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Experimental Thermal and Fluid Science 30 (2006) 203–212

Experimental Thermal and Fluid Science

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Application of stereoscopic tracking velocimetry for experimental and numerical investigation of directional solidification

D.J. Lee [a], S.S. Cha [b,*], N. Ramachandran [c]

[a] University of Illinois at Chicago, Chicago, IL 60607, United States
[b] Department of Mechanical and Industrial Engineering, University of Illinois at Chicago, M/C 251, 842 West Taylor Street, Chicago, IL 60607-7022, United States
[c] BAE Systems Analytical Solutions Inc., SD46, NASA Marshall Space Flight Center, Huntsville, AL 35812, United States

Received 1 November 2004; received in revised form 30 April 2005; accepted 28 May 2005

Abstract

A previously reported stereoscopic tracking velocimetry (STV) is further refined and applied to measure directional solidification. The flow involves complicated three-dimensional (3-D) convection, being subject to both buoyancy and surface tension forces in addition to conjugate conduction. For our STV, the 3-D tracking of numerous particles is the most important and challenging process. Here, the performances of the tracking algorithms, which are based on artificial neural networks, are first presented with a brief summary of the STV principles. The 3-D experiment measurements of the convective phenomena are then discussed together with the results from two-dimensional numerical modeling for qualitative comparison.

Keywords: Directional solidification; Particle tracking; Velocimetry; Stereoscopic tracking

1. Introduction

Convective motion of the melts in crystal growth is a dominant factor that greatly influences the quality of material processing. The characterization of their three-dimensional (3-D) three-component (3-C) velocity fields is thus of great importance for both terrestrial and extraterrestrial crystal growth investigation. Typical driving forces for convection are the buoyancy that can be induced by thermal and solute gradients in the bulk liquid and the surface tension that can also be caused by the aforementioned gradient non-uniformities on a free surface. The surface tension typically decreases with increasing temperature, driving the flow from a hot region to a cold area to be balanced by the viscous shear. Koschmieder [1], Shyy [2], and Sampath and Zabaras [3] discussed the convection in terms of the Marangoni or thermocapillary phenomena. Sparrow et al. [4] and Yeoh et al. [5] indicated that the convective flow can significantly affect solidification rate and the solid–liquid interface shape. Schwabe [6] addressed the importance of Marangoni convection in crystal growth with a particular interest in its influence on the impurity distributions in crystal structure. The effect of the Marangoni convection becomes even more dominant in reduced-gravity environments. Juhlmann [7] and Schwabe [6] presented an excellent summary for previous numerical and experimental studies on the surface-tension-driven flow in crystal growth. Yao and Groh [8] and Kakimoto et al. [9] reported measurements of 3-D velocity fields for the solidification process in crystal growth but only for few data points without addressing thermal capillary

* Corresponding author. Tel.: +1 312 996 9612; fax: +1 312 413 0447.
E-mail address: sscha@uic.edu (S.S. Cha).

0894-1777/$ - see front matter
doi:10.1016/j.expthermflusci.2005.05.007

Nomenclature

E	energy function	σ_n	normal stress at the free surface
M	number of candidate tracks	p	pressure
N	number of proper tracks	γ	specific gravity
$\overline{V}_x$	average velocity in x-direction	H	mean curvature of the free surface
$\overline{V}_y$	average velocity in y-direction	$\bar{u}$	velocity
a_x	acceleration in x-direction	T	temperature
a_y	acceleration in y-direction	Ma	Marangoni number ($\sigma_T \Delta T L \rho c_p / \mu k$)
w	weighting function for Hopfield NN	St	Stefan number ($c_p \Delta T / L$)
θ	artificial temperature	Pr	Prandtl number ($\rho c_p v / k$)
t	time	Gr	Grashof number ($g \beta \Delta T L^3 / v^2$)
SCN	succinonitrile	Ra	Rayleigh number ($Gr \cdot Pr$)

effects. In spite of the previous efforts for defining solidification processes in crystal growth, characterization of 3-D velocity is still a challenge for both numerical and experimental investigations.

The experiments in crystal growth most likely inhibit the application of conventional planar techniques for observing 3-D phenomena. Previously, Ge and Cha [10] reported the diagnostic technology development of stereoscopic tracking velocimetry (STV) for measuring 3-D 3-C velocity fields. STV is based on stereoscopic observation of particles seeded in a flow with CCD sensors. STV is advantageous in system simplicity for building compact hardware and in software efficiency for continual near-real-time monitoring. It has great freedom in illuminating and observing a volumetric field from arbitrary directions. However, it exhibits weakness insofar as it requires seeding of relatively small number of particles in the measurement volume as compared with conventional particle image velocimetry, primarily owing to the difficulty in particle tracking and limited detection resolution of CCD sensors. These restrict either the size of the observation volume or measurement resolution. However, in most applications, the STV strengths can outweigh its weakness. In STV, the particle tracking is the most important processing step and thus has been further refined to maximize data recovery to alleviate the weakness. In this paper, we present the refinement results of the tracking technique, STV application to the velocity measurement in directional solidification, and comparison with two-dimensional (2-D) numerical computation. Succinonitrile (SCN), which is a transparent metal analog, was employed as a test material. The flow involves complicated 3-D convection subject to both buoyancy and surface tension forces, in addition to solidification and conjugate heat transfer at the boundary. At now, uncertainties in the various physical properties and parameters that appear in numerical modeling as well as difficulties in accurately realizing experimental conditions would not warrant the reliability of 3-D flow modeling.

2. Description of STV and results of particle tracking algorithms

The STV consists of two CCD cameras apart at some reasonable angle to simultaneously observe the tracer particles seeded in an optically transparent fluid. The data acquisition and processing steps of STV are shown in Fig. 1 and the details of the methodology have been previously presented by Ge and Cha [10]. Camera calibration is the step for finding the relationship between CCD image positions to corresponding rays in space. This allows stereoscopic matching of two projection images. In the approach, individual particle centroids are identified for each camera image, 2-D tracks are found for individual particles, and then the

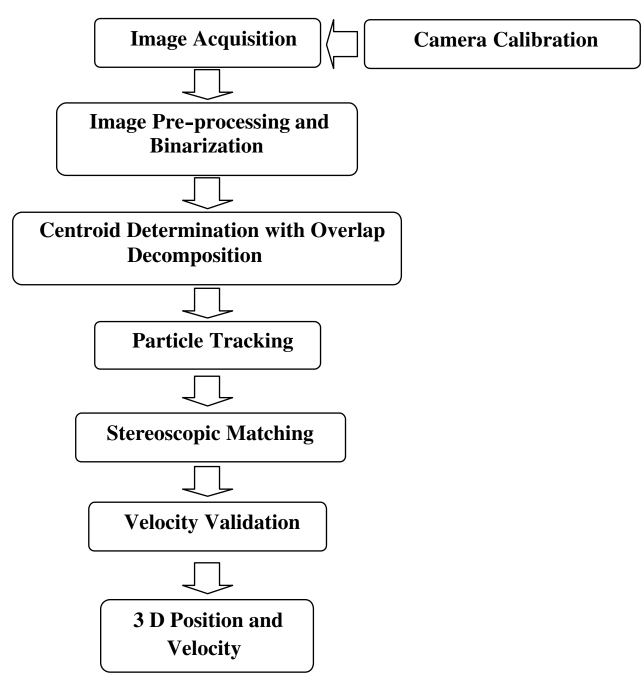

Fig. 1. Processing steps of the STV technique.