益之重大發現：□否　□是

說明：（以150字為限）

本研究方法不需積分轉換，便可求解一維熱傳導具兩邊界未知溫度之逆向問題。先藉由移位函數法求出解析解，再經最小誤差法，比對物體內量測實驗溫度值，與猜測解析解所估算的溫度數據，反求兩端的溫度函數。未知兩端溫度均利用半幅函數級數展開表示，只需十餘項即可得精確值，本法極具效率。