SUBTASK 3.4B
INVESTIGATE DYNAMIC SPRAY CHARACTERISTICS BY IMAGE PROCESSING

Contributor: Japan National Committee for IEA/CRD Implementing Agreement on Energy Conservation and Emission Reduction in Combustion (JECC). Tokyo JAPAN

Description:

The technical goal of the present report is to develop spray measuring techniques with high spatial and temporal resolution of size, velocity vector and local density by means of interferometry, light scattering, density image, and fluorescence techniques which are applicable for investigations in combustion systems.

The technical goal of the present report is to clarify the disintegration phenomena with thin plate nozzles as basic research of liquid atomization. This investigation is considered to be as a first step of development of the multi-holes fuel injectors fabricated by Micro-Electro-Mechanical-Systems (MEMS) technologies, especially the fuel injector for continuous combustion such as gas turbine combustor.

Other research was performed about image analysis tools for high-speed videography. This program is in yet basic state, but fundamental analysis menus are provided. It was verified that application to ultra high-speed video recording system such as Shimadzu's could be done. In addition more general movie file (AVI files in Windows OS) can be handled by this program.

Accomplishments:

The task realized the robust system for the planer simultaneous measurement of sizing and velocity vectors of individual droplets in dense spray and in bubbly flows which are applied to analyze mixing of injection nozzle spray. **The soft-ware was accomplished as a conventional easy handling and appeared as a commercially available system. The software is available as an academic version for IEA member. (non-comercialized)**

The model sector combustor, representing 120 degrees of the original annular combustor, was built and used for observation of mixing processes of fuel and air and combustion phenomena in the small gas turbine combustor.. Thin planar plate nickel nozzles are fabricated using electroforming process. The velocity of spray is measured by PIV methods.

VMAP was developped to utilizing networkly distributed environment. This could reduce processing time one to four.

Plans:

The work planned for next year will be follows:

Ultra high-speed video recording analysis will be applied to spray particles.

Publications:

Iki, N., Ebara, T. and Shimizu, D., "Spray from a thin plate nozzle with multi holes", ICLASS2006, ICLASS06-044, 2006

Similar work elsewhere:

None Known

Milestone Chart:

CY-85 -86 -87 -88 -89 -90 -91 -92 -93 -94 -95 -96

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I J K L M N O P

\+ Task completed

° Task will be completed

A: Refinement the homodyne techniques to yield the information on particulate formation
B: Development of holographic techniques for spray combustion.
C: Improve the two frame holographic system.
D: Design the quadruplet frame holographic system.
E: Improve the image processing techniques.
F: Develop new holographic system for frame recording/
G: Improve the LLS high-speed photographic system.
H: Develop new high intensity incoherent flash light system.
I: Improve visual technique for soot clouds.
J: Improve fringe-counting system.
K: Complete simple high-speed photo-recording system.
L: Develop new holographic recording techniques for small particle field.
M: Application of Linear Scan Camera System to Particle analysis
N Development of Versatile Motion Analysis Program for Ultra high-speed videography
O Application of Interferometric Laser Imaging Technique (ILI) to the Spray Behavior in a Swirling Hot Air Flow
P High speed digital video analysis for spray droplets sizing and vector field in combustion flows

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SUBTASK3.4B
Investigate Dynamic Spray Characteristics by Image Processing

3.4B-II (MAEDA)

Development of Simultaneous Measurement Technique of Size, Velocity Vectors and Local Density on Spray and Micro-bubbles by Interferometoric Laser Imaging Technique

M. Maeda*, Keio University, Yokohama, Japan

3.4B Objective

The present task is to observe formation, growth, flow and mixing with oxidant of fine fuel droplets or those of fine micro-bubbles in liquid. The task will be performed by laser assisted optical techniques by laser induced fluorescence techniques and by high speed movies as well.

3.4B-II (Maeda) Scope

The technical goal of the present report is to develop spray measuring techniques with high spatial and temporal resolution of size, velocity vector and local density by means of interferometry, light scattering, density image, and fluorescence techniques which are applicable for investigations in combustion systems.

3.4B-II (Maeda) Accomplishment

The task realized the robust system for the planer simultaneous measurement of sizing and velocity vectors of individual droplets in dense spray and in bubbly flows which are applied to analyze mixing of injection nozzle spray. The soft-ware was accomplished as a conventional easy handling and appeared as a commercially available system. The software is available as an academic version for IEA member. (non-comercialized)

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Accomplished Performances

Abstract

The present report shows the flow behavior of spray in a swirling chamber with hot annular air flow. It confirmed the method is applicable for analyzing the complex flow in combustor models effectively.

The processing system needs only line information to calculate the fringe spacing from the captured line image from the individual droplets. The images to be taken were compressed optically to those of broken lines of length by defocused image and width by focused image. The present novel ILIDS receiving optics, achieves the measurements of sizing in a denser spray or in a bubbly flow with small bubbles by avoiding overlapping of neighboring images with fringe. The simultaneous measurement of droplet size and velocity is possible by using a two-dimensional correlation PTV technique. A part of results by Prof. Akamatsu (Osaka uninv.) and one of those by Prof. Moriyoshi (Chiba univ.) were cited.

1. Application to spray in a swirling hot air (Takeuchi, Hishida, Keio univ.)

The present technique showed the high resolution for droplet sizing and will show further the size variation by the influence of droplet evaporation in a hot air. The swirl flow makes a recirculation zone in the test chamber even where the residual time of the droplets in a relatively low temperature region. The droplet size distribution varies as Fig.12. Especially they show an increase in the mean size of the droplets, where the smaller size droplets may evaporate faster i.e. those of larger sizes may remain relatively. The difference in the cold and hot states is shown at the central core zone of the flow axis significantly as is illustrated in Fig. 14.

Another comparison was made for the 3 classes (less than 20┌, 20-30 μm and 30-40 μm) of the size distribution in the flow. The small droplets with a low St. number diffused to whole field widely while those of larger one remain in the central core and recirculate, evaporate and diffuse as those of smaller size.

Get the spray involved large droplet size and the swirl must be higher to make them keep in the hot region.

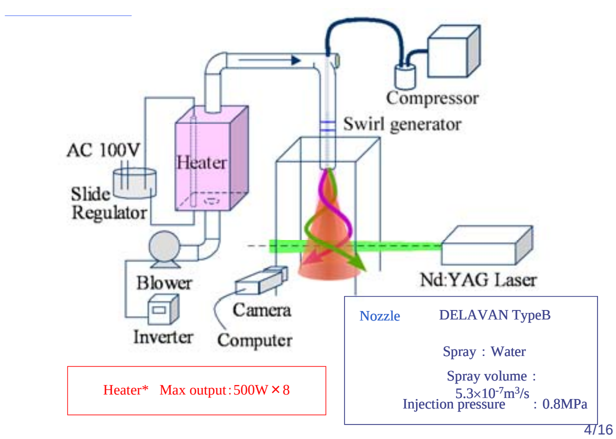


Fig. 1 Experimental setup for the spray in a swirling hot air flow

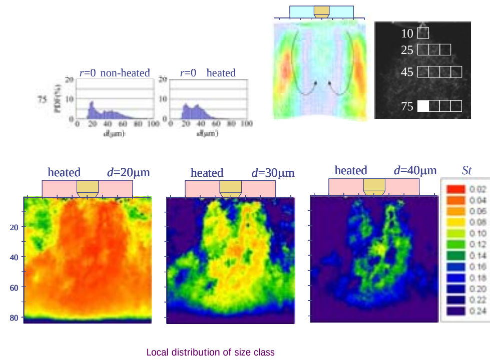


Fig.2 Visualization of local concentration of spray for sizes

2. Fuel droplets evaporation in a flat flame analyzed by a high-speed camera (Prof. Akamatsu, Osaka university and Kanomax Inc.)

The quick evaporation in a combustion system was analyzed in time series by high-speed camera system and the present ILI method.

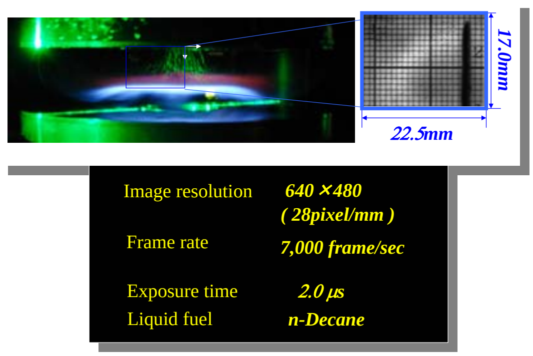
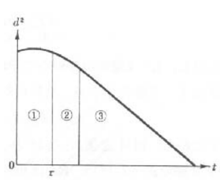


Fig.3 Flat flame burner and droplet trace



1. period of ignition delay
2. transient period to steady combustion
3. period of steady combustion

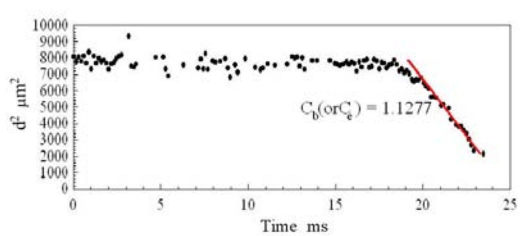
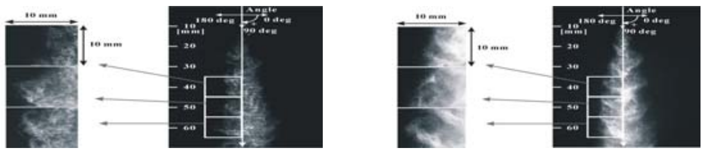


Fig.4 evaporation of 89.19μm droplets

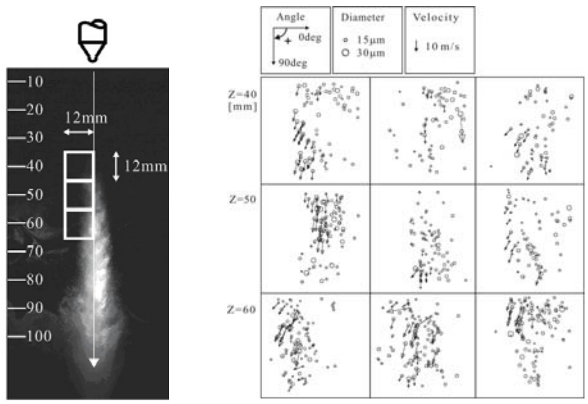
3. Application to a Diesel-spray analysis (Ryu, Moriyoshi, Aoyagi 2007)

Their investigations focused on the mixing zone of Diesel spray.



Ambient pr. : 0.1 MPa   Ambient pr. :1 MPa

Fig. 5 Diesel spray and the partial enlargements
(Pinj=100 MPa, Start of injection 3.5 ms)



1.5 ms after end of injection(Pinj=50 MPa)

Fig.6 Diesel spray and local particle sizes and their velocity vectors.

4. Conclusion

The present interferometric sizing technique provides also a PIV velocity map by individual droplet correlation and the pictures are taken as a 2D frozen data so that the spatial information of the distributions of droplet number density, velocity vectors, and the size became analyzable. The method confirmed its capability to obtain instantaneous cross-sectional and time series information of the flow field.

The software of ILI for compression technique is to be provided in Academic use by the authors T. Kawaguchi and M. Maeda.

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It is just necessary to prepare PIV system and sylindrical lens system with rectangular mask.

References

Pajot, O. and Mounaïm-Rousselle, C., "Droplet sizing by interferometric method based on Mie scattering in an I.C. Engine.", 9th. Int. Symp. Applications of Laser Techniques to Fluid Mechanics, Lisbon-Portugal, 18.2, 1998.

Skippon, S., M. and Tagaki, Y., "ILIDS Measurements of the evaporation of fuel droplets during the intake and compression strokes in a firing lean burn engine", SAE Paper no.960830:183-198, 1996.

Ryu, C.S., Moriyoshi, Y. and Aoyagi, Y., 2D simultaneous Measurements of droplets diameter and velocity in a Diedel spray by using improved ILIDS method, Trans. of JSME（B）73-725、pp.380-386 (2007)

SUBTASK3.4B
Investigate Dynamic Spray Characteristics by Image Processing

3.4B-III (IKI)

Spray from a Thin Plate Nozzle with several tens micrometer holes

N. Iki*, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki, Japan

3.4B Objective

The present task is to observe disintegration phenomena of thin liquid jet with the thin planar nickel plate nozzles fabricated by electroforming process. The task will be performed by laser assisted optical techniques by laser induced fluorescence techniques and by high speed movies as well.

3.4B-II (Iki) Scope

The technical goal of the present report is to clarify the disintegration phenomena with thin plate nozzles as basic research of liquid atomization. This investigation is considered to be as a first step of development of the multi-holes fuel injectors fabricated by Micro-Electro-Mechanical-Systems (MEMS) technologies, especially the fuel injector for continuous combustion such as gas turbine combustor.

3.4B-III (Iki) Accomplishment

The model sector combustor, representing 120 degrees of the original annular combustor, was built and used for observation of mixing processes of fuel and air and combustion phenomena in the small gas turbine combustor.. Thin planar plate nickel nozzles are fabricated using electroforming process. The velocity of spray is measured by PIV methods.

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Accomplished Performances

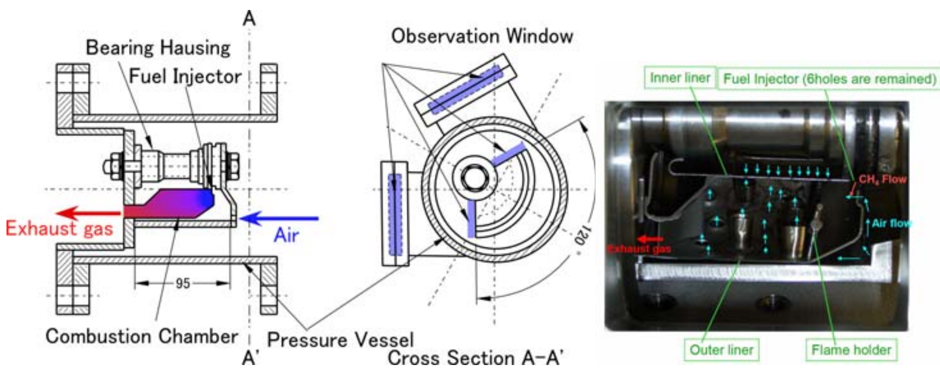
Abstract

The combustor of this small engine has many problems such as unstable ignition, spurt of flame at starting up, unburned combustibles

etc. Not only these problems, temperature pattern factor, thermal heat loss, combustion efficiency and pressure loss are common issues for small high-intensity combustors. Therefore the author tries to visualize the mixing processes of fuel and air and combustion phenomena in the small gas turbine combustor. The liquid fuel injector for such a small gas turbine has many problems. For example, fuel spray is not fine enough at starting up condition due to low flow rate of fuel; there is not enough space to evaporation process of large fuel droplets; etc. If a volume, weight and energy consumption of a fuel injection system is not small, this injection system spoils the merit of a small gas turbine such as compactness, power to weight ratio. Therefore improvement of the pressure atomization is important issue. The author considers possibility to adopt a planar plate nozzle with small holes to an internal combustion engine such as gas turbines. If fuel flow rate and injection pressure are limited, there are many variable design parameters which effects on atomization phenomena, such as number of holes, size of holes, hole shape, intervals of holes, hole patterns, etc.

1. Atomization of liquid fuel injector of small gas turbine

The model sector combustor, representing 120 degrees of the original annular combustor, was built and used for the experimental investigation. As shown in Fig. 1, this model combustor is set in the pressure vessel with two optical windows.



(a) Overview *(b) Gas flow images*

Fig. 1 Sector model combustor

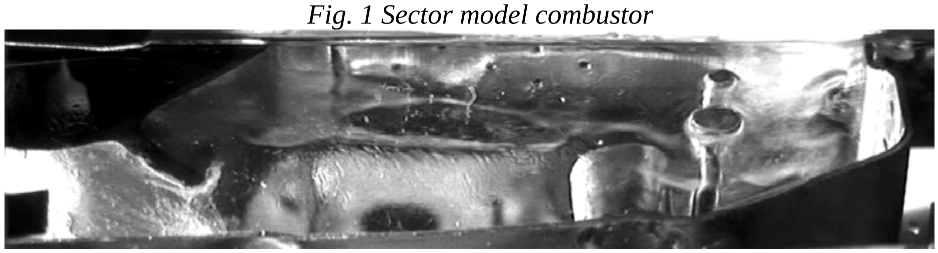
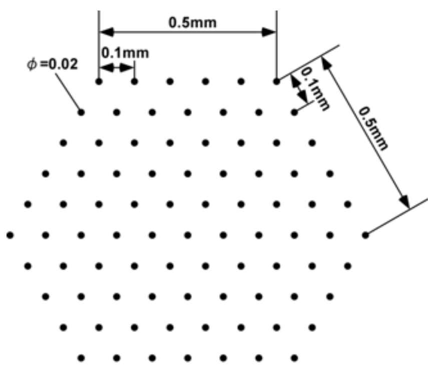


Fig. 2 Liquid fuel atomization in air flow in the sector model combustor(Air 16NLS, Pi=0.05MPa at atmospheric pressure)

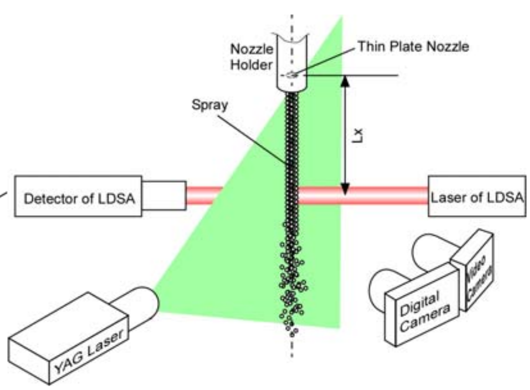
Figure 2 shows behavior of the liquid fuel in the high air flow in the combustion chamber. This condition corresponds to the operation with low power output. The liquid film on the outer combustor liner disintegrated near combustion chamber exit. However the liquid fuel does not disintegrate enough and attached on the observation window as liquid film around the flame holder. These phenomena means that the acceleration of the liquid atomization by the combustion air is not expected near the fuel injector. This seems consistent to the small ratio of the air flow from the front side. Therefore it is difficult to burn liquid fuel completely in this combustion chamber.

2. Spray of a thin plate nozzle

Figure 3 (a) shows the holes pattern of the 91-holes nozzle. This thin planar plate nickel nozzles are fabricated by electroforming process by Optnics Precision Co., ltd. Fluorine coating is processed on the both sides of the nozzle. The thickness of each nozzle is 0.02mm. The nozzle hole diameter ***Dn*** is 0.02mm. Therefore, L/D is 1.0. The edges of holes are sharp. Ion exchanged water is sprayed vertically downward into static atmospheric air from small holes of thin plate nozzle as shown in fig.1 (b). Injection pressure ***Pi*** is from 0.1 to 1.0MPa. The flow rate of this nozzle is almost same as that of 1 hole of the above mentioned fuel injector. The water jet was illuminated by light sheet of YAG laser. Photographs of disintegration phenomena of the water jets are taken by digital camera and laser sheet of YAG laser. Size of droplets in the spray is measured by laser diffraction method using LDSA1500A (Tohnichi computer applications co. ltd.). The velocities of the droplets are measured by PIV method (TSI Insight version 3) with a high-speed video camera (Photron FASTCAM-X1280PCI).



(a) Thin plate nozzle



(b) Setting of instruments

Fig. 3 Experimental apparatus

Figure 4 shows atomization phenomena with 91-hoels nozzle. Many liquid jets are observed. Most of jets are injected and several jets are tilted. Water jet already disintegrates into small droplets array where distance from the nozzle hole exit ***Lx*** is 6mm. The interval of the droplets array is almost constant at ***Lx***=10mm. The interval of the droplets array becomes larger and inconstant with ***Lx***. Number density of spray is seemed to decrease with increase of ***Lx*** from the photographs. Width of dense area becomes larger with increase of injection pressure ***Pi***.

Figure 5 shows ***SMD*** increases with ***Lx***. ***SMD*** decreases with increase of ***Pi***. The velocity of the droplet ***V*** is expressed in form ***Vc / V*** where the corrected velocities of injected liquid jet ***Vc*** are estimated at contraction area near nozzle exit. As shown in fig.6, ***Vc / V*** increases linearly with ***Lx / Dn***. That is the multiplicative inverse of ***V*** increases linearly with ***Lx***.

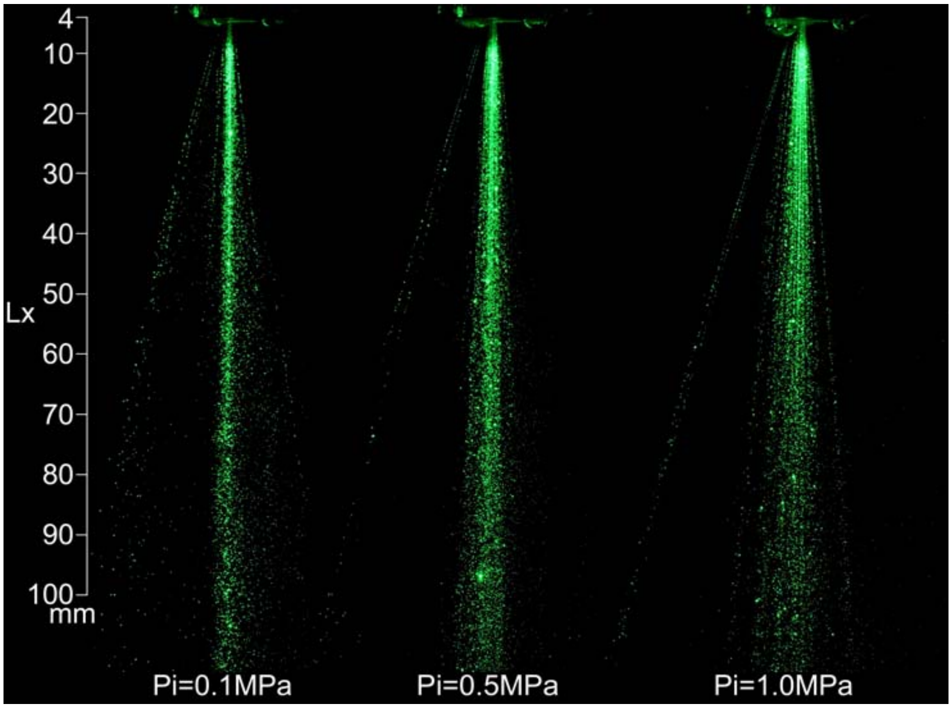


Fig.4 Spray with thin plate nozzle

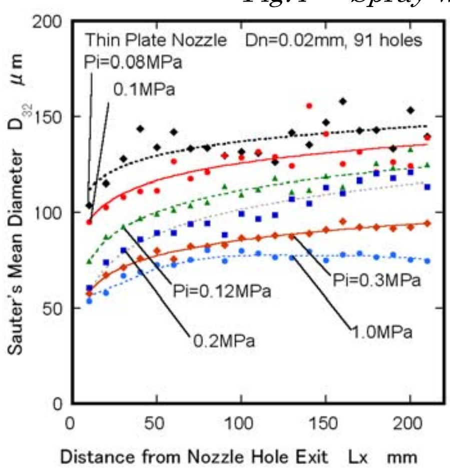


Fig. 5 Sauter mean diameter

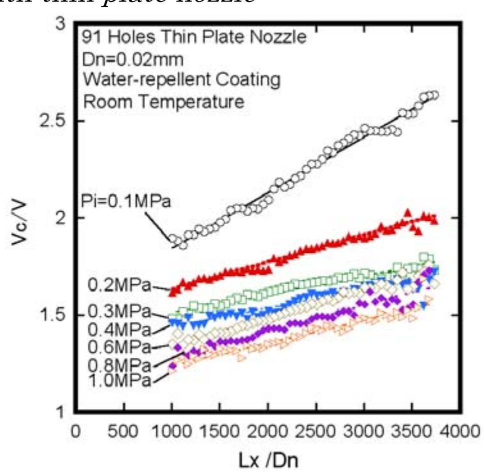


Fig. 6 The multiplicative inverse of velocity of spray

4. Conclusion

The atomization in the small gas turbine combustor is observed. The spray with the original liquid fuel injector was not fine enough. Spray with thin plate nozzle is observed and measured. The multiplicative inverse of ***V*** increases linearly with ***Lx***.

References

Iki, N., Ebara, T. and Shimizu, D., "Spray from a thin plate nozzle with multi holes", ICLASS2006, ICLASS06-044, 2006

Development of Network distributed Motion analysis Program for Particle Tracking: Evaluation of template size effects

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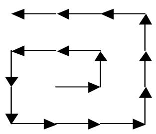
Motion analysis program for images acquired by high-speed videography was developed and tested so far. In the case of actual analysis scene, particle or object density can be very high. So some scheme of distributed computation will be required for practical use of this program. CORBA is adapted to perform cross-correlation calculation over networkly distributes computers. In this paper evaluation of template size effects in correlation calculation time was discussed.

1. INTRODUCTION

Original motion analysis program is called VMAP (Versatile Motion Analysis Program for Ultra high speed videography). Its features are as follows,

- ✓ Can read internal file format of movie files obtained by Shimadzu' ultra high-speed video system.
- ✓ Can handle general movie file such as AVI files in Windows.
- ✓ Position detection is carried out by cross-correlation calculation. And positions of object in each frame are estimated in sub-pixel resolution.
- ✓ More effective object tracking method is used. Spiral search. It is effective in most case of motion analysis.



- ✓ Rotational compensation: Try best match with rotating template partial image.
- ✓ Can handle still images. And successive still images can be combined to one AVI file using other utility program. Then this AVI file can be analyzed by theVMAP.
- ✓ Can write out AVI file with tracked marker in each frame.
- ✓ Operator can override automatic ROI detection easily. So manual analysis can be done.
- ✓ Can enhance each still image in movie file with histogram equalization technique.

Its correlation calculation can be very heavy load, when ROI is relatively big or search area is wide. In case of tracking many spray particles in images, it will be too much heavy for one host machine. So calculation load should be divided. ROI based division was used here. That is, tracking of single particle will be handled by single calculation server.

2. EXPERIMENTS

2.1 Target image and ROIS

Fig.1 show sample image and ROIs. ROI is Region of Interest, that surrounds bubbles. These images were recorded Photron's 1,000fs/s 512x512 high-spatial resolution type video camera. This time ROIs are limited to 8. In Fig.1 red-rects are ROIs and numbered 0 to 7. These will be tracked from frame 0 to 50. Division by these frames can be done, but division by ROIs is much easier to implement. So this strategy was adapted.

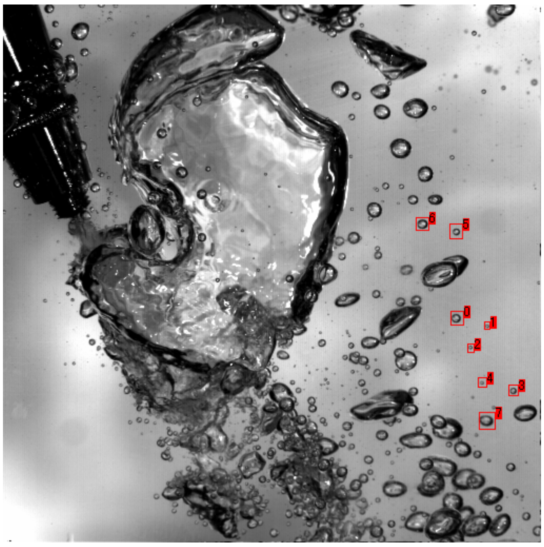


Fig. 1 Many ROIs in target

2.2 Single host machine processing

Original VMAP processed these particles in 30 seconds using AMD Athlon-1.2GHz (Memory 512MB) host machine. Because spiral search was utilized, it is not so slow. [1)] But this processing time could be very large if we track many particles in specific case. So load balancing is required. If we separate each ROI tracking, their processing times were, unit in seconds

ROI0	2.10583
ROI1	0.758535
ROI2	0.923261
ROI3	1.37359
ROI4	1.21834
ROI5	2.37732
ROI6	2.03116
ROI7	3.01389

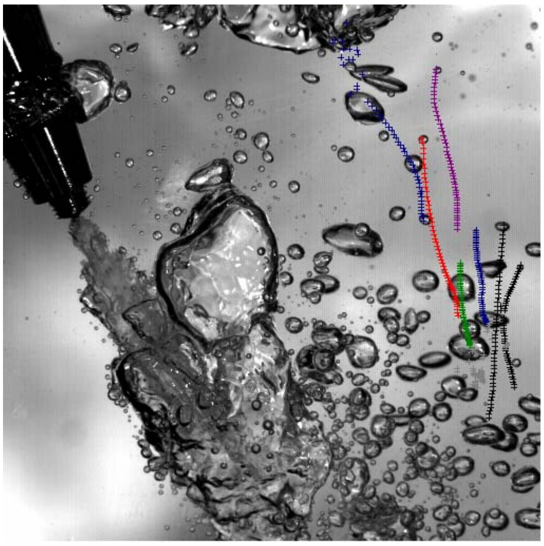
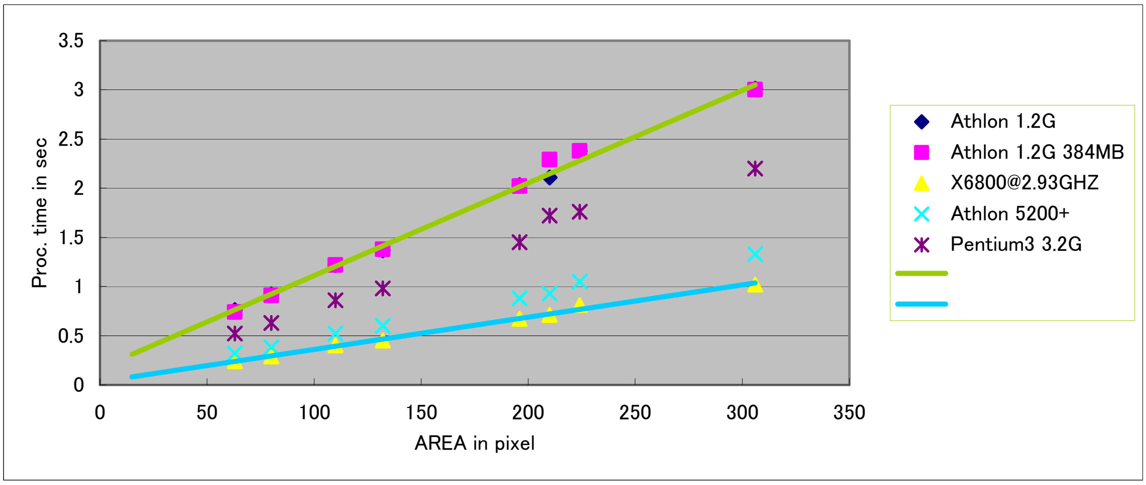


Fig. 2 Tracking results

and total proc time was 13.8019. This is much shorter than above mentioned 30secs. It is due to overhead of Visual Feedback of VMAP.

2.3 Effects of template size to processing time

Fig. 3 shows template size effects to processing time in several computers. Processing time can be evaluated roughly to be proportional to ROI size in pixel. That should be quadratic though. This linearity may be valid in these relatively small pixel regions. At larger pixel region, processing time should rise rapidly. And processing time can be reduced about to one-third by CPU and/or DISK power. But that is at most. We should reduce template size in pixel as much as we can. That is the key to minimize processing time.



2.4 Effects of template size to traceability

Fig. 4 shows three types of template size relative to original target. From left there are maximum size template, middle and minimum ones. Processing times were 3.35, 1.56 and 0.49secs. Just about processing time, smallest template is best, naturally. But tracing result was erratic.

3.35 1.56 0.49

Fig. 4 Various template sizes

Tracing results were shown in fig.5. In the case of minimum size template, erratic jumps in trace were observed. And this has no fidelity in trace especially in small x-position region. This size of template was not enough to identify the target bubble which is surrounded by this template. But how the optimum template size can be decided? Changing template shape is an option. We can use "flattened" template to reduce pixel size. This example is shown in fig.6. If we use template like this, we can reduce processing time while maintaining traceability. Typical trace results were identical to success traces in fig.5. But processing time was still 0.38secs.

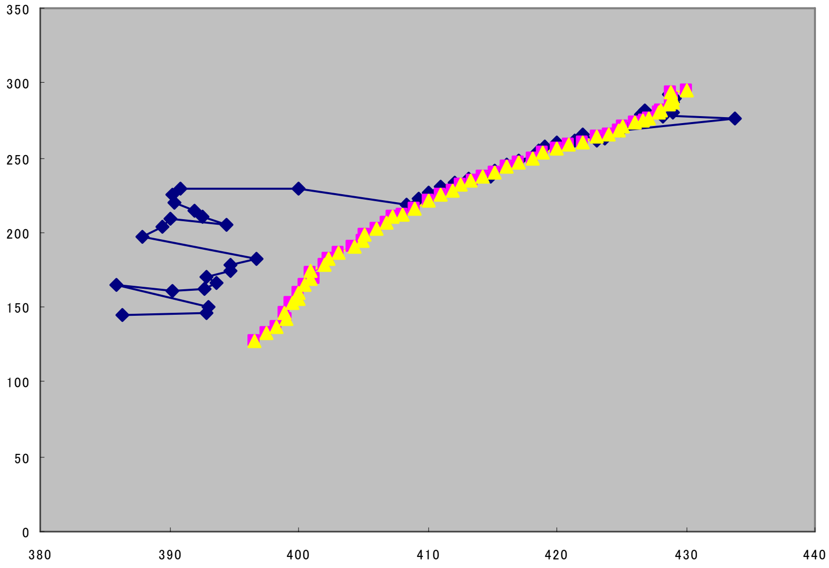


Fig.5 Traceability of various template sizes

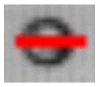


Fig.6 Flattened template

3. CONCLUSIONS

Prior to networkly distributed cross-correlation calculation, template size should be reduced. That was the key to processing time reduction. New strategy of template size and shape was introduced and evaluated to be effective in bubble trace experiments. Further study on decision of shape for template will be performed.

REFERENCES

[1] Yokoyama, N. Development of Versatile Motion Analysis Program for High-speed Videography Proceedings Twenty-Fifth Task Leader Meeting, 2003, 135-139.

[2] Steve, V. CORBA: Integrating Diverse Applications Within Distributed Heterogeneous Environments, *IEEE Communications Magazine*, Vol. 14, No. 2, February, 1997.