ARTICLE IN PRESS

Flow Measurement and Instrumentation ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

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

Measurement of Joule-heating flow convection induced by internal heat generation using ultrasound velocity profiler in glycerin fluid

Thanh Tung Duong [a,1], Hiromasa Tanaka [a], Nobuyoshi Tsuzuki [a,*], Hideki Kawai [b], Hiroshige Kikura [a]

[a] *Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, 2-12-1-N1-7 O-okayama, Meguro-ku 152-8550, Tokyo, Japan*
[b] *Department of Mechanical Engineering, Muroran Institute of Technology, 27-1, Mizumoto-cho, Muroran 050-8585, Hokkaido, Japan*

ARTICLE INFO

Keywords:
Joule-heating flow
PIV
UVP
Chaotic flow
Cubic cavity

ABSTRACT

Joule-heating flow behavior in a square cavity was experimentally investigated by means of Ultrasonic Velocity Profiler (UVP). Two electrode plates are placed on opposing side walls and connected a constant AC voltage. Chaotic unstable flow occurs in the square cavity which was volumetrically heated, mainly by electric current as Joule-heating while top surface was cooling by constant temperature. Besides, the other walls are under adiabatic condition. The quantitative investigation of chaotic flow was become more difficult with increasing the internal heat source. Thus, an ultrasonic velocity profiling method was used to observe chaotic flow by giving the spatiotemporal flow pattern. UVP method was appropriated for this kind of flow because of its capability for opaque flow and instantaneous velocity profile measurement. The spatiotemporal behavior of chaotic flow in a cubic Joule-heating cavity was observed as a temporal variation of the velocity profile. The accurate of UVP measurement system was confirmed with PIV (Particle Image Velocimetry) method for the two-dimension of velocity distribution. As a result, the comparison of vertical velocity profile between UVP and PIV method presents less than 5% error. The Joule-heating flow was observed continuously when electrodes connected with AC voltage. The chaotic level with increasing the internal heat source was investigated quantitatively by analyzing the fluctuation frequency of velocity using Fast Fourier Transform (FFT).

1. Introduction

Natural convection flow driven by thermal in an enclosure rectangular cavities has attracted the attention of several researchers for both experiment and numerical simulation. The natural convection was based on the externally gradient temperature given to the top and low surface (low surface was hotter), called, Rayleigh–Benard [1] convection. This phenomena has been an important topic until now as a model of large-scale of turbulence model [3]. On the other hand, the flow convection induced by internal heat source has been also paid much attention since 1960s by Tritton et al. [4–5]. Flow behavior in this case is different from the Rayleigh–Benard convection. Schwiderski et al. [6] and Tasaka et al. [7] found that cell shape in horizontal direction was greatly distorted and moreover, the flow direction was entirely opposite to the Rayleigh–Benard convection.

The flow driven by internal heat source is very important in geophysics, astrophysics, and nuclear engineering such as heat removal of debris in severe accident, glass flow behavior inside a Glass melter which is aimed to isolate High Level Liquid Wastes (HLLWs) from spent fuel reprocessing. The glass melter immersed a pair of electrodes on the side walls in order to melt the glass beads. The mixing process is carried out by the natural convection. The homogenous Joule-heating in the volume generates complex chaotic flow in the glass melter and the unsteady flow makes stable operation of the melter difficult. Thus, glass flow is a significant characteristic which allows to understand the effect of some parameters on the chaotic flow, e.g. top cooling surface temperature, shape of the cavity, temperature condition of the electrodes, heating rate, etc. The upward flows and downward flows are changing their positions while sufficient heat is supplied and equivalent heat is emitted. The flow behavior is very complicated and changes its position in time. Thus, the flow behavior is considered as a kind of chaotic flow and is named ‘chaotic steady state’. Several measurement techniques such as PIV (Particle Image Velocimetry), PTV (Particle Tracking Velocimetry) and LDA (Laser Doppler Anemometry) has developed to measure velocity field. However, to measure the opaque fluid, UVP (Ultrasound Velocity Profiler) is the most appropriated instead of optical method.

The author [2] has reported the success application of UVP method to observe the Joule-heating flow in a cubic cavity. The most advantage of this technique is non-invasive and applicable in opaque fluids such as molten glass. The effect of cooling temperature on the

* Corresponding author.
E-mail address: duongttung@us.nr.titech.ac.jp (T.T. Duong).
[1] Tel.: +81 3 5734 3059; fax: +81 3 5734 2939.

http://dx.doi.org/10.1016/j.flowmeasinst.2014.10.007
0955-5986/

Joule-heating flow behavior was presented experimentally and numerically. However, the flow behavior was reported only in the steady state. The chaotic level was not discussed experimentally using UVP method. Therefore, the long-term observation of Joule-heating flow characteristic is reported.

The instantaneous velocity profiles of vertical component is measured in time-dependence and then compared with PIV method that provides two-dimension velocity distribution. The results reveals a good agreement between two measurement methods. For UVP measurement, a spatiotemporal velocity map is used to represent the flow convection in a cubic cavity. The flow fluctuates frequently. Thus, the fluctuation is observed by the UVP method and the frequency is analyzed by using the Fast Fourier Transform (FFT) method.

2. Experimental apparatus and method

2.1. Experimental apparatus

The dimension of cavity is 100 mm × 100 mm × 100 mm (Fig. 1). Two carbon electrode plates are placed on opposing side walls. The working fluid was 80 wt% glycerol–water solution with LiCl as electrolyte for Joule-heating. The initial temperature of working fluid is kept at room temperature (20 °C). The UVP measurements require the suspension of US (ultrasonic) wave reflecting particle in the fluid. Nylon powder ($\overline{d}$ = 80 μm; ρ = 1020 kg/m^3) is dispersed in working fluid as reflector particles for both UVP and PIV measurement (Figs. 1 and 2). A CCD camera is used to record the movement of particles illuminated by a laser sheet. From this data, one could analyze the 2-dimension velocity distribution using PIV method. The top surface is made of copper with thickness of 10 mm and cooled at 20 °C. Temperature on the top is controlled by Circulator (CTW401/801). The other walls are made of 20 mm thickness acrylic. The internal heat is generated by applying a constant voltage on the electrode plates. A stabilized AC power (EPX4104, NF Co. Ltd) supply the electric current to electrodes. The polyimide film (Kapton sheet) is used for electrical

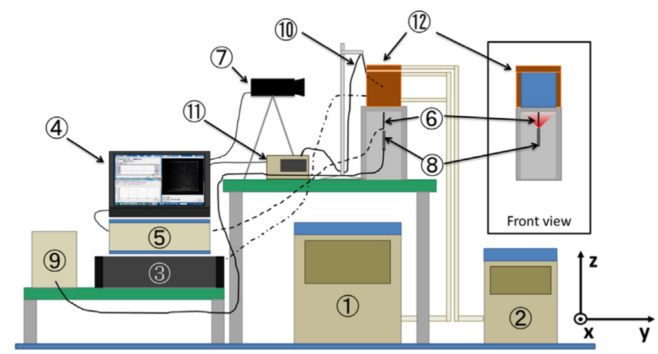

Fig. 2. Experiment set up. (1 and 2) Cooling system; (3) AC power supplier; (4) personal computer; (5) UVP monitor; (6) UVP transducer; (7) CCD camera; (8) laser sheet; (9) laser unit; (10) thermocouple (K-type); (11) data logger; (12) Joule-heating cavity.

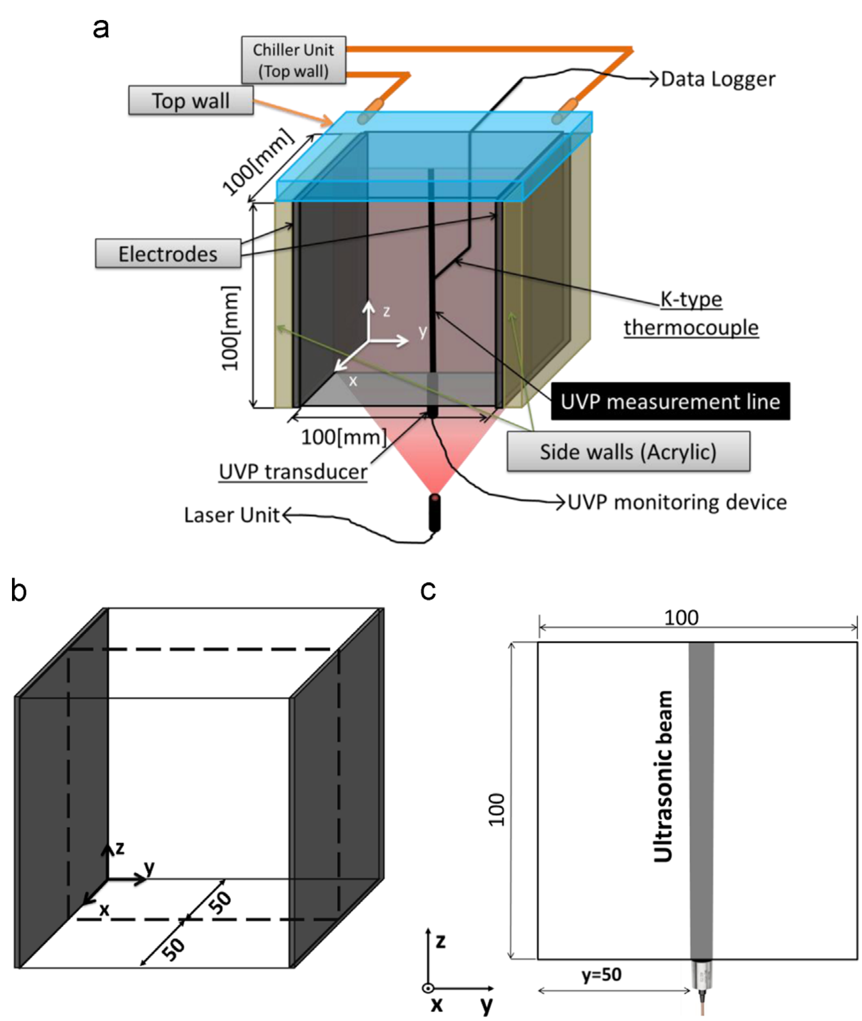

Fig. 1. (a) Sketch of Joule-heating cavity and (b), (c) test section for measurement. Number show the length in mm.

Please cite this article as: Duong TT, et al. Measurement of Joule-heating flow convection induced by internal heat generation using ultrasound velocity profiler in.... Flow Measurement and Instrumentation (2014), http://dx.doi.org/10.1016/j.flowmeasinst.2014.10.007