International Journal of Heat and Mass Transfer 100 (2016) 1–10

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Algorithms for the estimation of transient surface heat flux during ultra-fast surface cooling

Zhi-Fu Zhou, Teng-Yu Xu, Bin Chen *

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 9 January 2016
Received in revised form 17 April 2016
Accepted 19 April 2016
Available online 4 May 2016

Keywords:
Surface heat flux
Inverse heat conduction problem
Duhamel's theorem
Sequential function specification method
Transfer function method
Cryogen spray cooling

ABSTRACT

Surface heat flux is an important parameter in various industrial applications. This paper compared several algorithms for estimating surface heat flux using both simulated heat flux and measured temperature in response to ultra-fast surface cooling. Two different strategies were employed to measure the surface temperature, using the thin film thermocouple with a 2 μm depth deposited directly on the cooling substrate surface (direct surface temperature measurement) and the fine thermocouple with a 100 μm bead diameter placed on the surface of the cooling substrate and covered with aluminum foil (indirect surface temperature measurement). The algorithms of Duhamel's theorem, sequential function specification method (SFSM) and transfer function method are briefly analyzed. A new method is proposed that the surface temperature is first calculated based on Duhamel's theorem and then the surface heat flux can be estimated, in order to improve the accuracy of results in the case of the indirect surface temperature measurement method. The transfer function is obtained by solving an auxiliary problem and thus the transfer function method can be implemented to solve multilayer, semi-infinite inverse heat conduction problems. Accuracy and sensitivity to noise are examined using both the simulated triangular pulse heat flux and the measured temperature data. Duhamel's theorem is insensitive to noise, but is unsuitable for predicting surface heat flux in the indirect measurement method of surface temperature. The SFS method can provide acceptable results of surface heat flux using both measurement methods. However, a noticeable discrepancy exists as the heat flux changes extremely quickly and it suffers considerably from noise. The transfer function and newly proposed methods are both effective in inhibiting noise, and produce very similar results, which match the simulated heat flux exactly and have a negligible standard deviation and residual temperature.

1. Introduction

Spray cooling is an efficient and powerful thermal management technique for achieving ultra-fast surface cooling and high heat flux removal. It is widely applied in the steel industry, electronics devices, power plant and laser dermatology for vascular skin lesions [1–7]. Generally, in such fields of thermal management engineering, surface heat flux is a key parameter for assessing whether the equipment or body works under the normal heat load condition. However, it is relatively difficult to measure the time-varying heat flux directly at the solid surface for the initial cooling period or the pulse spray cooling. Alternatively, it can usually be estimated from the temperature measurement made at accessible locations, which is termed an inverse heat conduction problem (IHCP).

The IHCP is mathematically ill-posed, and far more difficult than the direct problem. It is extremely sensitive to measurement noise and suffers considerably from the lag and damping of the measurements. Several analytical and numerical methods have been proposed for the solution of IHCPs, such as specified sequential function method (SFSM), regularization method, and transfer function method. The SFS method is one of the most widely used algorithms for solving IHCPs, as proposed by Beck in 1985 [8]. This method minimizes the effect of random errors by using future temperature data based on the least square method. The regulation method estimates all of the heat flux components simultaneously for all time and are usually presented as whole domain methods. It can be applied generally, whereas it is relatively complicated in mathematical terms [9,10]. The transfer function method analogizes the heat conduction problems to dynamic systems, where heat flux is treated as the input of the system and the temperature profile as the response [11]. By using the Laplace transform, the relation between input and output can be given by the transfer

---

* Corresponding author.
E-mail address: chenbin@mail.xjtu.edu.cn (B. Chen).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.04.058
0017-9310/

Nomenclature

c	specific heat capacity (J/(kg K))
f	surface temperature (K)
G	Green's function
h	transfer function
H	Laplace transform of transfer function
k	thermal conductivity (W/(m K))
K	whole time step of measured data
n	whole time step of simulated data
q	heat flux (W/m^2)
Q	Laplace transform of heat flux
r	future time steps
S	standard deviation of temperature (K)
S_M	error between measured and estimated temperature (K^2)
t	time (s)
T	temperature (K)
x	spatial coordinate (m)
$x(t)$	input function
X	Laplace transform of input function
$y(t)$	output function
Y	Laplace transform of output function, or the measure temperature (K)
Z	sensitivity coefficient (K m^2/W)

Greek symbols

α	thermal diffusivity (m^2/s)
ζ	standard deviation of heat flux (W/m^2)
θ	temperature difference (K)
Θ	Laplace transform of temperature difference
ρ	density (kg/m^3)
τ	current time step
φ	non-dimensional stream function

Subscripts

c	position of temperature measurement
erf	error function
i	time index or layer index
k	chosen time index
L	Laplace transform
r	residual
0	initial state
1	first layer

function as determined by the Green's function [12]. This method is simple in concept and one of the most accurate ways of estimating surface heat flux. However, it is relatively difficult to determine the analytic solution of the transfer function for the complex geometry problem.

Although IHCPs have been extensively investigated with regard to various other applications, little work has been conducted related to heat flux on skin surface during cryogen spray cooling in laser dermatology. Cryogen spray cooling with several tens of milliseconds provides an effective way to cool the epidermis and therefore reduce the thermal injuries induced by the absorption of laser energy by melanin, when lasers are radiated on the skin of port wine stain (PWS) patients [13,14]. The heat flux on skin surface during CSC is strongly time-dynamic, which is a critical parameter for judging the cooling effect and characterizing the interaction between skin and spray cooling. However, it is relatively difficult to measure surface heat flux directly. Therefore, the indirect technique employing internal temperature measurement is often used to estimate surface heat flux. Two algorithms have been employed to estimate heat flux based on measured temperature data due to CSC. Tunnell et al. predicted surface heat flux during and following cryogen spurt using the SFS method based on internal temperature measurement, in which a wire-like thermocouple with a bead diameter of 30 μm was imbedded in epoxy resin [15–18]. Aguilar et al. also employed the SFS method to estimate surface heat flux based on internal temperature data using a faster response temperature measurement method [19–21]. In their work, a fine thermocouple (50 μm bead diameter) was placed on the surface of cooling substrate (Plexiglas) and covered by a thin (20 μm) layer of aluminum. Using the same temperature measurement method, Franco et al. calculated the surface heat flux by solving a direct problem through Duhamel's theorem, where the measured temperature was treated as the real surface temperature [22,23]. More recently, Zhou et al. used a thin film thermocouple with a depth of 2 μm deposited on an epoxy resin surface through the Magnetron spurting technique in order to measure surface temperature directly during CSC, and then predicted the surface heat flux based on Duhamel's theorem [6,13,24]. From the above literature review, various temperature measurement methods and algorithms for estimating surface heat flux have been employed. However, few of them provide a comparison of the algorithms for the estimation of surface heat flux under different surface temperature measurement methods. The accuracy and applicability of the algorithms should be further explored to promote the accurate estimation of surface heat flux due to CSC.

In this paper, we use epoxy resin as the cooling substrate and measure the surface temperature during and following a pulse spray cooling using R404A with two different measurement methods: the thin film thermocouple with a 2 μm depth deposited directly on the substrate surface and the fine thermocouple with a 100 μm bead diameter placed on the surface of the substrate and covered with aluminum foil. Duhamel's theorem and the SFS method are implemented to predict time-varying surface heat flux. Then, a new method is proposed based on Duhamel's theorem to improve the accuracy of surface heat flux when using the indirect surface temperature measurement method. An auxiliary problem is established to obtain the transfer function numerically, and thus this method can be implemented to solve multilayer, semi-infinite inverse heat conduction problems. The accuracy and applicability of each algorithm in different measuring methods are evaluated based on both the simulated heat flux and the experimental temperature data.

2. Experiment system

2.1. Spray cooling system

Fig. 1 shows a schematic of the cryogen spray cooling system. It consists of a cryogen container for the storage of liquid cryogen, a 3D positioner for controlling the distance between the nozzle tip and cooling substrate, a fast response solenoid valve (Parker) and a straight tube nozzle. The nozzle is made of stainless steel with an inner diameter of 0.38 mm and length of 40 mm, which resembles those used in clinical surgeries. Cryogen R404A (Dupont) is used to form the pulse spray due to its superior cooling capacity compared with R134a to protect the epidermis [6,25]. The spurt duration of the pulse spray (usually less than 100 ms in clinical surgeries) can be accurately controlled since the response time of