WATER-DROPPING AERODYNAMICS FOR FIRE-FIGHTING AMPHIBIAN

Takeshi ITO*, Hiroyuki KATO*, Yushi GODA†, Shinji TAGAWA†, Eiichi NEGISHI‡
*** Japan Aerospace Exploration Agency (JAXA), †ShinMaywa Industries Ltd., ‡Japan Aircraft Development Corporation (JADC)**

***Keywords*: Fire-fighting, Amphibian, Low-speed wind tunnel, Two-phase flow.**

Abstract

When water is dropped from the Fire-Fighting Amphibian, a large amount of water splits up into fine particles and spreads in all directions affected by aerodynamics of water. It is essential to establish analysis and evaluation techniques of water-dropping aerodynamics for efficient fire-fighting. We investigated the behavior of water that was dropped from fuselage models of a Fire-Fighting Amphibian in 6.5 m x 5.5 m Low-speed Wind Tunnel in JAXA. The whole behavior of water by high-speed camera, the velocity of droplets by PIV, size of droplets by shadow imaging, and the spreading pattern data on the ground were obtained and discussed through the wind tunnel testing. CFD calculation was also successfully conducted and was able to be validated. These results will be helpful to determine how to drop water from an amphibian to extinguish a fire more efficiently.

1 Introduction

Recently, large scale fire disasters have been increasing due to the forest fire by global warming, large earthquakes, and plant accidents, and those have seriously damaged personnel and infrastructures. Especially, increase of forest fire which might be related to global warming has become serious problems all over the world. The Fourth Assessment Report[1] of Intergovernmental Panel on Climate Change (IPCC) stated about effect of climate change by global warming which is known to alter the likelihood of increased wildfire sizes and frequencies. Extent of those wildfires had sometimes become very large such as the forest fire at California, U.S in 2008 and Melbourne, Australia in 2009, and frequency of the wildfire is also increasing in Mediterranean area. It was very difficult to extinguish or prevent fire spreading by the ground forces safely, because those methods could not approach directly to the fire safely, whereas, aerial fire-fighting might be effective. Especially, aerial fire-fighting using amphibians is more efficient because a fire-fighting amphibian can carry a large amount of water and easily take water from lakes or rivers by landing on the water and scooping.

However, aerial fire-fighting is very specialized and difficult technique because the water-drop to the fire from aircraft can be affected by the air speed, altitude, mass and rate of water, and so on. Therefore, it is important to investigate and understand phenomena of the water-drop, and we aim to establish efficient extinguishing fire-fighting technique. JAXA, ShinMaywa Industries, Ltd., and JADC have been conducting joint technical research to develop a fire-fighting amphibian, as shown in Figure 1. In this report, we investigate water-dropping phenomena through wind tunnel testing using advanced measurement techniques, and experimental data will be shown and discussed in order to enable efficient aerial fire-fighting.

Fig. 1. Image of fire-fighting amphibian

2 Efficient water-dropping technique

2.1 Fire-Fighting Amphibian

It is important to control behavior of the dropped water to extinguish by aerial fire-fighting. To realize efficient extinguishment by using limited amount of water from the airplane, adequate and minimum water only has to be scattered to the accurate area of fire. The more accurate and adequate water-dropping, the more efficiently and widely airplane can extinguish fire. For example, as shown in reference 2, guide line of minimum amount water for extinguishment indicates that 1.6 liter/m^2 of foam is needed to extinguish and 0.8 liter/m^2 of detergent is needed to prevention of fire. Therefore, optimal water-dropping has to be conducted not only to accurate area of fire but also with the minimum and uniform amount of water.

When water is dropped from airplane, a large amount of water splits up into fine particles and spreads in all directions. The size of this water particle, the distribution pattern, and the amount of water that reaches the ground, determine effectiveness of the fire fighting. These factors are greatly affected by velocity and altitude of the aircraft. Consequently, it is essential to determine the relationship between distribution patterns and flight conditions and establish analysis and evaluation techniques for efficient fire-fighting. Although some flight tests were carried out[3, 4] and numerical analysis tried to be validated,[5] more accurate investigations under the known flow condition are considered to be still important. For this reason, controlled known flow in large-scale wind tunnel is one of the desirable experimental environments to investigate the behavior of water and make clear phenomena of water from mass to droplet. These data can validate CFD analysis code, and it will predict actual and various operations of fire-fighting flight.

Physically, at first mass of water shows free-surface flow. And next, it is separated into some volumes and subdivided into droplet. These phenomena can be understood as two-phase flow and liquid atomization which are strongly affected by surface tension in the mixed fluid. Those phenomena are very complicated, and scale of the phenomena exists not only in large size of water mass based on airframe length but also in very small size and huge number of particles based on atomized droplet. Therefore, both investigation and analysis are very difficult. Especially, it is difficult to obtain accurate and various kinds of data from flight tests because of the actual flight condition including unfavorable uniformity and unknown disturbance, and limitation measurement method.

Here, controlled flow condition and sophisticated measurement setup were applied to investigate these complicated phenomena of water and air-flow by using large-scale wind tunnel facility. Difference of aircraft speed and altitude was able to be demonstrated using wind speed of uniform flow and height from floor in the wind tunnel. Behavior of the water, ground spreading pattern, speed and size of droplet were measured by using high-speed camera, precipitation measurement, PIV method, and so on. On the other hand, CFD analysis based on Volume Of Fluid (VOF) and Discrete Particle Method (DPM) was applied to predict those phenomena. Calculated results were validated by using experimental data and it should become prediction tools to find efficient aerial fire-fighting technique.

2.2 6.5m x 5.5m Low-speed Wind Tunnel

In JAXA, 6.5m x 5.5m large-scale Low-speed Wind Tunnel (LWT1)[6] as shown in Fig. 2 has been used to obtain low-speed aerodynamic performance of aircraft and flow field around aircraft during take-off and landing, and low speed flight condition. The maximum wind speed is 70 m/s at the test section. This tunnel is operated in atmospheric pressure condition. The test section is the largest in Japan as low speed wind tunnel for aircraft. The length of the closed circuit is 200 m at total, and the long leg and short leg is 75 m and 25 m, respectively. Since the completion in 1965, many wind tunnel tests, such as vertical and short takeoff and landing (V/STOL) aircraft, low-speed aerodynamic research and development, conventional aircraft, and space vehicles, have been conducted. This wind tunnel has two types of support system for experimental model, which are a strut support with pyramid-type force balance and a sting support with internal force balance. Sometimes half-span models with external force balance are used without support system. Aerodynamic force and pressure have been measured to obtain performance and characteristics of those models, but also some flow visualization techniques such as oil flow, china clay, and tuft are also able to be used.

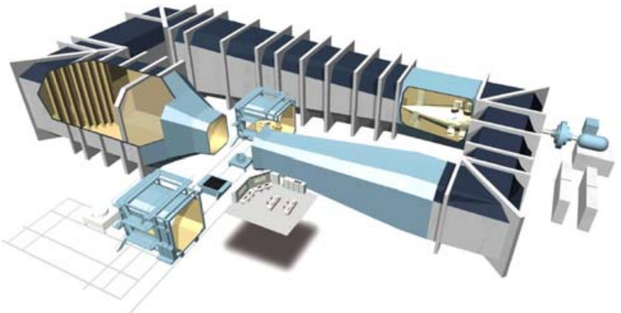

Fig. 2. 6.5m x 5.5m Low-speed Wind Tunnel in JAXA (LWT1)

2.3 Experimental setup

Testing model in the wind tunnel is a fuselage model of a Fire-fighting Amphibian as shown in Fig. 3. This amphibian is assumed to be able to carry 15 ton of water. The concept came from larger amount of water than 6 ton of water on CL-415[7] for the efficient fire-fighting. Scale of models are 1/8 and 1/16, and the length are 3.7 m and 1.8 m, respectively. Shape of cross section of the fuselage is not circle because of a performance capable of taking off and landing on water in the open sea. It has two doors in both sides on lower surface of the fuselage to drop water from a tank. The doors are rectangular shape and open to lateral direction. The door can be opened fast, and water start to be dropped in very short duration. The volume of the tank are 34 liter and 4.2 liter for 1/8 and 1/16 model, respectively, which relate to 15 ton for 1/1 airplane.

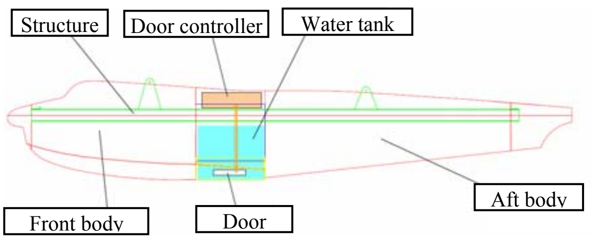

Fig. 3a. Wind tunnel testing model

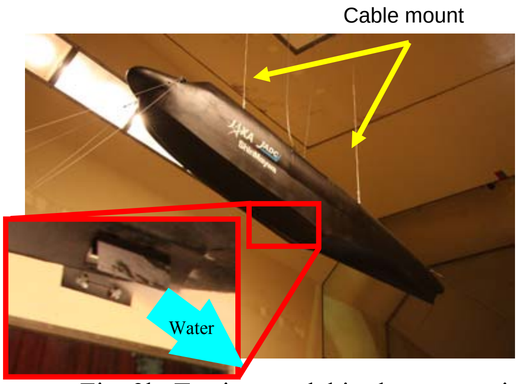

Fig. 3b. Testing model in the test section

Table 1. Dimension of the model

Scale	Length	Vol. of tank	Door
1/8	3.7m	34 liter	240mm×80mm
1/16	1.8m	4.2 liter	120mm×40mm

The rate of water-dropping was investigated by measuring time history of water level in the tank as shown in Fig. 4. The plot shows actual airplane scale by using time on x-axis divided by square root of the model scale to match Froude number and volume on y-axis divided by cubic of the scale. The full-scale of this plot (2 sec) corresponds to about 0.7 sec and 0.5 sec of 1/8 model and 1/16 model, respectively. At first the water level started decrease slowly until 0.3 sec during transient phase by the door opening. After maximum rate of water-dropping, the rate decreased because of decrease of water pressure due to decrease of the volume of the water in the tank. It did not show very large

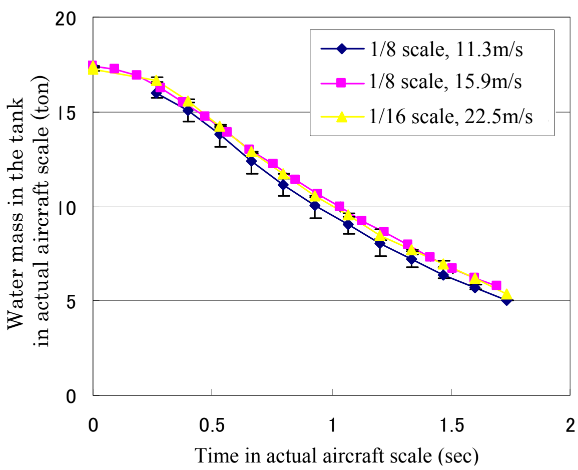

Fig. 4. Time history of volume of water

difference in the scale and wind speed, so size and shape of door and gravity were considered to be dominant.
Testing conditions of water dropping are shown in Table 2. Main parameters of testing were wind speed, size of model and height of model. Actual and minimum flight speed and height of water-drop will be 90 knots (45m/s) and 100 ft (30m). Scaled conditions and parametric studies were planned for the wind tunnel testing. Froude number for global behavior of falling water by gravity is one of the important non-dimensionalized parameter. Moreover, as a more important non-dimensionalized parameter, Weber number which determines effect of surface tension is also considered to affect shape of volume and subdivision of water mass.
Using these parameter, wind tunnel tests were conducted to investigate the behavior of water dropped from the model by applying a high-speed camera, PIV (Particle Image Velocimetry) technique, and measurement of water distribution on the ground, with respect to various wind velocities and flight altitudes. CFD calculations are validated by these experimental data, and we establish an evaluation method of water-dropping aerodynamics for effective aerial fire-fighting method.

Table 2. Testing Conditions

Flight		Scale	Wind tunnel				
V	H		V	H	Fr	We	Case
90 kts	30m	1/8	15.9m/s	3.75m	18	353	(a)
		1/16	11.3m/s	1.88m		88	(b)
	60m			3.75m			
	90m			5.63m			
180	30m		22.5m/s	1.88m	35	353	(c)

3 Wind tunnel experiment results

3.1 Behavior of dropped water in the wind

The behavior of water dropped from the model in the air flow of the wind tunnel was observed with a normal camera (Fig. 5) and high-speed camera (Fig. 6). A large amount of water was split up into particles by the air flow while going downstream and changed into fine mists. The behavior of water depends on the wind velocity, gravity, surface tension and the scale of the model, which means Froude number and Weber number are important parameters, as stated later. Here, these phenomena will be globally understood by some photographs.
In the uniform air-flow at the test section, water was dropped down and flew backward by wind. And it also spread symmetrically to the lateral direction due to the shape of door, as shown in Fig. 5. On the downstream area of the model, water was subdivided to droplet or mist, and flow mainly affected. On the other hand, on lower area of the model, water remained the volume shape and effect of gravity was strong.
Decreasing rate of water changed because of the change of remained volume in the tank. At first, a little water was only dropped, but then, maximum mass flow was obtained, and it decreased as decreasing of volume in the tank. At maximum condition of the second picture, water mist was denser due to the high rate of water-drop than later condition in which the water became smaller particle.
Next, photographs with high-speed camera are utilized to investigate of detailed behavior of water. As shown in Fig. 6, the big volume of water was divided to some parts of droplet, and became small mists at downstream area. Here,

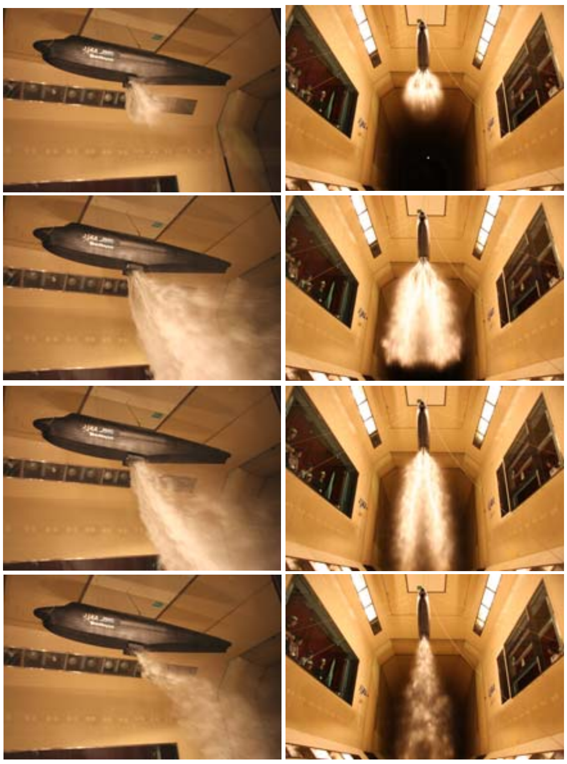

Fig. 5. Dropped water behavior. 1/8 model,15.9m/s

different scale models of 1/8 and 1/16 were shown in same size at these photographs by resizing them. In the first line and the second line of photographs ([a] and [b]), photographs in the same column show the same time in the same Froude number. Resultantly, global configurations of water agreed very much in same time in the area of these photographs. On the other hand, microscopic phenomena were very different between the different model scales. The smaller size of droplet in large scale model which means larger Weber number was shown. Larger Weber number means a condition of weak surface tension. Droplets should become small, so these results are reasonable. This difference of droplets might lead to difference of extension of water at downstream area.

On the other hand, the third line of the photographs shows different Froude number, which means different wind speed. Naturally, the global configuration of water dropping was very different from other photographs. However, Weber numbers of these photographs in line [c] and [a] are same. Actually, both of size of droplets are very similar each other. These results show that Weber number was dominant to size of droplet in the water-dropping behavior, and decided microscopic phenomena.

From these results, it was found that Froude number is related to macroscopic phenomena dominated by gravity and aerodynamic force and Weber number is related to microscopic phenomena dominated by surface tension. Water-dropping aerodynamics can be made clear and controlled to realize efficient extinguishment by considering these parameters of scale of model, wind speed, height of model, gravity and surface tension.

Reynolds number might also affect these phenomena. Actually, the difference of Reynolds number was $2\sqrt{2}$ between [a] and [b]. Especially, during separation of volume of water, shear stress between air-flow and surface of water must affect the separation of water at the surface. Here, viscous effect in lower Reynolds number can make separation easy by strong shear stress of air-flow, but strong viscosity of water prevent from separation. Therefore, Separation phenomenon can not be affected very much by the difference of Reynolds number, but this is also important topic to be investigated in future. Here, Weber number is considered to be the most important parameter of microscopic phenomena in water-dropping aerodynamics.

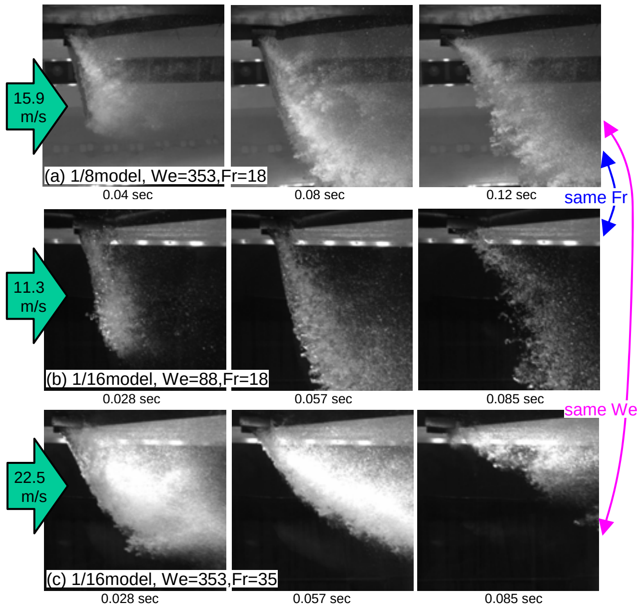

Fig. 6. Effect of Fr and We number on High-speed camera photographs

3.2 PIV measurement of droplet velocity[8]

PIV (Particle Image Velocimetry) technique is useful and powerful method to obtain detailed and quantitative data on flow field survey. In JAXA, this non-intrusive measurement technique has been developed for large-scale wind tunnel tests.[9] Normally, Oil mist is inserted to the flow as tracers and strong laser

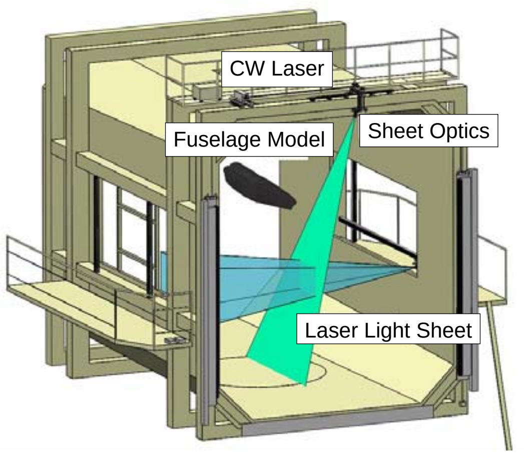

Fig. 7. PIV setting of laser and camera for LWT1

light, which is sometimes double pulse laser, irradiates the tracers. High-resolution CCD camera takes pictures of tracers and velocity of flow was evaluated from the movement of tracer of particle of oil. However, in this measurement, oil mist was not needed and water droplet itself was substituted for the oil mist. We applied continuous laser light sheet as shown in Fig. 7, and captured the image of a droplet with a high-speed camera. Velocity of the droplet was determined by trace of the same droplet from two continuous frames of the image.

The laser light system was Spectra-Physics, Millennia II (532nm of wave length, 2W of power). Laser beam from laser head was expanded to laser sheet by optical system and irradiate the measurement area. High speed camera took pictures for 4 sec from 0.5-sec before door opening with 2000 fps and exposure time was 400 micro sec. The normal area of PIV photographs was not large, so the model was moved vertically (changed the height) to measure the droplet in wide area. In a global image by normal camera in PIV measurement as shown in Fig. 8 Left, the droplets were illuminated by the laser, and radiated strong scattered light. Figure 8 Right shows a measurement image of high-speed camera in PIV measurement. The position and movement of droplets are recorded on the image. Image of droplets was almost circle shape as same as oil tracers in normal PIV measurement. However, density of droplets was comparably lower and it was difficult to calculate velocity vector in normal PIV processing. For this reason, PIV sum of correlation method in the processing[10] was applied in order to erroneous vector due to low particle density. Applying this method to this experiment, velocity vectors of droplets even in low density were able to be obtained. The number for averaging was 100 frames (=50msec). In Fig. 9, time histories of velocity of droplet and evaluation of repeatability are shown. The beginning and end of the droplet showed higher velocity, and also the droplets in lower position showed higher velocity. The repeatability was considerably good except of the beginning period because of the lower density of droplet which might lead to bad

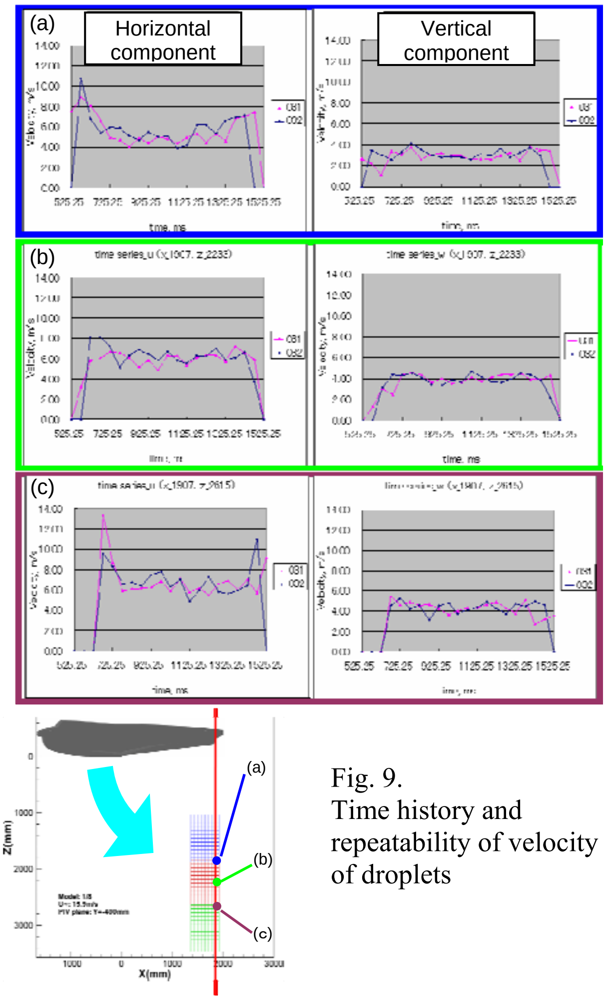

Fig. 9. Time history and repeatability of velocity of droplets

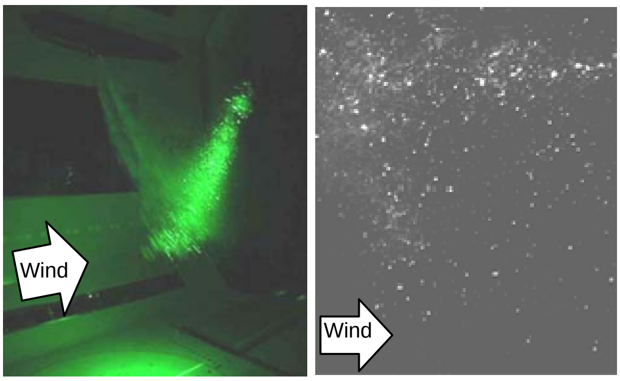

Fig. 8. PIV measurement for water dropping (Left). Particle image of high-speed camera (Right)

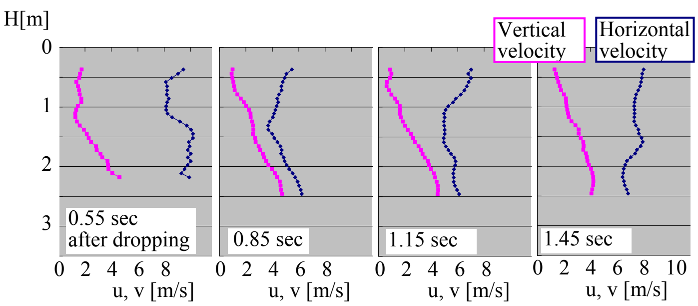

Fig. 10. Droplet velocity distribution by PIV measurement

accuracy of PIV or bad repeatability of water-dropping phenomena.

Fig. 10 shows PIV results in the condition of a model (1/8 scale), wind speed was 15.9m/s and Y=400mm. In the case of 0.55sec after dropping, vertical velocity increased to a downward direction due to gravity. On the other hand, horizontal velocity showed almost flat, and less than freestream velocity. In the case of 0.85sec, vertical velocity distribution was almost same as 0.55sec, but horizontal velocity distribution was very different. The horizontal velocity should be affected by the water particle diameter. It has to be measured and partially reported in reference. [8] Same influence is observed at 1.15sec and 1.45sec. Those data was very important and used for validation of CFD.

3.3 Shadow image measurement for water droplet size

Diameter of water droplet is important information for evaluation of water dropping and spreading pattern. Shadow imaging method is one of the useful methods to obtain this data. A shadow imaging system was placed at the floor as shown in Fig. 11. A position of the system was manually traversed in order to changing measurement point. The system consisted of a high-speed camera and a flat illumination. The flat illumination has 720 red LEDs. Shadow image of water droplet was captured by the high-speed camera as shadow image like in a Fig. 13. Water droplet was sampled by the shadow imaging system. Particle diameter was calculated from shadow image by the commercial software. Fig. 13 shows a result of shadow imaging and a sample of water particle histogram. Particle diameter was calculated as Heywood diameter. Number of small particle was more than number of large one. The largest one was about 4mm in this case. A peak of the histogram was 0.4mm. Arithmetic mean diameter (D10) was 0.82mm, and Sauter mean diameter (D32) was 1.98mm.

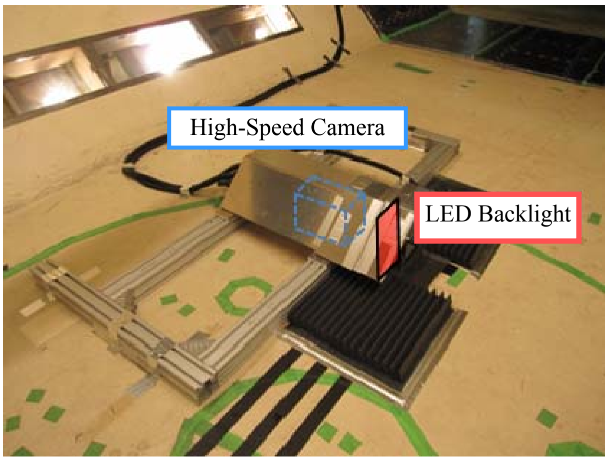

Fig. 11. Shadow imaging system on the floor in the test section of wind tunnel.

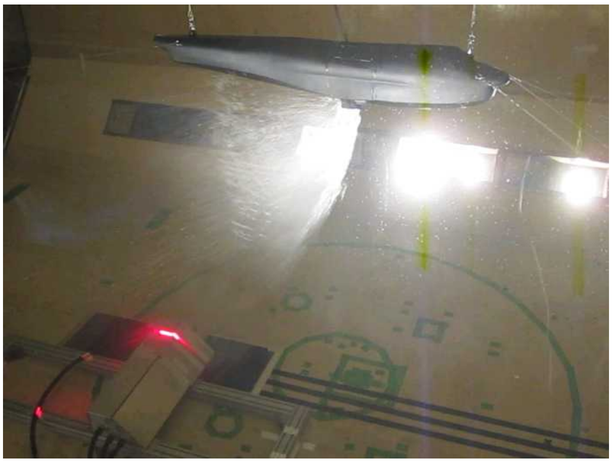

Fig. 12. Shadow imaging measurement for water dropping in the wind tunnel.

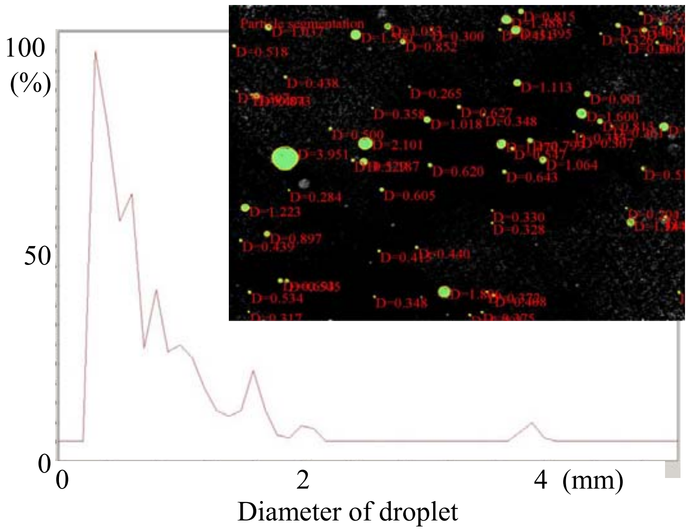

Fig. 13. A sample of Shadow imaging results and water particle histogram. (1/16 scale, Height 5.63m).

3.4 Water spreading pattern

Water spreading pattern on the ground was evaluated by measurement of the precipitation with a measuring cylinder and an increase in the weight of water absorbed by a polymer sheet as shown in Fig. 14. Four hundred measuring cylinders were set with 150 mm separation in flow direction and with 100 mm in lateral direction on the floor of wind tunnel. Size of polymer sheets was 150 mm x 300 mm, and those were set in 450 mm separation in flow direction and in 150 mm in lateral direction.

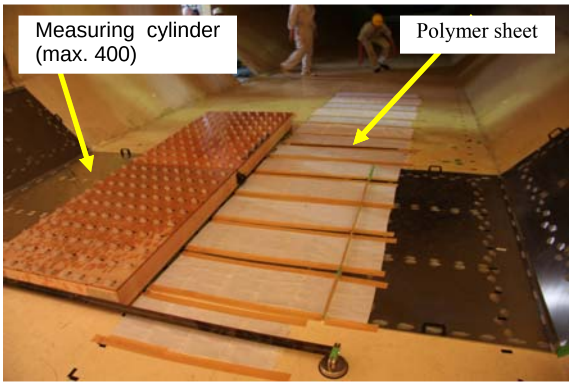

Fig. 14. Measurement setup of water spreading pattern in the wind tunnel.

Difference of height of the model, which means altitude of airplane, under the condition of 11.3 m/s of uniform flow is shown in Fig. 15. As increasing of distance from model, location of the contour moved downstream, area of contour became wider, and water mass of peak decreased. The results agreed with the photographs of front view. Maximum precipitation was 5 mm at near position from model, and 2 mm at lower position. Note that the measurement cylinder did not move with wind together, while actual ground stops against air in actual flight, in which the precipitation needs about 0.1 mm. Therefore, the precipitation of cylinder is different from the contour in actual fire-fighting, and it cannot be compared with wind tunnel data and flight data directly. For example, CFD analysis is needed for comparison.

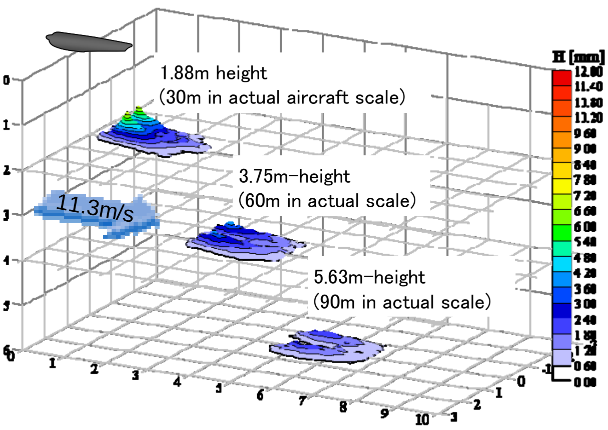

Fig. 15. Water spreading pattern in the wind tunnel by height difference

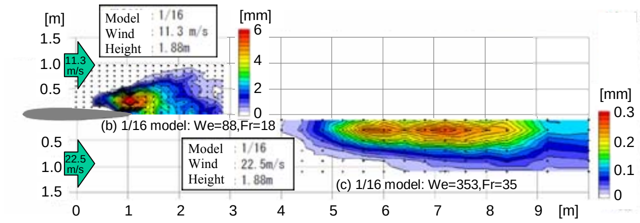

Fig. 16. Effect of wind speed (Fr number) on water spreading pattern

Next, effect of Froude number is shown by comparing with wind speed in Fig. 16. As wind speed increasing, its contour dramatically moved downstream and this agreed with the results of high-speed camera. Its area was spread much wider and amount of precipitation became very small. It means that size of droplet became also very small like mist and flew in wide area. Maximum of amount of water decreased to 1/10 of low air-speed condition. Then, the amount of water might not be sufficient for the extinguishment.

At last, effect of Weber number is shown by compared with different scale of model, as shown in Fig. 17. The x-axis and y-axis are converted to actual scale of fire-fighting flight in this figure. When Weber number was large and effect of surface tension was weak, position of dropped water was indicated downstream. Size of droplet should be small by small surface tension, and droplet was easy to be flowed more. On the other hand, contour of small Weber number shows more spread in lateral direction. It is considered that the initial velocity from the tank can be kept because of the large size and mass of the droplet.

From those results, Weber number or Froude

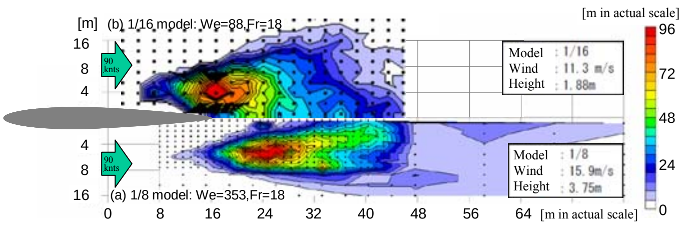

Fig. 17. Effect of We number on water spreading pattern (30m-height and 90 knots in actual aircraft scale)

number can affect the area of dropped water dramatically, and it is important parameter for fire-fighting amphibian. Moreover, these accumulated experimental data are useful to understand the phenomena and also to validate results of CFD analysis.

3.5 Numerical Simulation

There experimental data and understanding of phenomena are very important to validate and improve CFD analysis. Models of change of water mass and subdivision to droplet for CFD analysis were designed and calculated. Change of shape of water mass was calculated by using VOF model which could express the surface transformation including the effect of surface tension as volume of fluid. After separation of water, DPM model which showed that discrete particle flew away was used. The separation and subdivision of water was difficult problem and no known model or method. We applied a new water separation model from VOF to DPM by considering the level of transformation of water mass as shown in Fig. 18. In this model, when the size of volume decreased and became smaller than a certain size, the model subtracted volume from VOF and added corresponding particles to DPM.

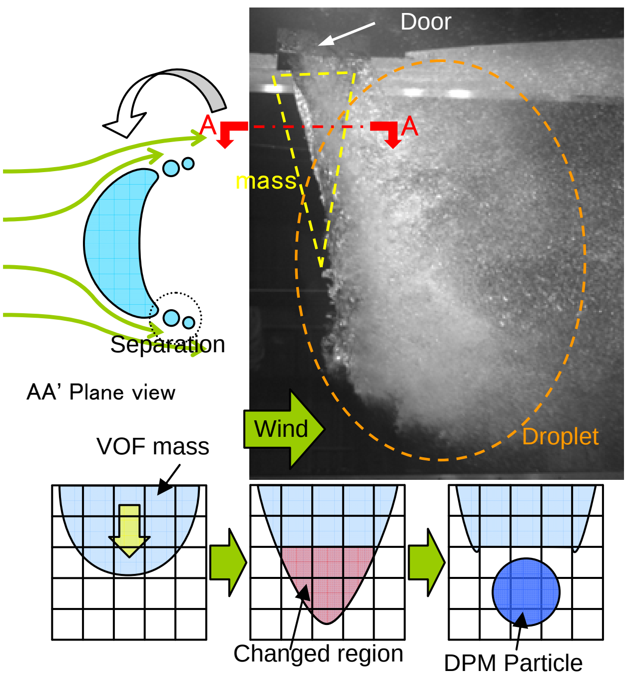

Fig. 18. Model between VOF and DPM for CFD

Using this model, CFD results were obtained as shown in Fig.19 for water-dropping behavior and in Fig. 20 for water spreading pattern. Those results showed good agreement with experimental results. Although detailed comparison with PIV results is the future work, global and macroscopic phenomena were reasonable and it is considered that this model would be useful for actual fire-fighting analysis.

In future, other problems such as side wind and up-wash and gust by fire should be studied for the accurate simulation considering actual water-dropping aerodynamics. Not only experimental test in the wind tunnel but also field work including innovative measurement method are needed.

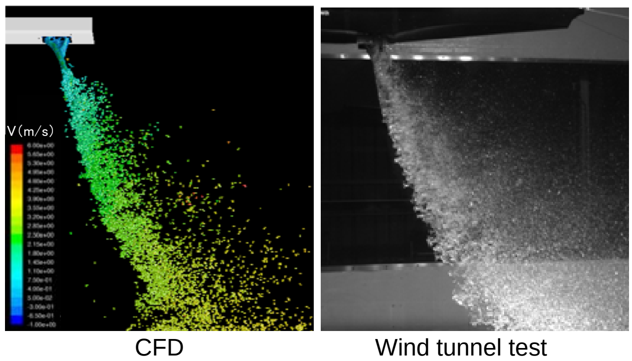

Fig. 19. Comparison of CFD and wind tunnel.

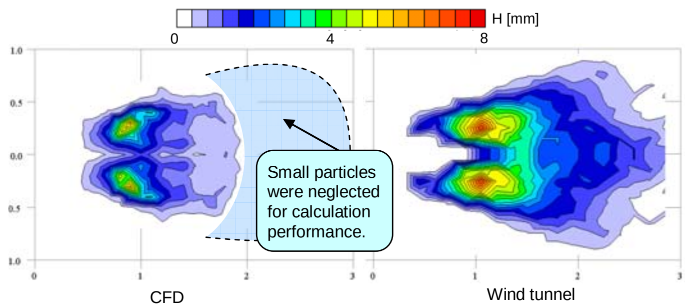

Fig. 20. Comparison of water spreading pattern between CFD and wind tunnel.

4 Concluding remarks

By using large-scale low-speed wind tunnel, we made it possible to comprehend the whole behavior of water dropping from fuselage model of fire-fighting amphibian by the photographs of the entire phenomenon taken with a high-speed camera, the velocity of droplets with PIV, size of droplets by shadow imaging, and the spreading pattern data on the ground. Phenomena of water dropping aerodynamics were discussed along with Weber number, Froude number, and so on. CFD calculation was also successfully conducted and was able to be validated. The data obtained from these tests will be helpful to determine how to drop water from an amphibian to extinguish a fire more efficiently.

Acknowledgement

The authors would like to gratefully thank to members of Low-speed Wind Tunnel Section and Advanced Technology Section in Wind Tunnel Technology Center in JAXA and members of ShinMaywa Industries Ltd. for their experimental support and their cooperative research works.

References

[1] M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[2] Report of research for small-scale civilian airplane development in FY2008 (conversion of US), JADC, 2009. (in Japanese)

[3] Kasahara, Y., Aerial Extinguishment Experiment by Fire-Fighting Sea Plane (CL-215), Fire, Japan association of Fire Science and Engineering, Vol.25, No.4, pp234-240, 1975. (in Japanese)

[4] Watanabe, A., Kasahara, Y., Kaneda, S., Test on Aerial Fire Attack using Four-Engined Flying Boat, Report of Fire Research Institute of Japan, No.44, pp13-19, 1977. (in Japanese)

[5] Rimbert, N. et al., "Aerial dropping of water and retardant fluid by a firefighting airplane," 5th International Conference on Multiphase Flow, ICMF'04, Paper No.394.

[6] 6.5m x 5.5m Low-speed wind tunnel (LWT1), Wind tunnel technology center, ARD, JAXA, http://www.ard.jaxa.jp/research/fudo/pdf/6.5x5.5_teisoku.pdf

[7] http://www.aerospace.bombardier.com/en/aerospace/products/amphibious-aircraft/bombardier--415

[8] Kato, H., Watanabe, S., Hosoe, N., Koike, S., Ito, T., Tagawa, S., Negishi, E., PIV and Shadow Imaging Measurements of Water Dropping For Fire-Fighting Amphibian, Proc. of 14th International Symposium on Flow Visualization, Jun., 2010.

[9] Watanabe, S., and Kato, H., "Stereo PIV Applications to Large-Scale Low-Speed Wind Tunnels", AIAA 2003-0919

[10] Meinhart, C. D., Wereley, S. T., and Santiago, J. G., "A PIV algorithm for estimating time-averaged velocity fields," 3rd ASME/JSME Fluids Engineering Conference, 1999.

[11] Sasahara, K., Kaneda, S., Kasahara, Y., Sumi, T., Takeda, S., Flow Temperature measurement over the Fire, Fire, Japan association of Fire Science and Engineering, Vol.29, No.1, 1979. (in Japanese)

Copyright Statement