HiSST: 3rd International Conference on High-Speed Vehicle Science Technology

14 -19 April 2024, Busan, Korea

TEMPERATURE FIELD MEASUREMENT OF EXTERNAL FLASH BOILING SPRAY IN REGION WHERE BUBBLES GENERATE AND GROW

Hyunchang Lee[1]

Abstract

Modern high-performance engines like liquid rockets, gas turbines, and hypersonic scramjets use regenerative cooling. As a result, superheated fuel is likely to be injected into combustion chamber. Here, flash boiling spray is likely to occur for the lower pressure in the chamber, and the mechanism of generation and growth of bubble should be thoroughly understood in the regards of heat transfer. In this study, temperature field in the region where bubbles generate and grow has been measured by using 2-color-ratio laser induced fluorescence method using FL and SRh as the dyes. The effect of dye on flash boiling spray has been assessed by comparing discharge coefficient before and after mixing the dye. Based on measured temperature fields, detailed heat transfer between the jet and the ambient, heat flow into the region of phase change could be investigated. Heat transfer affects bubble dynamics significantly and measured temperature fields in this study will support numerical model validation.

Keywords: *2c-ratio method, bubble dynamics, laser induced fluorescence, heat transfer.*

1. Introduction

Most of high-performance liquid propulsion system nowadays use regenerative cooling to overcome high temperature that exceeds melting point of their combustor material. As a results, the fuel is superheated and flash boiling occurs. This phenomenon should be understood in detail to supply fuel safely and maximize combustion efficiency.

Flash boiling spray is known to be explained by bubble nucleation and growth [1] . For bubbles to grow, surplus energy should be supplied both for overcoming surface energy and phase change. This comes from available energy of superheated liquids, thus temperature field measurement in high speed with ambient pressure will be crucial to validate numerical model. However, thermometry using intrusive probe like thermocouples are very limited for use, because they interfere the phenomenon itself: velocity field, especially abrupt bubble nucleation in metastable state could be enhanced by interaction with the surface.

Previous studies investigated the dynamics of bubble growth and it is known that the viscosity, surface tension, pressure difference, heat transfer should be considered as summarized in the review paper [1]. Temperature field is one of the main quantities of interest to understand flash boiling and was measured by using thermocouples [2], linear Raman scattering [3], and 2c LIF [4]. In this study, we measured temperature fields to understand heat transfer in bubble nucleation and growth region by using 2c LIF thermometry considering main issues regarding uncertainties such as laser fluence, dye concentration, and lasing effect [5].

[1] *Kyungnam Univ., 7, Gyeongnamdaehak-ro, Masanhappo-gu, Changwon-si, S.Korea, leehc53@kyungnam.ac.kr*

2. Experimental

2.1. Test rig

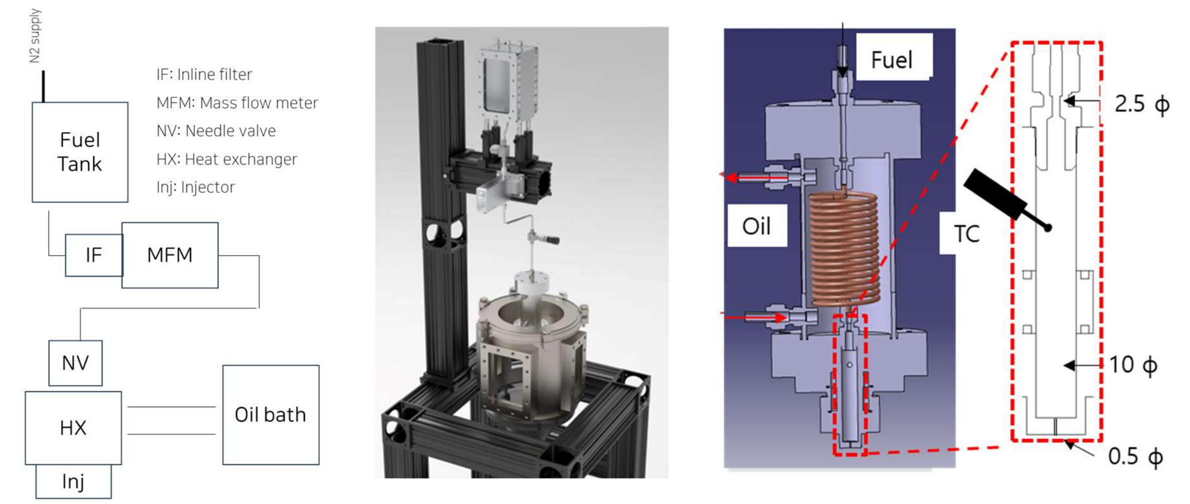

Fig. 1 Test-rig. (a) P&ID (b) 3-dim modeling of the test rig (c) details of heat exchanger

In Fig.1, the test-rig to realize flash boiling spray is shown. The fuel tank filled with tap water was pressurized by using nitrogen gas. The fuel was sprayed through inline filter, coriolis mass flow meter, needle valve to control the mass flow and injection pressure and heated during passing coil immersed in hot oil bath. The injection temperature was measured by a K-type thermocouple inserted in the path of the fuel as shown in the panel (c) of Fig.1.
The experimental procedure is as follow. First, the oil bath was heated to desired temperature without oil flowing to the heat exchanger. After the oil bath reaching the desired temperature, the needle valve was slowly opened to the target mass flow. Then, the pump of the oil bath was turned on and the oil was filled in the heat exchanger and fuel was started to be heated. The heated fuel was injected through a nozzle which has 0.5 mm diameter and 4 mm length. The injection pressure, temperature, mass flow rate were monitored every seconds by using DAQ. A typical variation of the experimental values are shown in Fig. 2.

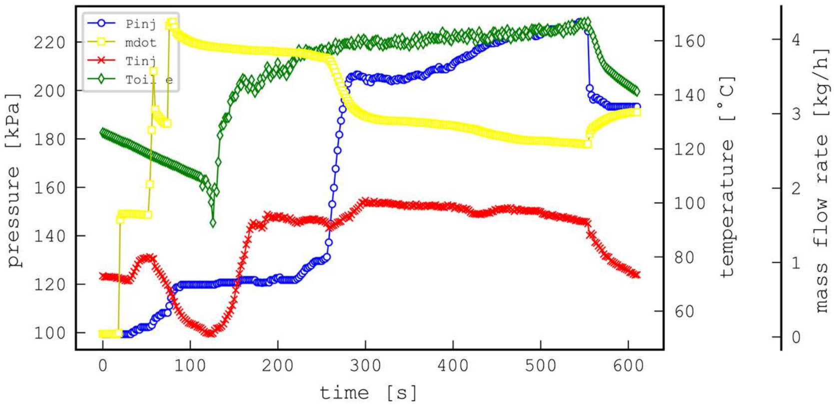

Fig. 2 temporal variation of Tinj, Toil, Pinj and mass flow.

2.2. Dyes and their spectra

Dye solution used in this study was prepared by dissolving 37.1 mg of Fluorescein sodium salt (FL, $C_{20}H_{10}Na_2O_5$) and 1.8 mg of SulfoRhodamine 101(SRh, $C_{31}H_{30}N_2O_7S_2$) in 2 liters of tap water. This combination of dyes has been well studied in the previous study and concluded as a good candidate for 2 dye 2 color ratio method [5]. The absorption cross section of FL from 532 nm increases significantly according to the temperature, while the quantum efficiency of SRh is so high that the fluorescence intensity does not vary severely according to the temperature. As the relevant filters, the center wavelength of 550 nm with 15 nm FWHM(Chroma, ET550/15x) was used for FL and center wavelength of 670 nm and FWHM of 50 nm has been used for SRh (chroma, ET670/50m). The spectra of the solution with the both dyes at various temperatures and the filter set are shown in Fig. 3.

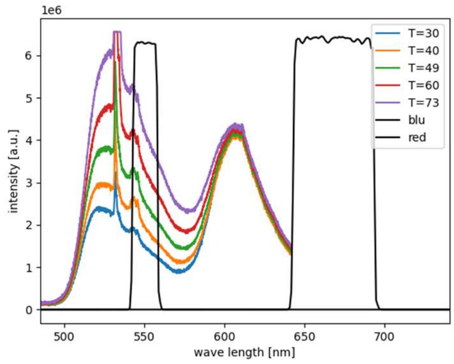

Fig. 3 Spectra of FL and SRh at various temperatures and relevant filter set.

2.3. Optical setup and image processing

2c LIF setup is shown in Fig 4. The laser sheet formed by second harmonic of Nd:YAG laser through serial cylindrical lenses was used to excite fluorescent dye mixed in the spray. The fluorescence dependent on temperature was imaged on the two cameras mounted respective filters after 70R/30T beam splitter(Edmundoptics, 62-883). The intensity ratio image of two cameras was converted to temperature by previously acquired calibration curve. The calibration curve was acquired by using the setup in Fig.4, but posing cuvette on electric heater block in the laser sheet. The detail of setup for the laser and camera is summarized in Table 1.

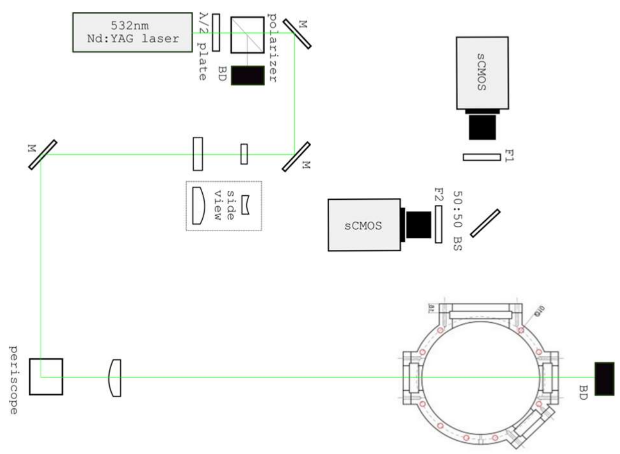

Fig. 4 2c LIF setup

Table 1. Optical setup.

t_{Laser} [ns]	texp [us]	ROI [mm²]	Pixel	FPS [Hz]	Mag
10	50	34.5 × 10.0	936×271	10	0.35

The acquired raw images were subtracted with the reference image which was average of 100 instant images without laser and spray. Pixel to pixel misalignment between two cameras was modified by using intensity-based image registration algorithm in Matlab(imregtform). After image registration, to exclude area with low signal under certain threshold, masks for instant images were created and temperature in this area was not calculated. The two images were divided pixel by pixel and median filter with 5 by 5 kernel size was applied for smoothing and this smoothed intensity ratio images were calculated into temperature by using calibration curve.

2.4. Experimemtal conditions

The mass flow rate was 3.85 kg/h and Pinj was 0.2 bar before heating the fuel. After heating, the fuel was cavitated inside the injector by depressurization and fluctuation and the mass flow rate was decreased and Pinj was increased as exemplified in Fig. 2. The maximum Tinj was around 120 ℃.

3. Results and discussion

3.1. Calibration

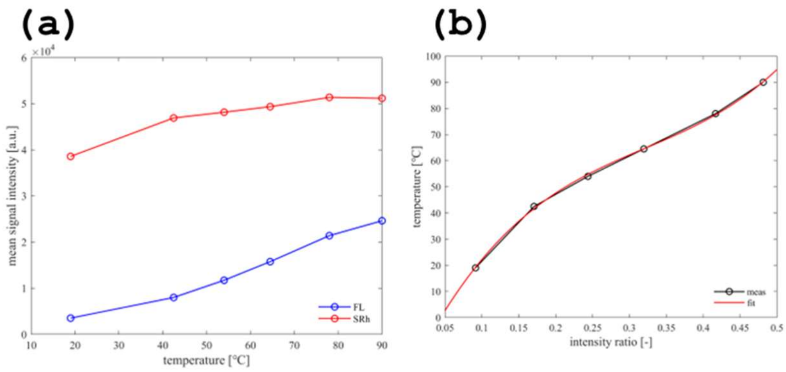

Fig. 5 (a) signal variation of FL and SRh according to temperature. (b) acquired calibration curve

By using cuvette on electric heater block the dye solution was heated to the desired temperatures and the fluorescence from FL and SRh was recorded. By using certain area of average from 100 instant images, mean signal for FL and SRh was calculated and summarized in the panel (a) of Fig. 5. The signal of FL was increased significantly, however SRh exhibited less sensitivity to the temperature. The intensity ratio according to temperature is plotted in the panel (b) of Fig. 5 and 3rd order polynomials fit has been applied and it was used to reduce temperature from intensity ratio afterwards.

3.2. Demonstration of temperature measurement: mixing of cold drop in hot water in cuvette

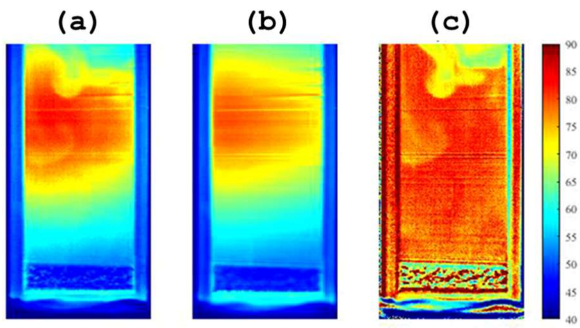

Fig.6 Demonstration of temperature measurements in cuvette. Cold drop is mixing with hot water. Laser sheet was excited from left to right. image of (a) FL, (b) SRh, (c) temperature.

Temperature measurement with this technique was first applied to mixing of cold water drop with hot water in cuvette for demonstration and the result is shown in Fig.6. The mixing of cold drop can be shown in the panel (a) of Fig. 6 for the FL's large dependence on temperature, but in the image of SRh (panel (b) of Fig. 6), mixing of cold drop is hardly recognizable. The laser intensity difference resulted in characteristic stripe in the FL and SRh images, but the shape is almost not seen in the temperature field (c) in Fig. 6.

3.3. Temperature measurements in flash boiling spray

Backlight images in different Tinj and Pinj are shown in Fig. 7. It is evolving from typical cylindrical jet(panel (a) in Fig. 7) into flash boiling spray with increasing superheat. The difference between panel (b) and (c) is suggested to coming from different in-nozzle flow of slug and annular as proposed in the previous study [6].

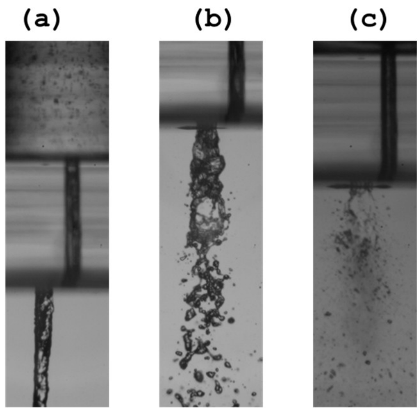

Fig. 7 Backlit images of flash boiling spray at various superheat. (a) Tinj = 70.9℃, Pinj = 0.40 bar (b) Tinj = 110℃, Pinj = 0.48 bar, (b) Tinj = 110.4℃, Pinj = 0.54 bar

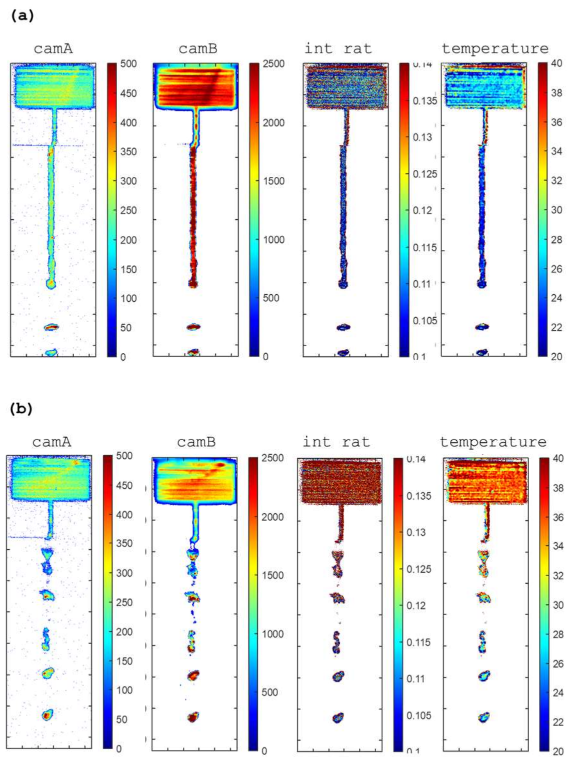

Fig. 8 Temperature measurement in flash boiling spray. (a) Tinj = 98 ℃, Pinj=0.21 bar, (b) Tinj = 107 ℃, Pinj=0.32 bar

Fluorescence images and its reduced intensity ratio and temperature at two different Tinj and Pinj are shown in Fig. 8. The signal from FL(camA) is much weaker than SRh(camB) and the intensity ratio exhibit strong noise for the weak signal. The measured temperature field is much lower than the one by thermocouple. The difference can be physically reasonable considering strong phase change or heat transfer to unheated nozzle. However, it may also be possible that significant measurement error exist ed in this study, and further investigation should be performed in the near future. Here one can clearly see that fluorescence is easier to measure in the area of liquid than vapor, because the number density of dye molecules will be very low for the expansion from phase change.

4. Conclusion

In this study, measurement of the temperature field of flash boiling spray has been attempted, which is very limited to the technique using probe e.g., thermocouples. FL and SRh exhibited relatively high temperature sensitivity and by applying suitable measurement setup, preliminary temperature field of flash boiling spray has been achieved. However, discrepancies between results from the technique and conjecture based on the Tinj upstream measured by thermocouple exists and further investigation to increase the measurement accuracy and precision is required. Such investigations could be the effect of dye concentrations, laser intensity on the measurement. Furthermore, improving imaging setup is also required by reducing remained image disparity after image registration, different imaging spatial resolution, increasing solid angle for better signal to noise ratio. By using high magnification setup, the detail of heat transfer in the area of phase change could be studied.

References

[1] T. Bar-Kohany, M. Levy, State of the art review of flash-boiling atomization, Atomization and Sprays. 26 (12) (2016).

[2] O. Miyatake, T. Tomimura, Y. Ide, M. Yuda, T. Fujii, Effect of liquid temperature on spray flash evaporation, Desalination. 37 (3) (1981) 351-366.

[3] A. Guenther, A. Braeuer, P. Siegler, B. Kninger, K. Wirth, Temperature characteristics in a flash atomization process, Atomization and Sprays. 26 (12) (2016).

[4] M.R. Vetrano, A. Simonini, J. Steelant, P. Rambaud, Thermal characterization of a flashing jet by planar laser-induced fluorescence, Experiments in Fluids. 54 (2013) 1-10.

[5] W. Chaze, O. Caballina, G. Castanet, F. Lemoine, Spatially and temporally resolved measurements of the temperature inside droplets impinging on a hot solid surface, Experiments in Fluids. 58 (2017) 1-16.

[6] B.S. Park, S.Y. Lee, An experimental investigation of the flash atomization mechanism, Atomization and sprays. 4 (2) (1994).