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PIV ANIMATION OF COOLING AIR MOTION WITHIN A HOME REFRIGERATOR

Chang-Jo YANG*, Jin-Young KIM*, Jeong-Hwan KIM*, Young-Ho LEE** and Kazuhiro TANAKA***

*Graduate School, Korea Maritime University
Dongsam-dong 1, Youngdo-ku, Pusan, 606-791, Korea

**Division of Mechanical & Information Engineering, Korea Maritime University
Dongsam-dong 1, Youngdo-ku, Pusan, 606-791, Korea

***Dept. of Mechanical System Engineering, Kyusyu Institute of Technology
680-4 Kawazu, Iizuka, Fukuoka 820-8502, Japan

ABSTRACT An experimental study was performed to investigate the flow characteristics of the freezer room and cold storage room in a home refrigerator. As multi-point simultaneous velocity acquisition, 2-D PIV system based on the two-frame gray level cross correlation method was adopted using PC image-grabber and simple video system. Image intensifier CCD camera to cope with the illumination problem was arranged for the accurate PIV measurement of the unsteady flow field. And all PIV procedures including animation jobs that give macroscopic and quantitative description of complex flow fields such as the temporally continuous distribution of the instant vectors, kinetic energy, vorticity and turbulent intensity were displayed in a real-time sense. As a result, both the quantitative analysis and qualitative visualization by artificial particle-injection to the outlet region of a cooling air supply fan revealed that very complicated turbulent behavior was dominant in the separate region and around obstacles existing along the cooling air passage.

Keywords: Home Refrigerator, Cooling Air, Freezer Room, Cold Storage Room, PIV(Particle Image Velocimetry), Image Intensifier CCD Camera, Cross-Correlation, Animation

1. INTRODUCTION

The refrigerator or freezer is one of the most important and biggest energy consuming appliances and there are several references that discuss the development of the refrigeration system [1]. The fundamental function of the home refrigerator is to implement effective control of the cooling capability within separate compartments where different room temperatures should be maintained. Among the several problems remaining yet for its high operating efficiency, appropriate supply of cold air within the refrigerating system must be considered first in terms of less flow losses, consequently lower power consumption and the least flow-induced noise [2]. The freezer room connected with an evaporator room shows very complicated flow phenomena and their understanding is quite essential in effective control of circulating cooling air. Oh et al. [3] studied the circulation phenomena of cold air by numerical study in a domestic refrigerator introducing the concept of the distributed pressure resistance. Choi et al. [4] visualized cold air distribution of the simple evaporator room. The energy efficiency of the refrigerator is affected by the distribution of cooling air, which depends on the position and size of the cold air duct. In particular, optimized duct system is considered to be the most essential technology of the refrigerator design.

The present study is focused on the behavior of the

cooling air motion which passes through slots into the freezer room and cold storage room at the home refrigerator. The cold air is a little rectified due to the regular arrangement of cooling coils and attached fins in the evaporator room. But the stable flow is abruptly disturbed by the obstacles existing at the inlet regions and shows typical separation characteristics at the two upper corners. These flows inevitably make large friction losses and concurrent non-uniformity of the approaching velocity toward the fan renders unsatisfactory effects on the performance, which may usually cause air-borne noise problem. Therefore, quantitative analysis will be helpful to suggest optimal design of the configuration of cold air slot to reduce the friction losses. And it is also helpful to obtain a solution to reduce fan noise which must be avoided particularly for the indoor uses. For the experiment, a prototype of the evaporator room together with shelf and ice holders were made precisely. Velocity measurements were carried out by the two-dimensional PIV system [5]. Instantaneous and time-mean velocity distributions were discussed at two representative regions.

As results, active three-dimensionality of the complicated turbulent flow and non-uniformity are reported. And, animation results in full colors to show the temporally continuous distribution of the instant vectors, turbulent intensity, kinetic energy and vorticity are displayed by simple PC mouse clicks. Unsteady streaklines, trajectories

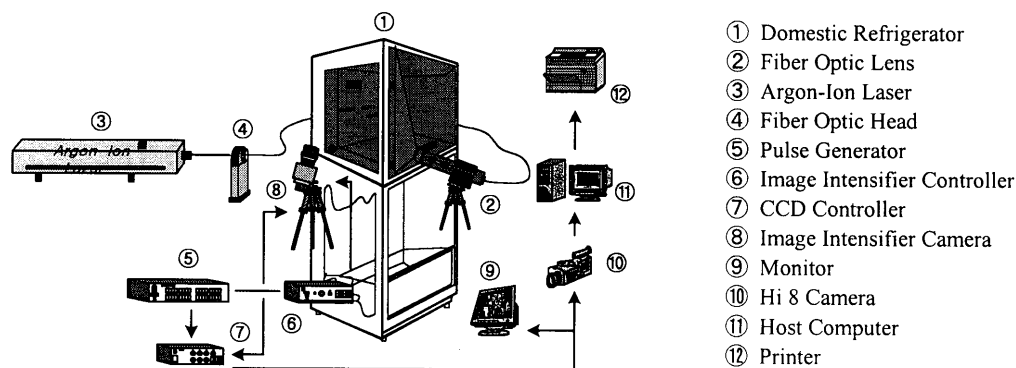


Fig. 1 Schematic arrangement of PIV system

and streamlines from any starting points are also represented cinematically from the animation routines and they give deeper insight of the cooling air motion dynamics.

2. EXPERIMENTATION

Fig. 1 shows the schematic arrangement used in the present PIV experimental study. A complete configuration of the commercial refrigerator (500 liter) is furnished by the proto-type experimental apparatus. Its evaporator fan is propeller-typed and rotates at 2,150 rpm constantly. A shelf lies halfway between upper and lower compartment and two ice holders are set up under the shelf in the freezer room. The freezer room (153 liter) and the cold storage room (387 liter) have five slots on the blowing backplate and one return duct at a bottom. Two cooling air slots are inclined 15° toward both wall side in the upper region and three slots are placed on the blowing plate in the lower part and return duct sets up at bottom of the freezer room. Transparent acryl-made window is fixed to the refrigerator casing for the easy access of the illumination via a fiber optic line and a cylindrical lens assembly to the measuring region. Photo 1 shows a view of the real experimental equipment. For illuminating flow field, 5 W water-cooled Argon-Ion laser (Coherent Co.) with a fiber optic assembly generates a two-dimensional thin sheet light of about 2 mm thickness. Fig. 2 represents a measuring region in the geometric configuration. Two measuring regions of 400 mm $\times$ 320 mm (freezer room), 497 mm $\times$ 310 mm (cold storage room) are shown. Circulating air formed at the two separate refrigerator compartment is collected together and turned downward at bottom of the freezer room and its heat is subtracted while passing through the evaporator. Rectangular holes are arranged beneath the evaporator room so that the role of collecting ducts connected to the vegetable room is maintained in the same conditions. Low temperature air (10°C) was used as the working fluid. For visualization, tracer particles are injected into the flow field. Tracer particle used in this experiment is 551DE Expancel and its average diameter is about $30\text{--}50\ \mu\text{m}$. High-accuracy CCD camera (B&W, SONY, XC77RR), and image intensifier gated CCD camera (HAMAMATSU Co., C 4273) were adopted to capture the flow field. Its frame image is consecutively recorded on a Hi-8 mm camcorder

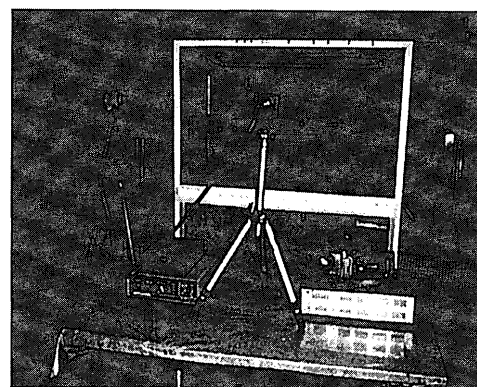
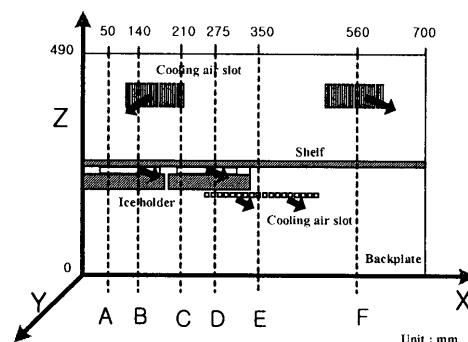
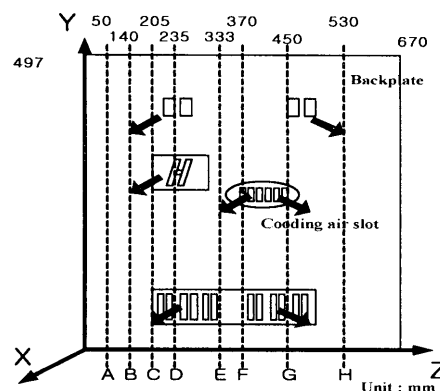


Photo 1 View of freezer room



(a) Freezer room



(b) Cold storage room

Fig. 2 Definition of measuring region

for the later replay of the original image. Obtained images are interlaced on each frame at every 1/30 second and it is field-integrated. The single frame image is divided into two fields (odd and even) with a time separation of one field, that is 1/60 second (NTSC) and they are used as the first frame (odd) and the second frame (even) for the cross correlation identification by direct calculation. To cope with the illumination problem, image intensifier CCD camera synchronized with a pulse generator was arranged for the accurate PIV measurement. Flow images recorded on the Hi-8mm camcorder tape are replayed and their consecutive images are usually transferred into the personal computer RAM memory space by a built-in image grabber (DT3155, 640x480pixel, 8bit) slotted into a PC board and they are finally digitized into 256 gray level images. Table 1 shows the experimental conditions.

Table 1 Experimental condition

Item	Specification
Image Board	DT3155 (640×480 Pixel)
Light Source	5 W Argon-Ion Laser
Particle	Expancel 551DE (30 μm × 50 μm)
Density	42 ± 4 kg/m ³
Sheet Light	Filber Optic Lens
Working Fluid	Air (10°C)
Host Computer	Pentium PC (CPU:333 MHz)
Calculation Time	30 sec/frame
Image Input	Image Intensifier CCD Camera
Number of Data for Time-mean	150 Frames
Identification	Two-Frame Gray-level Cross Correlation Algorithm
Vector Error Rate	Under 2%

3. PIV IDENTIFICATION

The procedure to obtain the individual 150 frame images for the pre-processing is first required. Flow images recorded by the camcorder are transferred onto the image grabber through the host PC. The grabbed frame images are digitized into 256 gray levels in integer values and these values are transformed into ASCII files for image processing. The PIV software, CACTUS 2000 was used for the pre-processing. Among the pre-processing, the most important thing is to eliminate the noise components which affect the reliability for the resulted velocity vectors. Background elimination is an effective method to reduce the noise and its main target is to minimize the useless image regions by eliminating the fixed image parts except the moving particle images from the original image. In this study, the background image is obtained by averaging about 150 consecutive images and this image is subtracted from the original analyzed images. This method is very powerful method to reduce noises and erroneous vectors. After the above process, the obtained images are rotated digitally to keep the measuring region and CCD plate parallel in horizontal and vertical direction. Particle identification for the velocity vector extraction is based on the two-frame cross correlation method in which the coordinate indicating the maximum coefficient is assumed to be the vector terminal point. The searching area is the maximum

allowable distance between the grid point of the first image and the terminal point of the second image. Eq. (1) is a mathematical expression to calculate the cross correlation coefficients.

$$C_{fg} = \frac{\sum_{i=1}^{n^2} (f_i - \bar{f})(g_i - \bar{g})}{\sqrt{\sum_{i=1}^{n^2} (f_i - \bar{f})^2 \sum_{i=1}^{n^2} (g_i - \bar{g})^2}} \quad (1)$$

Here, f_i and g_i mean gray levels of the pixels within the correlation region and upper bar $\bar{}$ indicates the average value of the gray levels of the pixels within the correlation region. And n^2 means the pixel number of the correlation area. Reliability of vectors and calculation are mainly determined by setting both CAS (correlation area size) and SAR (searching area radius). Shorter radius, for example, generates a lot of erroneous vectors and limits measurement dynamic range. And longer radius accompanies also increased outliers with more CPU load. In this study, the calculating time on the PC (Pentium 333MHz) was about 0.5 - 1 minutes for every frame. The grid size for the velocity vector extraction was given to 50×50. The size of the correlation area was set to 40×40 pixels for all cases and the radius for searching area was 8-10 pixels. A sub-pixel interpolation method for searching the maximum coefficients was adopted [6]. To obtain time-mean velocity vectors, 150 instantaneous velocity vectors of the consecutive image frames were overlapped. As a step for the post processing, error removing, reallocation in grid and conversion of pixel to real unit procedures were performed. The divergence criterion satisfying the continuity equation was adopted in error removal procedure. Error probability by the automated procedure was averaged less than 2 %.

4. RESULT AND DISCUSSION

The aim of the present study is to visualize the cooling air motion within the freezer room and cold storage room of a commercial refrigerator by the PIV application with I. I. CCD camera and to investigate flow properties of various sections. The results of PIV application to the freezer room are shown in Fig. 3(a) - Fig. 3(f), which are instantaneous velocity vectors distribution. Velocity vectors in these figures are normalized by the representative velocity, 20 cm/sec. The overall pattern is characterized by a clockwise movement of fairly uniform outcoming flow from the cold air slots. Fig. 3(a) is located 50 mm away from the origin coordinate, and cooling air is not discharged directly. But cooling air of Fig. 3(b) has an influence on the flow field. In the vicinity of cold air slot inclined 15° toward both wall side horizontally, a strong primary vortex exists. And cold air circulates around the whole region of the freezer room, which is induced into the return duct located downward. Fig. 3(c), Fig. 3(d) and Fig. 3(e) also make up circulation regions. Especially, a part of the cooling air flows into a return duct in the lower compartment. Fig. 4(a) - Fig. 4(f) represented time-mean velocity distribution which overlapped 150 instantaneous frames. Time-mean velocity distribution of Fig. 4(a) indicates a representative

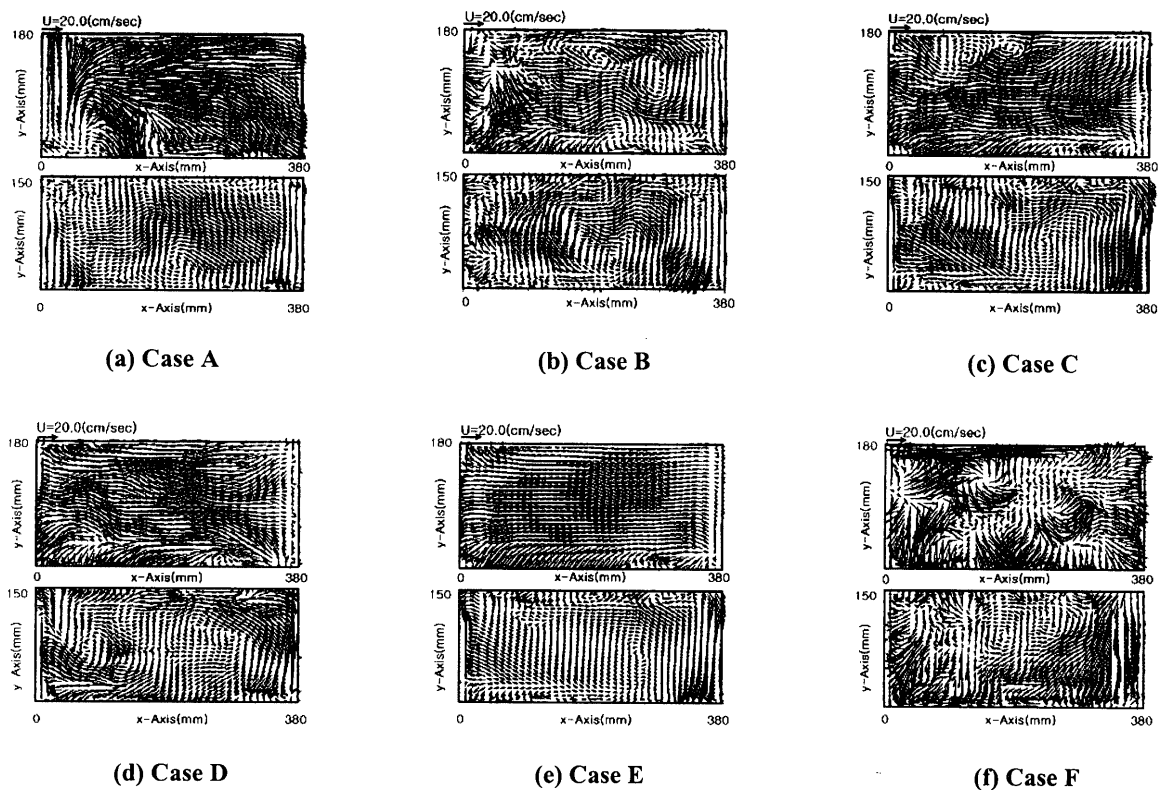


Fig. 3 Instantaneous velocity distribution in the freezer room

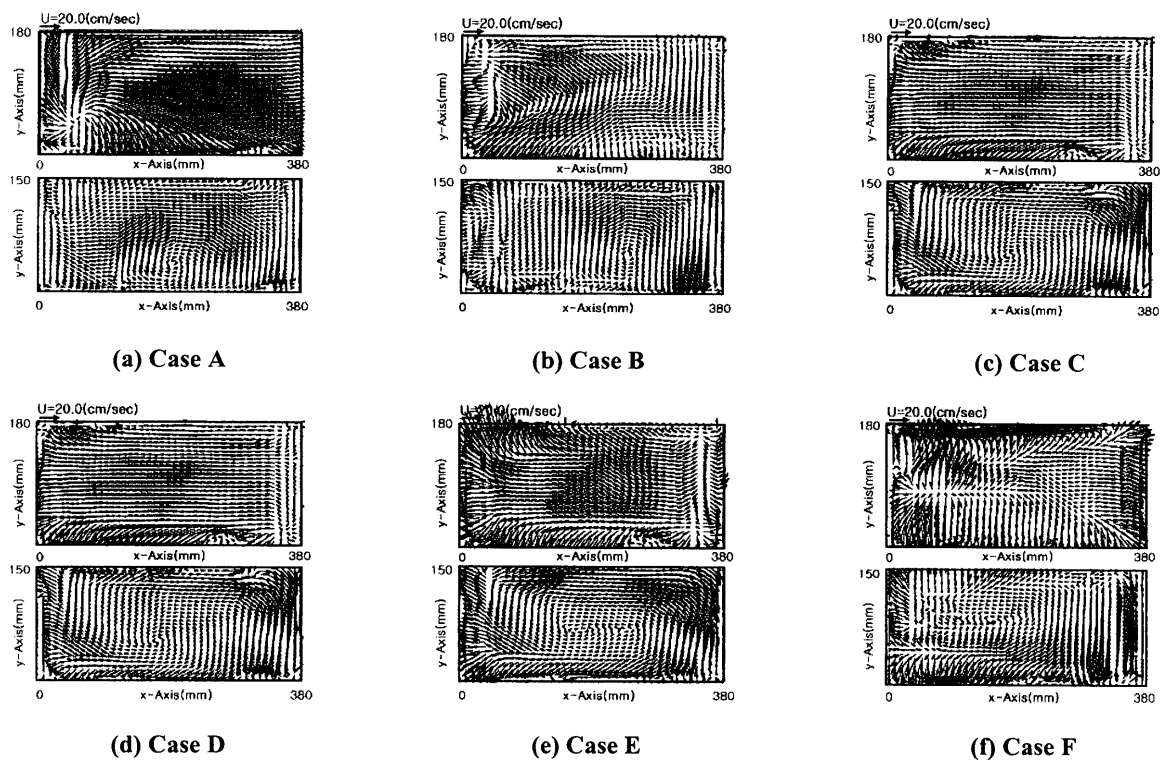


Fig. 4 Time-mean velocity distribution in the freezer room

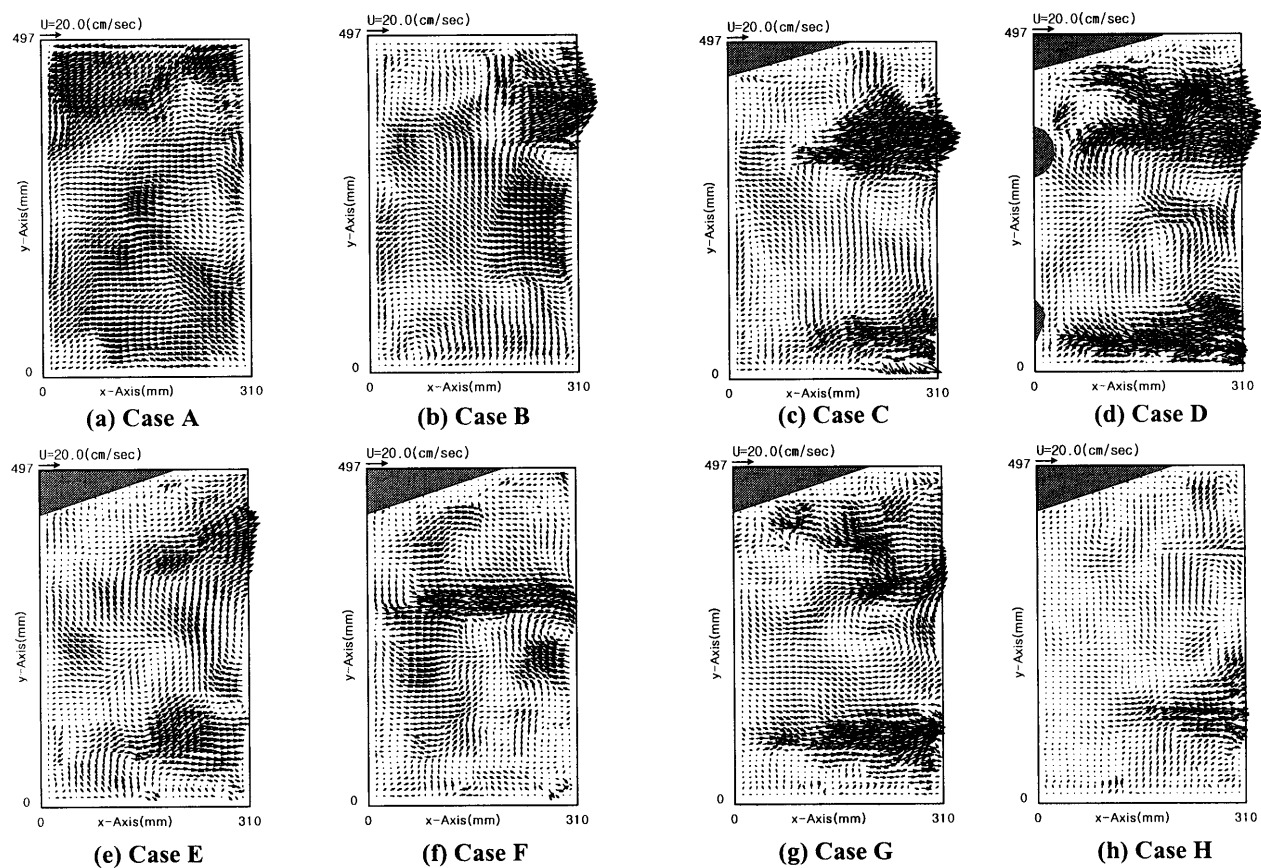


Fig. 5 Instantaneous velocity distribution in the cold storage room

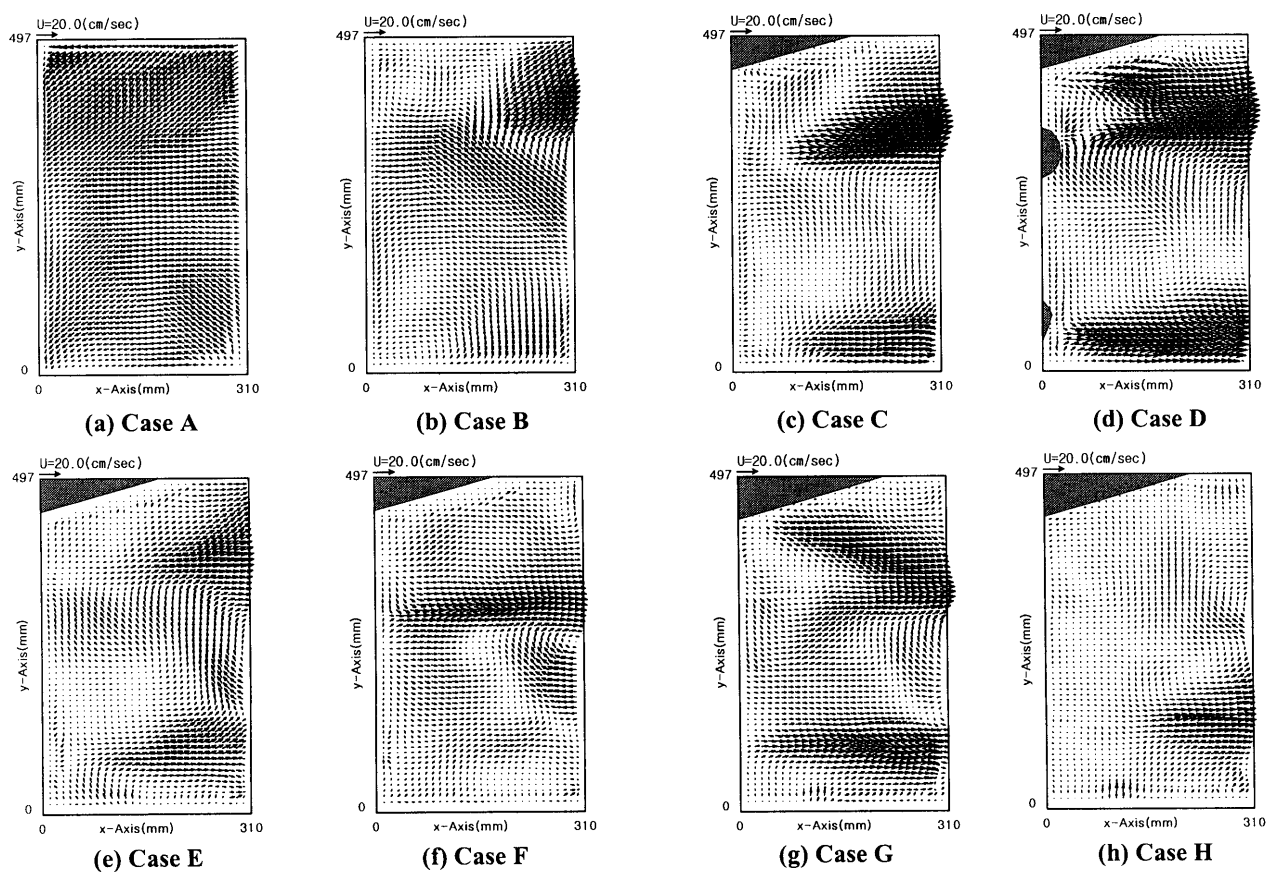


Fig. 6 Time-meaning velocity distribution in the cold storage room

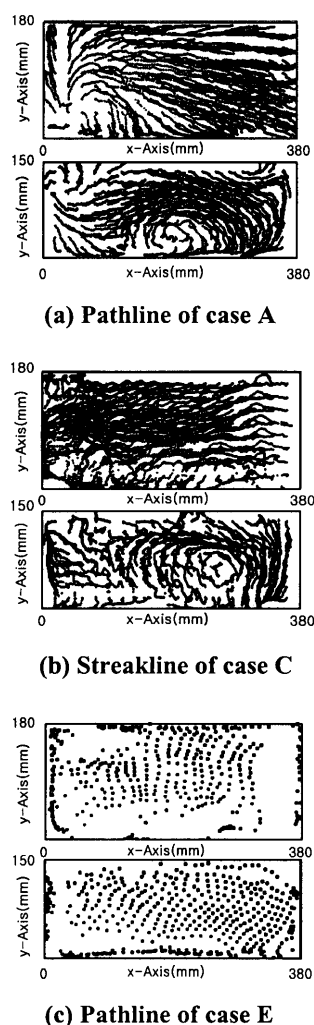


Fig. 7 Animation of flow patterns in freezer

pattern. Fig. 4(b) indicates that time average effect results in any kind of organized flow structure. Periodic vortex from the cold air slot is intermittent and quite three-dimensional due to the spanwise wall effect. And unstable irregular velocity vectors around the ice holders are noticed. Especially, Fig. 4(c) compared with Fig. 4(a) and Fig. 4(f) showed much stronger primary vortex and it is distinguished between upper and lower region due to the crosswise strong vortex as in instantaneous velocity vectors distribution. In Fig. 4(d), the flow is more fluctuated contrary to Fig. 4(e) mainly due to the unsymmetrical existence of the cold air slot on blowing backplate. Small fluctuating eddies are developing throughout the whole field, which is responsible for the turbulent generation and consequent large friction region. Non-uniform velocity pattern also exists around the ice holders. Results of the cold storage room also are shown in Fig. 5 and Fig. 6 (x-y section, A-H case). Velocity distribution of this compartment becomes also complicating compared to that of the freezer room. In case D and G, higher velocity peaks appearing adjacent to the right wall are due to the existence of the return duct beneath the freezer room. It means that overlapping of the time-varying fluctuation of various vortices characterizes the development of dominant large scale flow patterns in this region. These results suggest that

it is very important to consider the instantaneous and time-mean velocity distribution mentioned above at the design of the refrigerator. Consequently, with the control of the discharge cooling air and slot angle at the each section, distribution of cooling air will be more effective within the refrigerator. Fig. 7(a) - Fig. 7(c) are animation of flow patterns in a freezer room and they indicate pathlines and streaklines which are helpful to understanding the macroscopic flow pattern in measuring regions. Separation phenomena are also found and apparently large scale vortex or wake is developing. These experimental results reveal that the flow field within the refrigerator room is quite unstable and turbulent fluctuation is dominant due to the separation at corner walls and obstacles such as shelf and ice holders.

5. CONCLUSIONS

An experimental approach to investigate the flow characteristics within a freezer room and a cold storage room of single commercial indoor refrigerator was made by visualization and PIV measurement. It is revealed that flow patterns are very unstable and turbulent fluctuation becomes remarkable throughout the whole flow field due to the geometric configuration such as cooling air slots, corner walls and ice holders. Non-uniformity of the velocity distribution at the cooling air outlet region is also strong and related flow-induced noise is predicted. And animation results in full colors to show the temporally continuous distribution of the instant vectors, turbulent intensity, kinetic energy and vorticity are displayed by simple PC mouse clicks. And unsteady streaklines, trajectories and streamlines from any starting points are also represented cinematically from the animation routines and they give deeper insight of the cooling air motion dynamics.

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