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Measurement of boiling heat transfer coefficient in liquid nitrogen bath by inverse heat conduction method*

Tao JIN†, Jian-ping HONG, Hao ZHENG, Ke TANG, Zhi-hua GAN†‡

(*Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, China*)

†E-mail: jintao@zju.edu.cn; gan_zhihua@zju.edu.cn

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Abstract: Inverse heat conduction method (IHCM) is one of the most effective approaches to obtaining the boiling heat transfer coefficient from measured results. This paper focuses on its application in cryogenic boiling heat transfer. Experiments were conducted on the heat transfer of a stainless steel block in a liquid nitrogen bath, with the assumption of a 1D conduction condition to realize fast acquisition of the temperature of the test points inside the block. With the inverse-heat conduction theory and the explicit finite difference model, a solving program was developed to calculate the heat flux and the boiling heat transfer coefficient of a stainless steel block in liquid nitrogen bath based on the temperature acquisition data. Considering the oscillating data and some unsmooth transition points in the inverse-heat-conduction calculation result of the heat-transfer coefficient, a two-step data-fitting procedure was proposed to obtain the expression for the boiling heat transfer coefficients. The coefficient was then verified for accuracy by a comparison between the simulation results using this expression and the verifying experimental results of a stainless steel block. The maximum error with a revised segment fitting is around 6%, which verifies the feasibility of using IHCM to measure the boiling heat transfer coefficient in liquid nitrogen bath.

Key words: Inverse heat conduction method (IHCM), Liquid nitrogen bath, Boiling heat transfer coefficient
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INTRODUCTION

Cryogenic treatment has been applied in many industries over the past 40 years. While there are still some controversies on its functioning mechanism on materials, for which further study has its much necessity, heat transfer analysis is one of basic steps in exploring the mechanism (Zhirafar *et al.*, 2007). In addition to traditional experimental study, numerical simulation has attracted increasing attention in the heat transfer analysis of cryogenic treatment and has been widely applied. Generally with liquid nitrogen (LN_2) as cooling medium in cryogenic treatment, the boiling heat transfer coefficient of the work piece in the LN_2 bath is a key parameter for heat transfer analysis. Many methods can be adopted to obtain the boiling heat transfer coefficient, including an empirical formula method, a lumped parameter method, a fixed-heat flux method, and an inverse heat conduction method (IHCM) (Westwater *et al.*, 1986; Barron, 1999; Ozisik and Orlande, 2000). The empirical formula method has become a relatively common method owing to its simplicity. However, the possible inaccuracy at some stages may lead to an apparent error. The precondition of the lumped parameter method is that the inner thermal resistance could be ignored. This is, however, not the case for the cryogenic treatment process. Besides, the severe heat exchange at work piece's surface brings great difficulty in accurately measuring the surface temperature, which may invalidate the fixed heat flux method. IHCM uses the temperature variation inside an object to calculate the heat transfer coefficient at its surface. This is much more convenient since it avoids the necessity of measuring the surface

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‡ Corresponding author

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temperature and the internal thermal resistance can be included in the analysis (Blackwell, 1981; Beck *et al.*, 1985; Gu *et al.*, 1998). Many progresses have been achieved in the IHCM (Jackson *et al.*, 2005; Azim *et al.*, 2006) and the accuracy of its results is also satisfactory. However, the application of this method in cryogenic treatment is not yet widespread.

The use of IHCM in cryogenic treatment is expected to improve the accuracy in calculating the heat transfer coefficient. This will increase the reliability of the heat simulation transfer process and help to explore the functioning mechanism of the cryogenic treatment on material properties. In this paper, an experimental setup for cooling stainless steel in LN_2 bath is built for rapid temperature measurement, which is then used to calculate the heat flux and the heat transfer coefficient with an IHCM solution program. Fitting expressions obtained from these calculated data, by segment fitting and revised segment fitting, will then be adopted to simulate the whole heat transfer process of a test piece. The results will be compared with practical measurement to verify accuracy.

EXPERIMENTAL SETUP AND MEASUREMENT PROCESS

The experimental setup, as shown in Fig.1, includes a Dewar (for LN_2), a stainless steel block (made of 1Cr18Ni9Ti), a supporting shelf, thermocouples (Cu-constantan), and a LabView based temperature data acquisition (DAQ) system. The stainless steel block has the dimensions of 60 mm×60 mm×17.5 mm (length×width×thickness), with three holes (for thermocouples) of 2 mm diameter, as shown in Fig.2. In order to realize an approximation of 1D heat conduction, five faces of the block, except for the tested face, are covered with foam for thermal insulation, and the foam is wrapped tight to avoid the invasion of LN_2 to the in-between space. Analysis by ANSYS simulation (Hong, 2008) shows that the thermocouples' response time is 0.006~0.026 s. With a sampling rate of 0.1 s^{-1}, they can meet the requirement for measuring the dynamic temperatures.

The stainless steel block and the supporting shelf are cleaned with alcohol and then dried to avoid the inaccuracy in measurement result due to the freezing grease, dirt, or water at the surface. Connecting the thermocouples to the DAQ system through the temperature-treating module, we then initiate the experiments if the LabView based DAQ system runs regularly. The stainless steel block is fixed to the supporting shelf and then emerged into LN_2 bath. We inputted the dynamic temperature and recorded it using the DAQ system. When the temperature tends to be stable at a certain value, the DAQ operation is terminated and the data are output and saved in a file. The block is then taken out from the Dewar and put in air to recover to ambient temperature for next experiment.

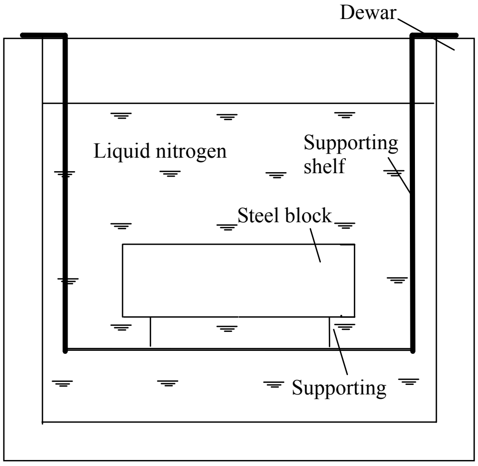

Fig.1 Schematic of temperature measurement setup for a stainless steel block in the LN_2 bath

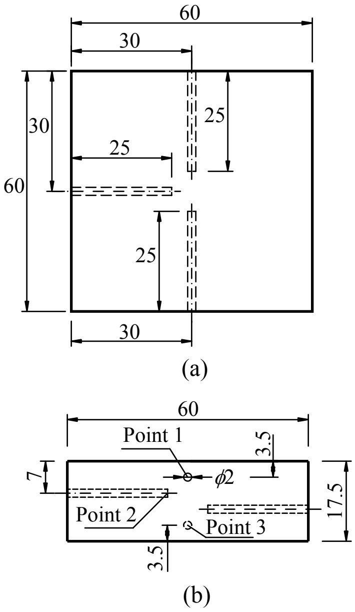

Fig.2 Geometry of the temperature measuring location. (a) top view; (b) side view (unit: mm)

INVERSE HEAT CONDUCTION CALCULATION

The deduction of surface heat flux is based on the sequential function definition method. Using Taylor series and the least square method, the revised expression of surface heat flux under 1D heat conduction is as follows (Beck *et al*., 1985; Gu *et al*., 1998):

$$q_M=q^*+[Y(x,t_M)-T(x,t_M)]/X(x,t_M), \qquad (1)$$

where q_M is the revised heat flux, q^* is the preset assumed heat flux, $Y(x,t_M)$ is the measured temperature at a certain location, $T(x,t_M)$ is the calculated temperature with the assumed heat flux q^*, $X(x,t_M)$ is the sensitivity factor and t_M is time moment.

The actual model to be studied by IHCM is a 1D heat conduction (along thickness direction) stainless steel block, as shown in Fig.2. The temperature and its sensitivity factor are calculated with explicit finite difference model (EFDM). Considering the restriction of EFDM (Morton and Mayers, 2005) and the difficulty in drilling thermocouples' holes, the distance and time steps are set Δx=3.5 mm and $\Delta\tau$=0.1 s, respectively, so that there are six nodes along its thickness, as shown in Fig.3. The measuring locations 1, 2 and 3 correspond to nodes 1, 2 and 4, respectively.

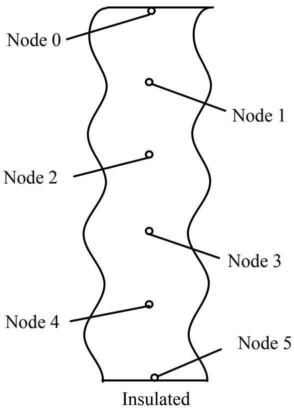

Fig.3 Node locations ilculating model

Fig.4 presents the procedures of inverse heat conduction calculation, including the following steps.

(1) Introduce the measured temperature (at a certain node) and then set the time step number according to measuring time and time step. Considering that a measuring location nearer to surface may lead to a better accuracy (Beck *et al*., 1985), the measured temperatures at location 1 (also node 1) are chosen for further analysis.

(2) Set initial temperature and sensitivity factor at the nodes with ambient temperature and zero, respectively.

(3) Predict a surface heat flux, which is used to calculate the instantaneous temperature at the surface nodes. Use explicit finite difference method to deduce the temperatures and sensitivity factors at the other nodes.

(4) Revise the surface heat flux with Eq.(1).

(5) Compare the predicted surface heat flux with the revised one. If the difference between them is higher than a preset limit, the adjustment of the surface heat flux is required. Repeat steps (3)~(5) till they tends almost to be equivalent.

(6) With the surface heat flux obtained from step (5), the surface heat transfer coefficient can then be calculated by dividing it by temperature gap, which defined the difference between the surface temperature of the stainless steel block and the temperature of the LN_2 pool. Due to the difficulty in accurately measuring, the surface temperature is calculated, with finite difference method, from the measured temperatures at the locations inside the stainless steel block.

(7) Repeat steps (3)~(6) till the time step length reaches the preset value. Finally, the boiling heat transfer coefficients can be obtained.

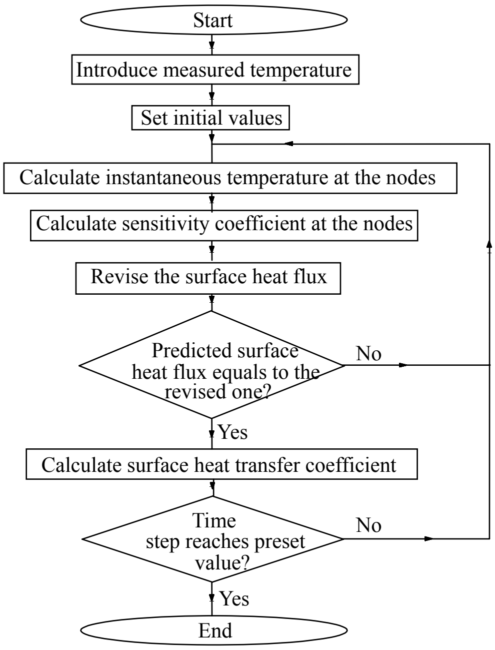

Fig.4 Configuration diagram of inverse heat conduction calculation program

SOLUTION OF BOILING HEAT TRANSFER AND VERIFICATION

The measured temperature at location 1 can be inputted into the IHCM program to calculate the heat flux and boiling heat transfer coefficients, as shown in Figs.5 and 6. From these figures, referring to typical pool boiling curve in (Barron, 1999), four boiling regions can be found (i.e., film boiling, transition boiling, nucleate boiling, and natural convection boiling). In film boiling and natural convection boiling regions, the data points are dense, due to their relatively low heat flux and ensuing slow temperature variation. By contrast, in transition boiling and nucleate boiling regions, the data points are scarce due to the high heat flux and severe temperature drop. Reading from these figures, the critical nucleate boiling heat flux is 68 918 W/m^2 at a temperature gap of 21.4 K and the minimum film boiling heat flux is 6261 W/m^2 at a temperature gap of 52.7 K.

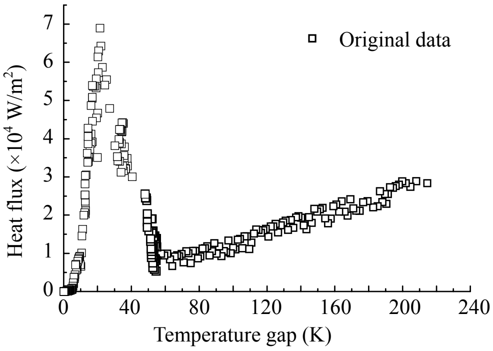

Fig.5 Heat flux from IHCM calculation

The heat transfer coefficients calculated from the discrete measured temperatures are discrete and also fluctuating, which is inconvenient to be used in heat transfer process simulation. For use convenience, a mathematical fitting was carried out to obtain expressions based on the calculated heat transfer coefficient data. Considering the apparent difference among different boiling status, a segment fitting method is used to provide segmental expressions in different region (Fitting I). The fitting curve (Fitting I) is shown in Fig.6, with the following expressions:

$$\begin{cases} h = 125 + 0.069 \times \Delta T, \quad 56.3 \le \Delta T \le 214, \\ h = 12292.13 - 709.32 \times \Delta T + 14.735 \times \Delta T^2 \\ \quad - 0.1061 \times \Delta T^3, \quad 18.94 \le \Delta T < 56.3, \\ h = 82.74 - 131.22 \times \Delta T + 37.64 \times \Delta T^2 \\ \quad - 1.13 \times \Delta T^3, \quad 4 \le \Delta T < 18.94, \\ h = 21.945 \times \Delta T, \quad 0 \le \Delta T < 4, \end{cases}$$

where h is the heat transfer coefficient, ΔT is the temperature gap between surface and LN$_2$.

On Fitting I, the beginning section of transition boiling stage (just adjacent to film boiling stage) is not as smooth in view of its extension to the rest section. Considering that the measured data at this beginning section may have a relatively big error, so we proposed to omit these data points before the fitting was made. The fitting after omitting partial data is called revised segment fitting, or Fitting II. Fitting II is shown in Fig.7, whose expressions can be written as follows:

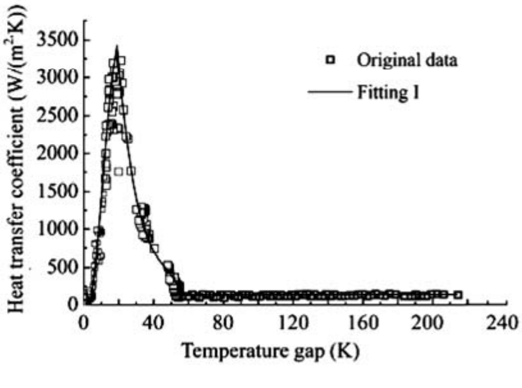

Fig.6 Heat transfer coefficient from IHCM calculation and Fitting I

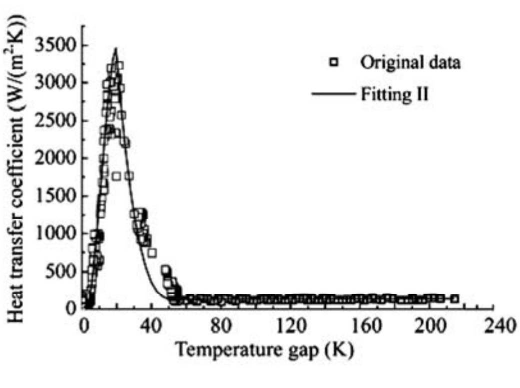

Fig.7 Revised segment fiing (Fitting II) of heat transfer coefficient

$$\begin{cases} h = 125 + 0.069 \times \Delta T, \quad 52 \le \Delta T \le 214, \\ h = 13087.8 - 723.04 \times \Delta T + 13.48 \times \Delta T^2 \\ \quad - 0.084 \times \Delta T^3, \quad 19.6 \le \Delta T < 52, \\ h = 82.74 - 131.22 \times \Delta T + 37.64 \times \Delta T^2 \\ \quad - 1.13 \times \Delta T^3, \quad 4 \le \Delta T < 19.6, \\ h = 21.945 \times \Delta T, \quad 0 \le \Delta T < 4. \end{cases}$$

The expressions of boiling heat transfer coefficient by the above two different fitting methods were both adopted to simulate the dynamic temperature field of a stainless steel block (for verification), with ANSYS as simulation tool. The simulation results were then compared with the measured results to check their degree of agreement. Figs.8 and 9 present the results comparison and error percentage at location 2, while Figs.10 and 11 are those at location 3.

From Figs.8 and 10, it can be found that simulation with Fitting II expressions have a better agreement with measured results than Fitting I expressions. However, Fitting II expressions are not perfect yet, according to Figs.9 and 11, since a maximal error of about 6% still exists at nucleate boiling and transition boiling stages. Therefore, more efforts should be made to improve the accuracy and stability of temperature measurement and then those of fitting expressions.

CONCLUSION

The measurement, calculation and verification of boiling heat transfer coefficient of a stainless steel block in LN_2 bath were carried out with an explicit finite difference inverse heat transfer method, which is not yet widely used in the heat transfer analysis of cryogenic treatment process. The main works done in the paper and our conclusions are as follow:

(1) An experimental setup for rapid

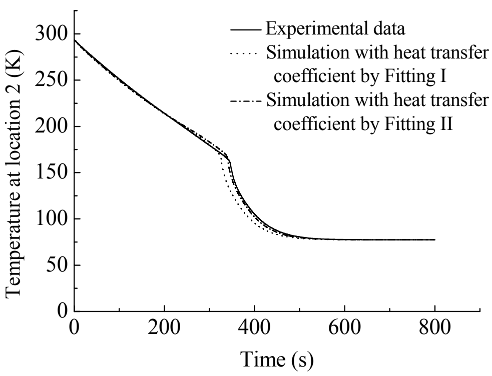

Fig.8 Agreement of measured results with simulation results with heat transfer coefficient at location 2

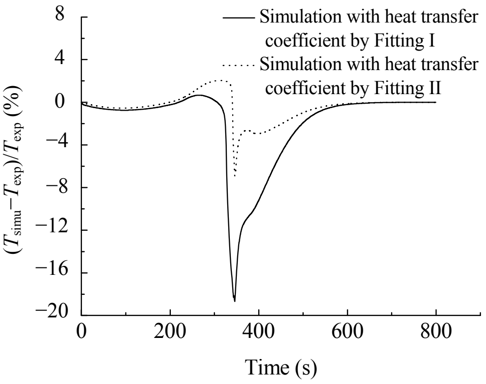

Fig.9 Errors of simulations with Fittings I and II with measured result at location 2

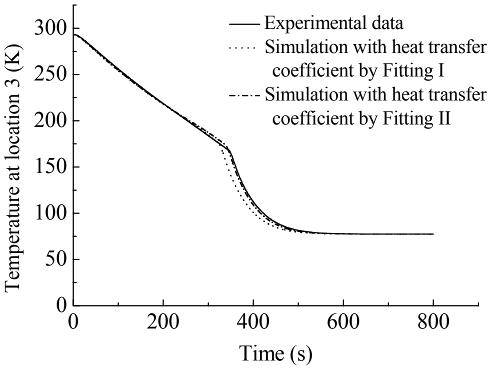

Fig.10 Agreement of measured results with simulation results with heat transfer coefficient at location 3

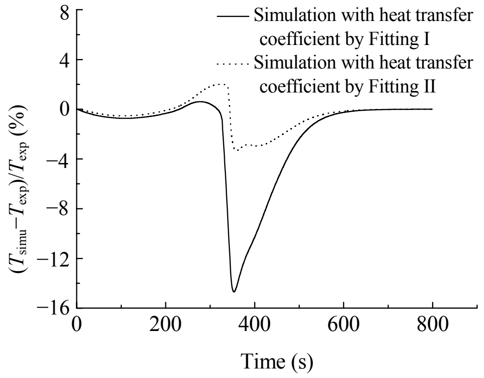

Fig.11 Errors of simulations with Fittings I and II with measured results at location 3

measurement of dynamic temperature was built up to measure the temperature variation inside the stainless steel block emerged in LN_2 bath.

(2) Based on the inverse heat conduction mechanism and explicit finite difference model, a program with a 1D heat conduction assumption has been written to calculate the boiling heat transfer coefficient and heat flux from the measured temperatures. For the use convenience in the heat transfer process simulation and the exclusion of data oscillation, two fitting methods (segment fitting (Fitting I) and revised segment fitting (Fitting II)) were proposed to obtain appropriate expressions for boiling heat transfer coefficients.

(3) Verifying simulation and measurement on the test block have also been done with the use of heat transfer expressions from the above two different fittings. The comparison among the simulation results and experimental results shows that Fitting II expressions can lead to a better agreement with measured results. The maximum error with Fitting II is around 6%, while that with Fitting I is about 19%.

In summary, even though the simulation with heat transfer coefficients from inverse heat conduction method has good agreements with the measured results, the apparent errors (as large as 6%) at nucleate and transition boiling stages cannot be neglected. These errors may have their origins from many aspects, such as the measuring error and the deviation from 1D assumption. Therefore, more efforts should be devoted to the working condition assumption, the calculation model and the measurement accuracy to improve the accuracy of boiling heat transfer coefficients achieved by IHCM.

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