공학석사학위논문

스월 분사기의 간격과 분사압이 분무 간의 상호작용에 미치는 영향

Effect of Swirl Injectors' Spacing and Injection Pressure on Interacting Sprays

2018 년 2 월

서울대학교 대학원

기계항공공학부

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

Effect of Swirl Injectors' Spacing and Injection Pressure on Interacting Sprays

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Mass flux distribution is generally regarded as one of the most critical parameters of a rocket combustion chamber. Because the mass flux distribution depends mainly on the interference effect of the spray, examining the interference phenomena is of vital importance to develop a rocket. Yegorychev established a numerical model that predicts the mass distribution of fuel and oxidant flux. Notwithstanding his groundbreaking achievement, Yegorychev neither clarified the constraint range of his numerical model nor visualized the jet. In order to fill the gaps in the Yegorychev `s study, we focused on defining the constraint range and visualizing the interference phenomena using high time-resolution laser diagnostics. In this study, we obtained vivid and high time-resolution images revealing the mechanism of interference phenomena. Also, we have shown that 30H is constraint range of Lefebvre`s numerical model. Our laser diagnostics images and advanced model can be used to analyze the combustion instability problems in a rocket combustor.

Keywords: liquid rocket engine, optical patternator, mechanical patternator, multi-element injector, multi-injector system, mass flux distribution, interacting sprays, collisional kinetic energy

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Nomenclature

ρ_g	Density of gas, kg/m^3
U_g	Velocity of gas, m/s
ρ_l	Density of liquid, kg/m^3
p'	manifold pressure fluctuation, bar
$\bar{P}$	Average of manifold pressure, bar
Q	Mass flow rate of liquid, kg/s
R_{inlet}	Radius of tangential inlet, mm
L_B	Breakup Length, m
L_I	Impinging Length, m

Chapter 1. INTRODUCTION

1.1 Necessity of investigation of interacting spray

The most critical part in developing a rocket is designing a combustion chamber. Parameters of the chamber affect mass flux distribution, and consequently influence specific impulse, combustion stability, and efficiency of a rocket. Because the mass flux distribution depends mainly on the interference effect of the spray, examining the interference phenomena is of vital importance to develop a liquid rocket. Although numerous researchers have been investigating the phenomena in gas turbines or diesel engine combustion chambers, few researchers have publicly addressed this issue in the field of rocket engineering.

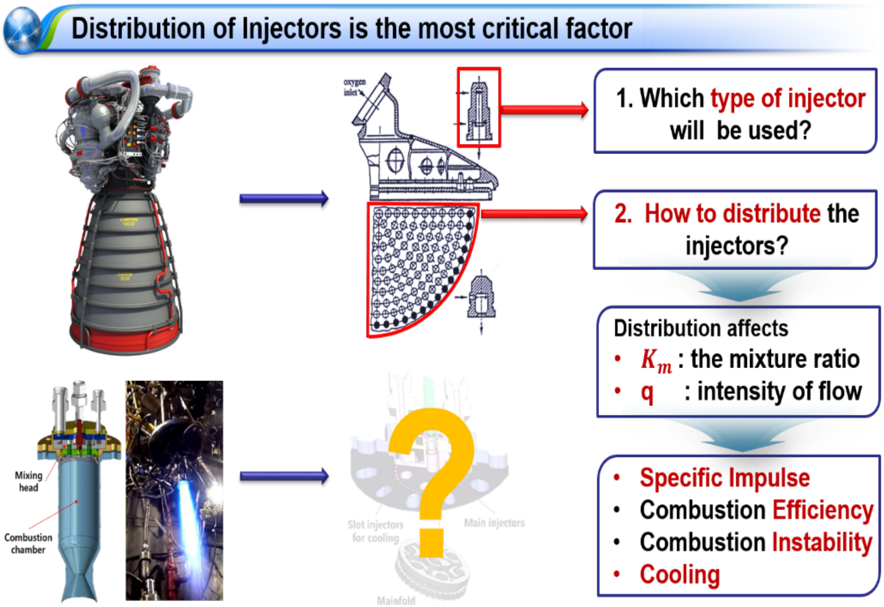

Figure 1.1 Motivation of this Study

1.2 Overview of previous research

Yegorychev was one of the scarce and established a numerical model that predicts the distribution of fuel and oxidant flux. He postulated a two-dimensional planar jet between the swirl sprays and formulated the mass flux of the jet using a normal distribution function. Although having demonstrated the decent concurrence between experimental data and the estimated values from his formula, Yegorychev neither clarified the constraint range of his numerical model nor visualized the jet. Compensating for the deficiency of the model, this study verified the specified the constraint range, and visualized the jet adopting laser diagnostics. We found that mass distribution patterns can be grouped by three distinct group A, B, and C. Also, this study explained the three diverting mechanisms that affect to mass flux distribution.

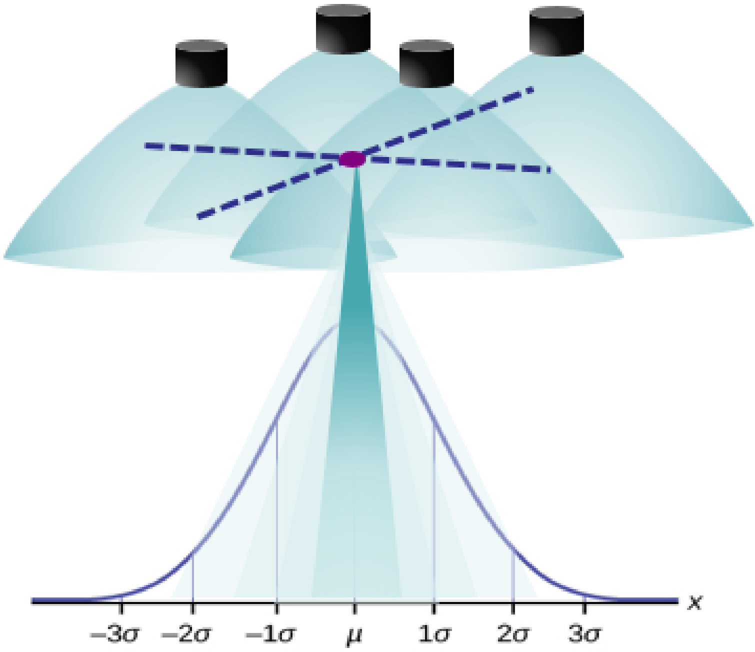

Figure 1.2 Concept of V. S. Yegorychev's Mathematical Formulation

1.3 Objectives

Main focus of this experimental study is to analyze the interference phenomena of two interacting swirl sprays. This study was mainly to measure mass distribution of the interacting spray; downstream of the impinging, colliding point. Also, this study was to find the patterns of the interacting spray mass distribution and the main factor of what makes mass flux distribution differ from the other.

Visualization is one of the important goal of this research. To find the underlying physical principle of colliding and factor of mass distribution, we use the optical patternator and various image recorder, high-speed camera, stroboscope, and continuous light source etc. To see the inside flow of interacting spray, we use the scope that has triangular cross sectional shape so that camera receive the signal of the inside flow directly. Pressure varied from 1.0Bar to 8.0Bar and spacing of two neighboring injectors varied from 15mm to 45mm.

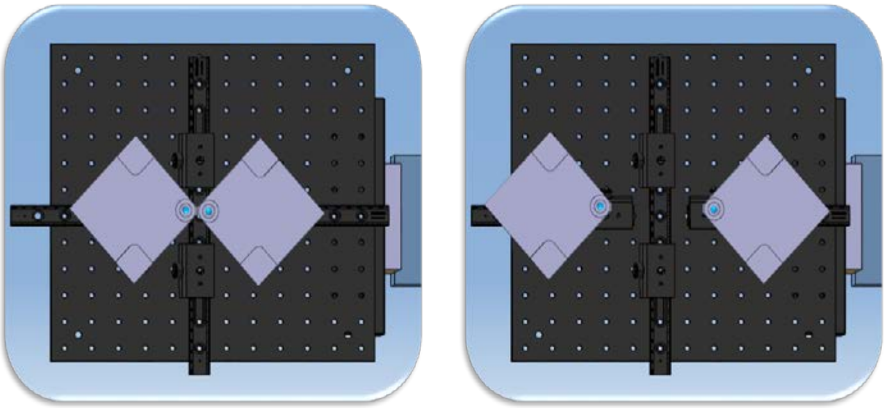

Figure 1.3 Injector Head Setup to adjust the Spacing between two injectors

Chapter 2. APPARATUS AND EXPERIMENTAL METHOD

2.1 Type of Swirl Injector

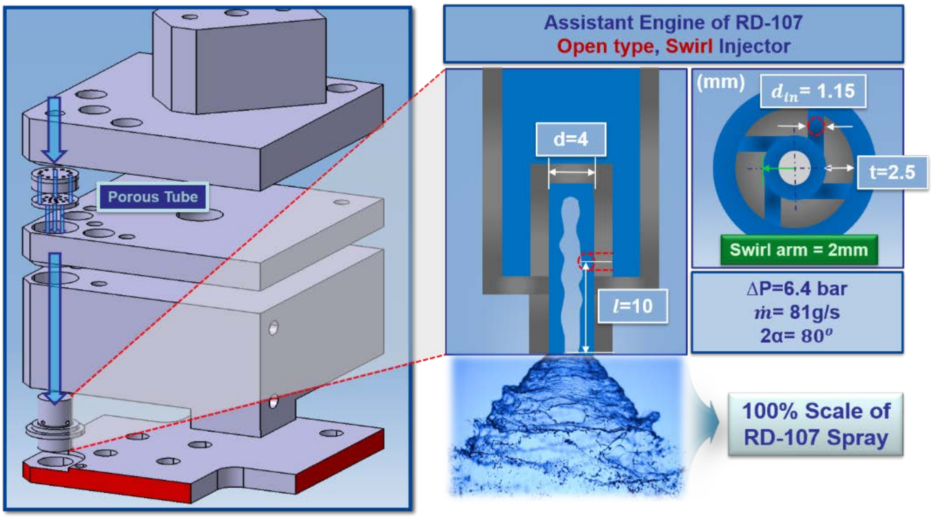

Figure 2.1 Structure of Experimental Injector

Every injector/atomizer has its own characteristics and therefore, makes unique spray. To make this research more general and fundamental, assistant engine of RD-107(Soyuz) type single swirl injector was chosen as experimental injector and is shown in Fig2.1. This type of injector is one of the most simple injector and it has been getting used in various fields of industry.

Although scaling down gives several benefit to lab. scale experiment, scaling was excluded to maintain original characteristics of rocket injector spray. Geometry of the injector is shown in Fig. 2.1 and this injector exactly reproduce 100% scale of assistant engine of RD-107(Soyuz). This rocket engine was operated at the condition that differential pressure is 6.4Bar. At this condition, RD-107’s spray have spray angle of 80 degree and mass flow was 81g/s so does experimental injector we used.

2.2 Injector Head Rail Setup

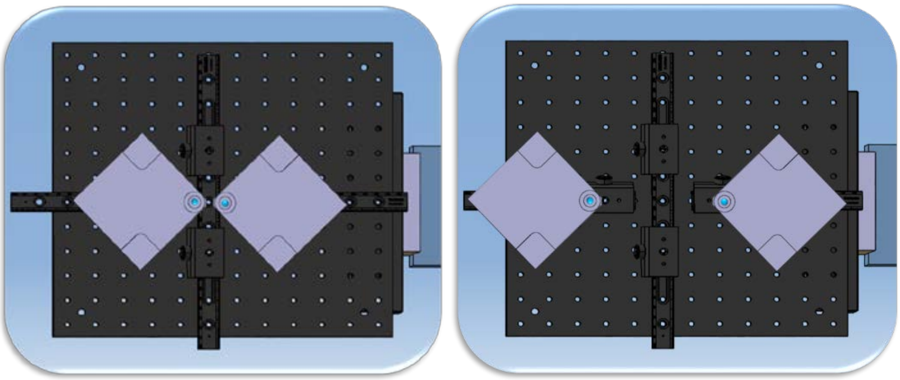

Figure 2.2 Injector Head Rail Setup

As shown in Fig. 2.2, injector can move along the rail of head so the spacing of two injector can be continuously adjusted. Spacing between two nozzles varied from 15mm to 45mm with various pressure condition. Injector heads are tightly hold on to rail cap and cap can moves along the rail smoothly and cap knop can hold tight cap itself. Nozzle has exactly same shape of swirl injector so they have same swirling or rotating direction and it makes co-rotating interacting phenomena.

2.3 Arrangement of multi-Injector

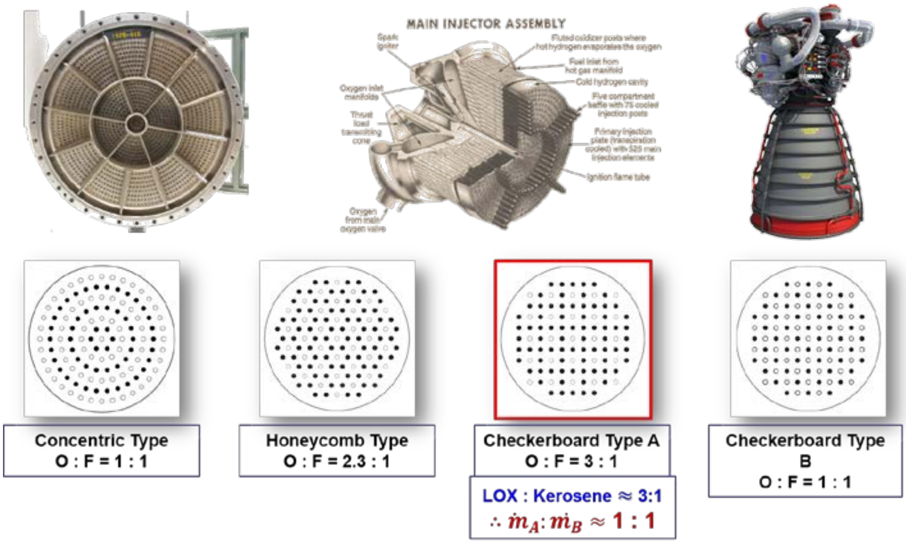

Figure 2.3 Type of Arrangement of Injector

It is well-known that arrangement of injector has critical impact on combustion instability, mass-flux distribution and specific-impulse etc. Generally, 4 arrangements are used for simple open type swirl injector. Each arrangement has specific geometry and therefore this decide O:F ratio. To simulate the LOX/Kerosene liquid engine of RD-107 and make momentum ratio of oxygen to fuel one to one, checkerboard Type A was chosen to simulate the exact symmetric spray interaction.

2.4 Optical Apparatus

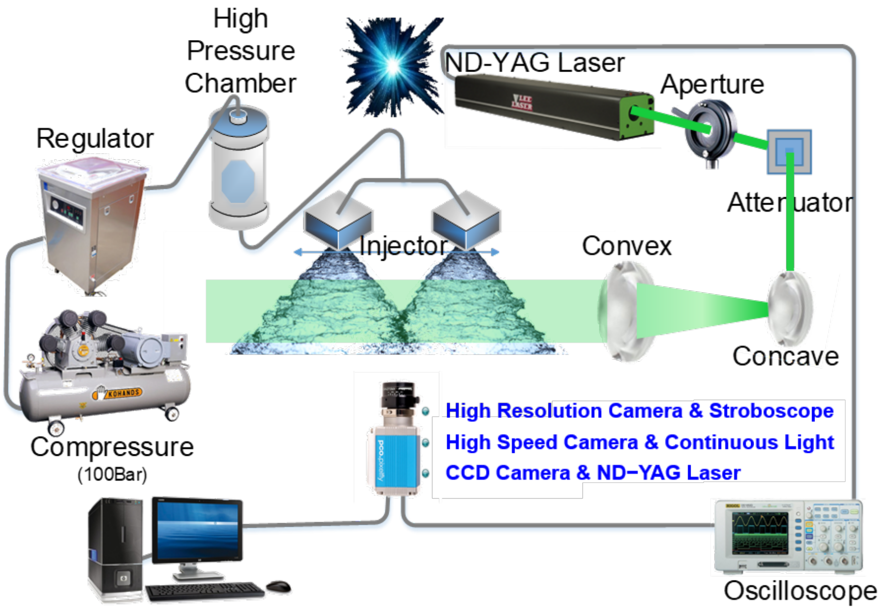

Figure 2.4 Three Optical Apparatus Systems

Three optical systems was used to analyze the interacting spray of the two injector downstream of impinging spray. First, high-resolution camera and stroboscope was used to freeze the spray and get still-cut images. Luminous time of stroboscope is 4μs so the droplet of 10m/s moves only 0.04mm during the luminous time. So this luminous time is enough to freeze the spray. This still-cut gives many information; outline of the spray and little sencondary-atomized droplet. How much this spray is unstable or not can be easily detected from this image.

Secondly, high-speed camera and continuous light system was set to look in to scattering procedure when two sprays are collided. Colliding and atomization happens very rapidly, so only high-speed camera (over 50,000 fps) can detect and analyze these phenomena. Only by this system, we could keep track of status of before, during and after the collision. High-speed camera and 180mm telephoto lens was used to magnify the phenomena. Triangular scope was inserted into the spray so that camera can capture receive the image of the inside of the spray.

Thirdly, CCD camera and ND-YAG laser system was chosen as system to capture the cross section image of the two spray. First and second system are limited to getting layout image of the spray. Using laser sheet beam of ND-YAG, we could get the Mie-scattering signal from the spray. This method make optical system be able to get inside phenomena of interacting spray. Mie-scattering signal is directly proportional to the droplet size. Therefore, we can interpret strong signal as large droplet and weak scattering signal as small droplet. This mechanism forms basis of optical patternator. ND-YAG laser has frequency of 10hz and this was synchronized with CCD camera. ND-YAG laser path through the aperture getting rid of out side of the beam profile so that we can use inner beam that strong and homogenous. This cut-beam come past the concave and convex lens in order changing its cross sectional shape from circle to long quadrangle. Intensity of ND-YAG laser should be strong enough to guarantee homogeneous beam are lit through the spray.

2.5 Mechanical Patternator

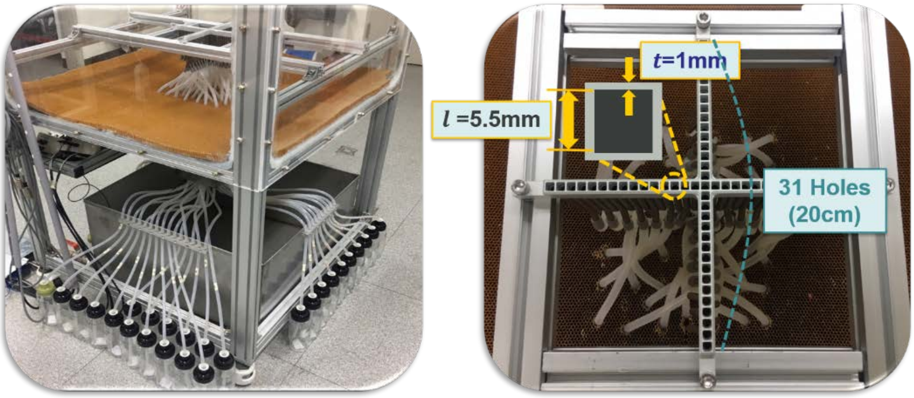

Figure 2.5 Structure of Mechanical Patternator

Structure of mechanical patternator is shown above Fig. 2.5. Mechanical patternator consists of 61 cells shaping cross. Each cells are square and length of its side is 5.5mm and thickness of its wall is 1mm. Therefore spacing of center of two adjacent cells is 6.5mm. This could be a bit large to be compared to optical patternator but if we get it smaller, cells may be choked and fluid may be overflow. That makes much more errors than large cells. So, this is kind of trade-off between high-resolution and preventing overflow. Compared to optical patternator, mechanical patternator has unique benefit. Only mechanical patternator enable us to measure the quantitative measurement. Although optical patternator can be the quantitative measurement system but there should be the rigorous calibration including attenuator impact adjustment, multiple scattering correction, etc.

Chapter 3.
RESULTS AND DISCUSSTION

3.1 Characteristic of single spray

Before going deeper into the interacting sprays phenomena, characteristics of single spray should be check and reconfirmed. Swirl injector has its unique characteristics and its breakup process is rigorously defined in many atomization texts. Fig3.1 shows the developing process of the breakup.

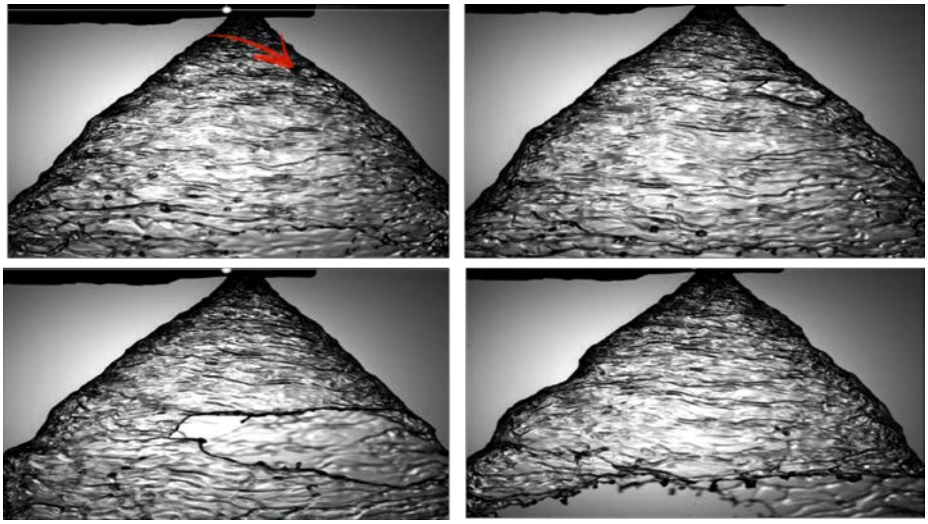

Figure 3.1 Perforation Develops into Breakup

Frist, liquid sheet is getting unstable. Second, little perforation appears. Third, it directly develops into breakup by propagation of opening.

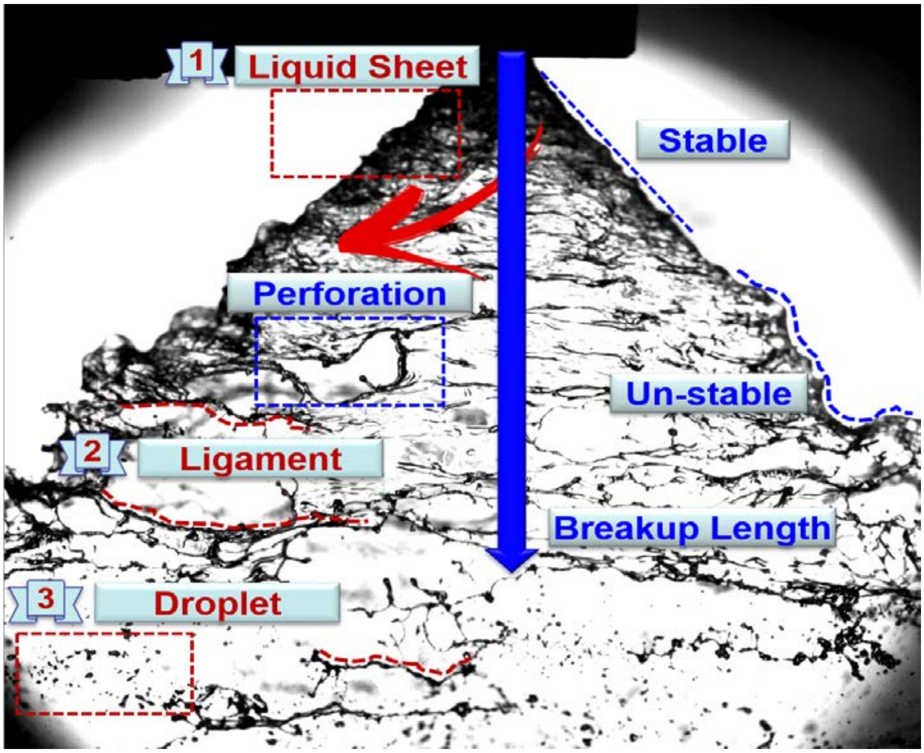

Figure 3.2 Process of atomization.

Liquid sheets are getting atomized by three steps; sheet-ligament-droplet. Fig 3.2 shows the process of atomization. When liquid sheet is coming out of nozzle outlet, its status is stable and thick. As it propagates, it is getting unstable and little ripple turns into large wave. During this process, sheets are turns into ligament. As ligaments expands, these turn into droplets. In above figures, these process are shown. And in specific condition, their breakup lengths can be defined as specific values, average of instant breakup lengths.

3.2 Co-rotating Swirl interaction

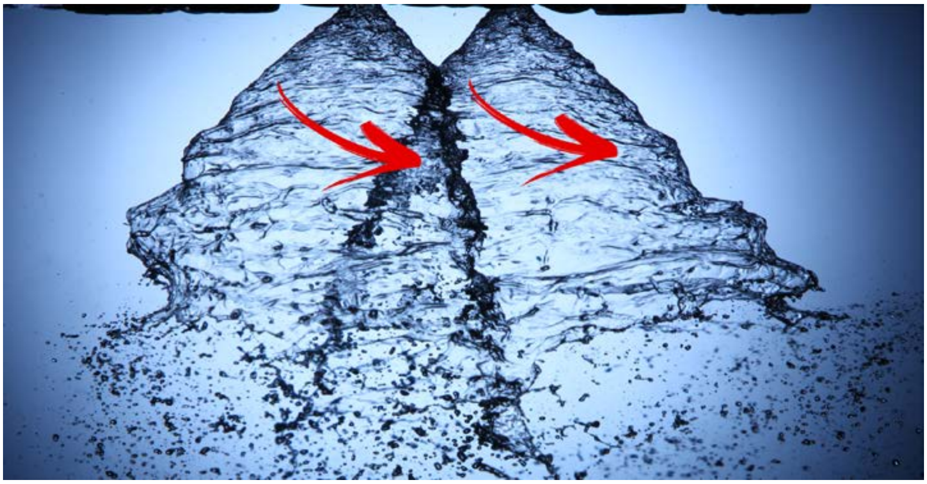

Figure 3.3 Co-rotating interaction of two swirl spray.

Each swirl cone rotate in a specific direction. If they rotate in a same direction we call it ‘co-rorating’ or ‘counter-rotating’. In our experimental system, every nozzles are identical so does its rotating direction. Therefore our systems are co-rotating and following all results and discussion are about co-rotating interaction.

As you can see above in the picture, two sprays are rotating in a same direction, when two spray collide, interacting spray boundary forms parabolic rim. Rim is very thick and most masses flow in it. Because of the co-rotating interaction, rim twisted in a same direction swirl sprays rotate.

3.3 Result of Backlight Images with varing P_{in}

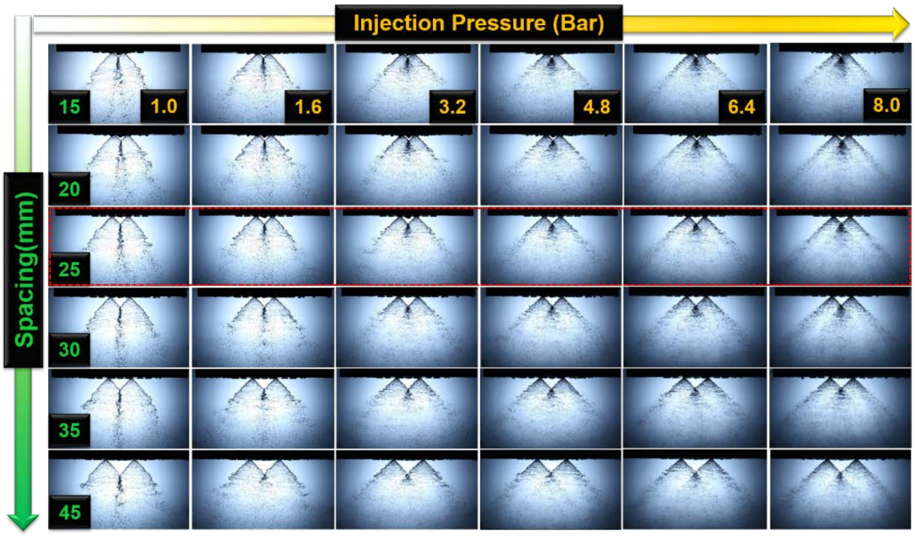

Figure 3.4 Backlight Images; Injection Pressure varies from 1.0Bar to 8.0Bar,

Spacing between two nozzle centers varies from 15mm to 45mm.

Firstly, Backlight images analysis is performed. Although backlight images is not proper method to analyze the inside flow of spray cone, it gives general and macroscopic information about the interacting phenomena.

To point out the effect of injection pressure and spacing, three cases are chosen and analyzed. First of all, three pictures featuring injection pressure effects are listed as follow.

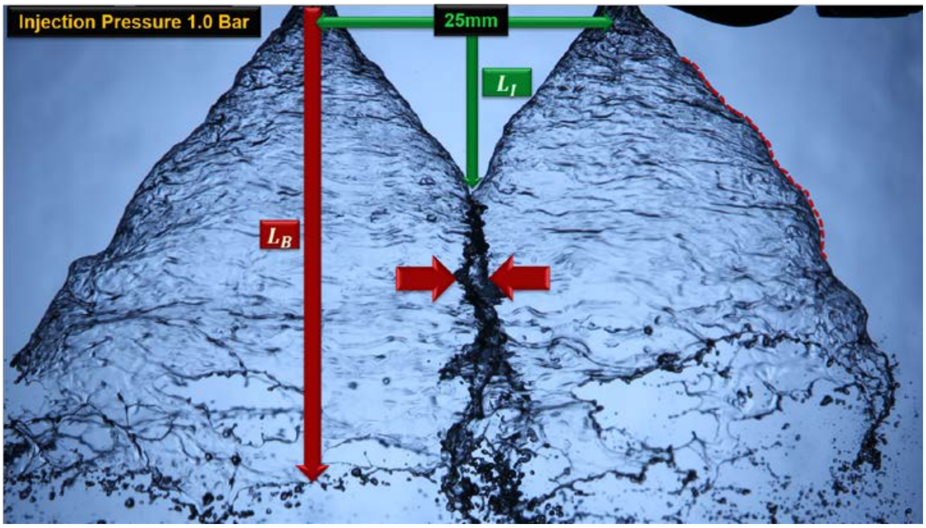

Figure 3.5 Injection pressure is 1.0Bar, Spacing is 25mm

Steady and stable flow is featured in this spray. Before breaks up, liquid sheet remains stable condition over almost all area and break up lengths are relatively longer than impinging length. As a result of it, two interacting sprays forms also stable and steady film wall. Small ripples are observed throughout the spray but it did not develop into bigger wave. Sheet is atomized very rapidly into droplets. Ligaments state of liquid are not that dominant condition in this case.

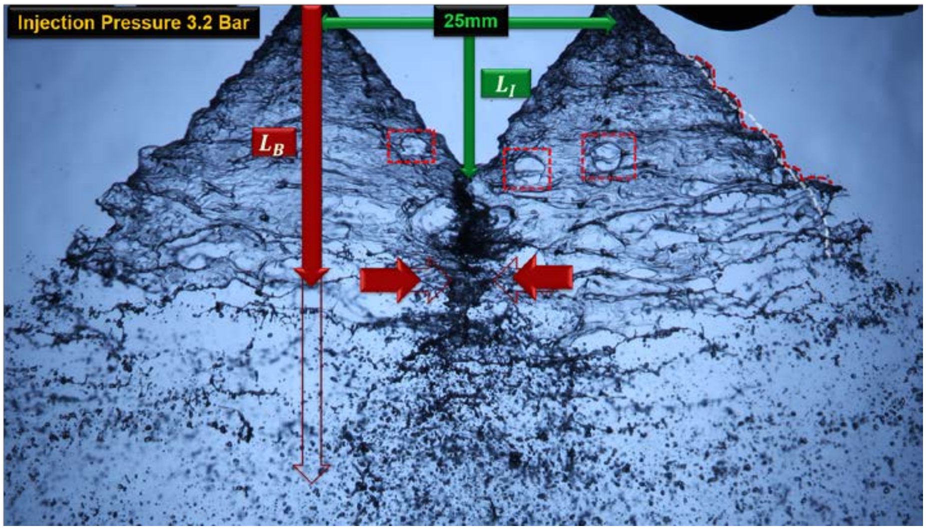

Figure 3.6 Injection pressure is 3.2Bar, Spacing is 25mm

In second case, injection pressure increased to 3.2Bar, while spacing between two center of nozzles remains still. As shown above figure, white spot line is outline of spray of 1.0Bar cases. Red spot-line can be compared to white spot line and now we case see the differences. Liquid sheets and its little ripple are getting unstable as they go downstream of the spray more quickly than 1.0Bar case. Several perforations are formed at the height of impinging point. Ligament like state of liquid are getting dominant. Therefore, breakup length is got short; nearly half of the previous case.

Thicker and wide unstable mass flows are shown at downstream of the collision point. We can say that previous case is more like sheet condition but this case is like ligament conditions are dominant.

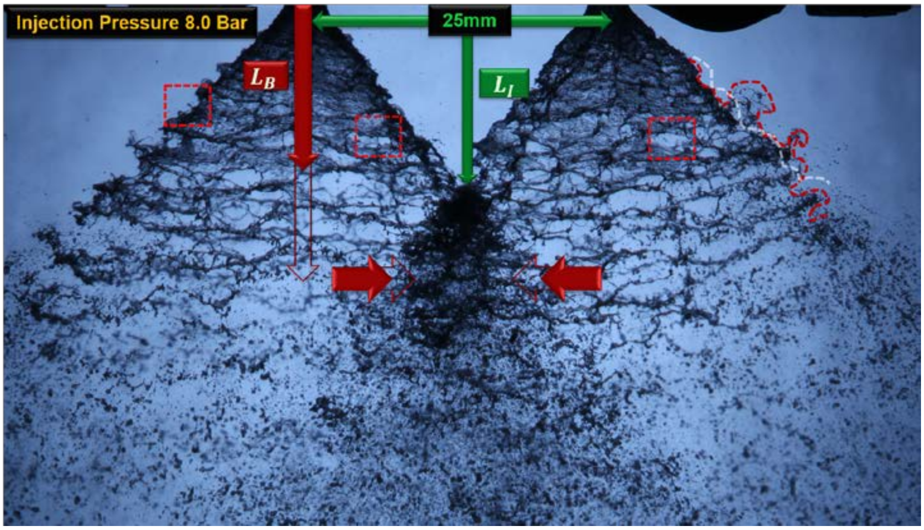

Figure 3.7 Injection pressure is 8.0Bar, Spacing is 25mm

As shown above Fig 3.6, sprays are much more unstable and their outlines are like bigger waves form. Much more perforation are found throughout the sprays and droplet-droplet interaction are dominant at the height of the collision. As a result of that, break-up length is more shortened than previous case. Almost all droplets are keep their trajectory path so their trajectory is straight.

Triangle-like spray shape is made and downstream is got much more thicker than previous case. Breakup length and impinging length is nearly same.

3.4 Relationship between Breakup length and Injection pressure

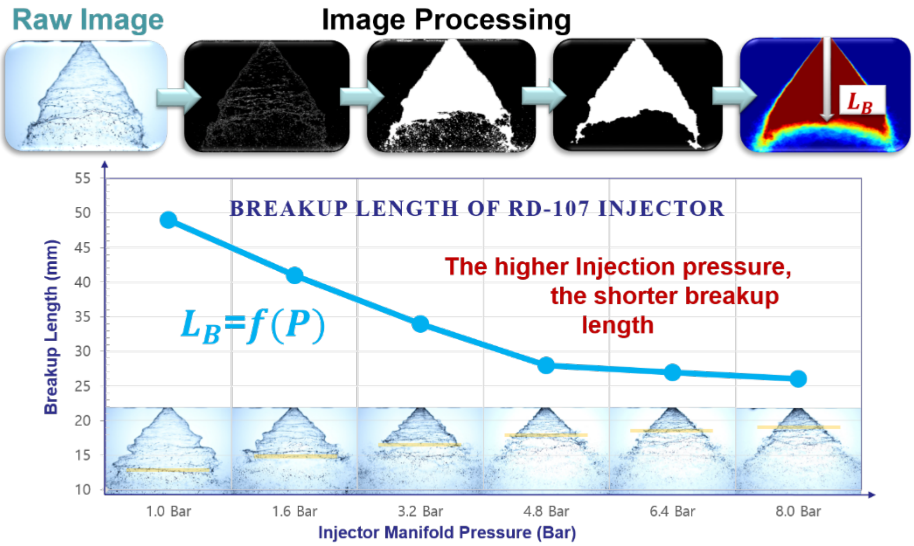

Figure 3.8 Breakup length of RD-107 Injector

As discussed earlier, breakup length have significant impact on spray effecting mass flux distribution in the downstream area. Accordingly, analyzing injection pressure is important to investigate the spray shape and mass flux distribution of the interacting spray.

To measure the breakup length of the each spray, two things are important. First, definition of the breakup length. Generally, breakup length is defined as length between nozzle outlet and point that swirling sprays are totally opened.

However, this length varies every seconds. So, we can define that length as averaged value during the certain time of period. But detecting and breakup length of instant time is very time-consuming and tedious job. We can make it simple by using mat-lab. code and image processing mechanism. Prof. Dr.-Ing. Cameron Tropea at Institute of Fluid Mechanics and Aerodynamics

Technische Universität Darmstadt binarized the every raw image files and expressed liquid as white dot(1) and background air as black dot(0). After that, averaged thousands images and define breakup length as length between nozzle outlet and first point that value of the point goes below the 0.5; point that chances that air exist more than liquid state at that point.

As shown above Fig. 3.7, break up lengths decrease as injection pressure goes up. Considering previous result of the discussion, we can conclude that more injection pressure means shorter breakup length and more un-stable spray and wide liquid flux distribution.

3.5 Result of Backlight Images with varing Spacing

Now we can discuss the backlight images that vary spacing while injection pressure is hold still. So, every cases show same breakup lengths but impinging lengths are getting larger.

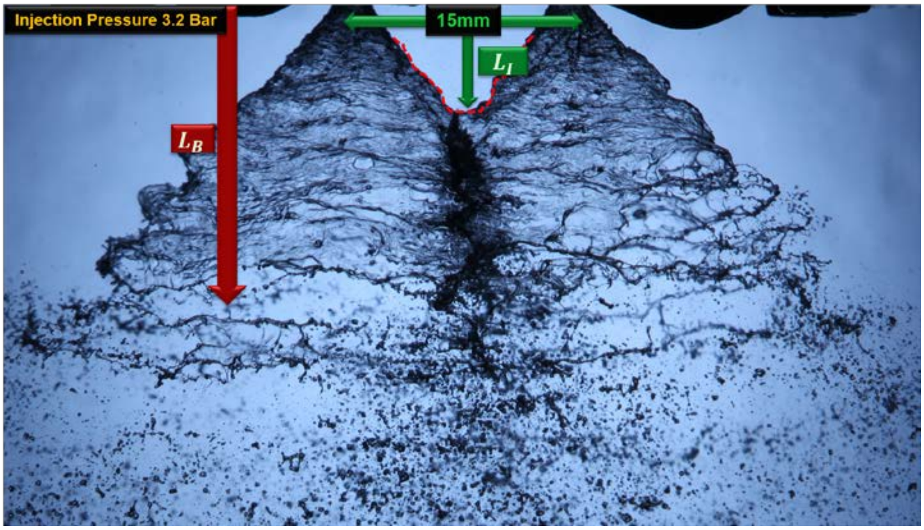

Figure 3.4 Injection pressure is 3.2Bar, Spacing is 15mm

Most closed cases are injection pressure is 3.2Bar and spacing is 15mm cases. As we can see in the fig. 3.8 two sprays are collide with very short impinging length. Therefor relatively stable and thick liquid forms downstream.

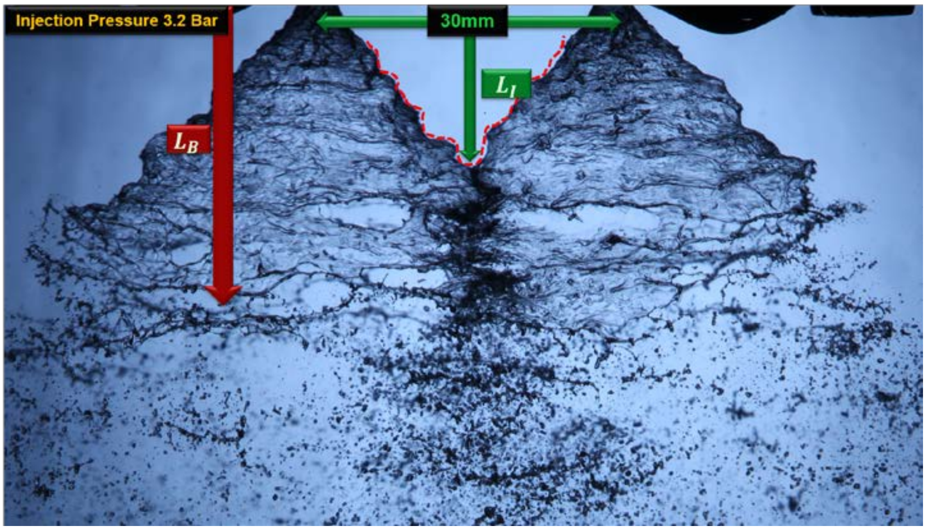

Figure 3.5 Injection pressure is 3.2Bar, Spacing is 30mm

Red spot-line is more unstable and changing into more wavy outline. The longer impinging length of two spray, the more unstable conditions are made when they collide while breakup length of each sprays are stay still. So, more ligament like spray conditions collide at that point. Therefore, more thicker interacting spray formation are made again like higher injection pressure case.

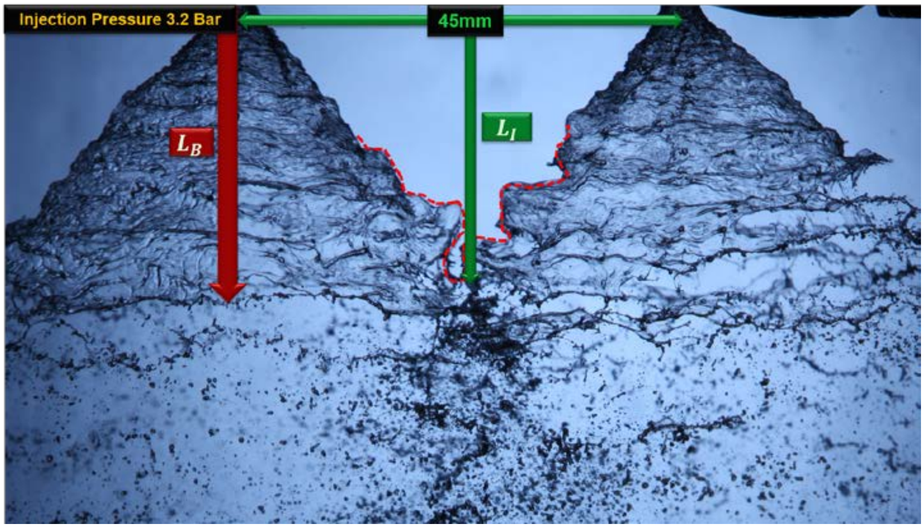

Figure 3.6 Injection pressure is 3.2Bar, Spacing is 45mm

As larger spacing is set, interacting condition change from sheet-sheet interacting condition to droplet-droplet condition. Outline of sprays are much more wavy and curly shape. After they collide, droplet conditions are dominant than any other state. Impinging length and breakup length is nearly same.

To sum up, more spacing means longer impinging length and more unstable condition at colliding point. Therefore, after they collide they form more droplet-droplet atomization state. So, more spacing have analogy with higher injection pressure condition making more wide and scattered mass flux distribution.

3.6 Mechanical Patternator Result

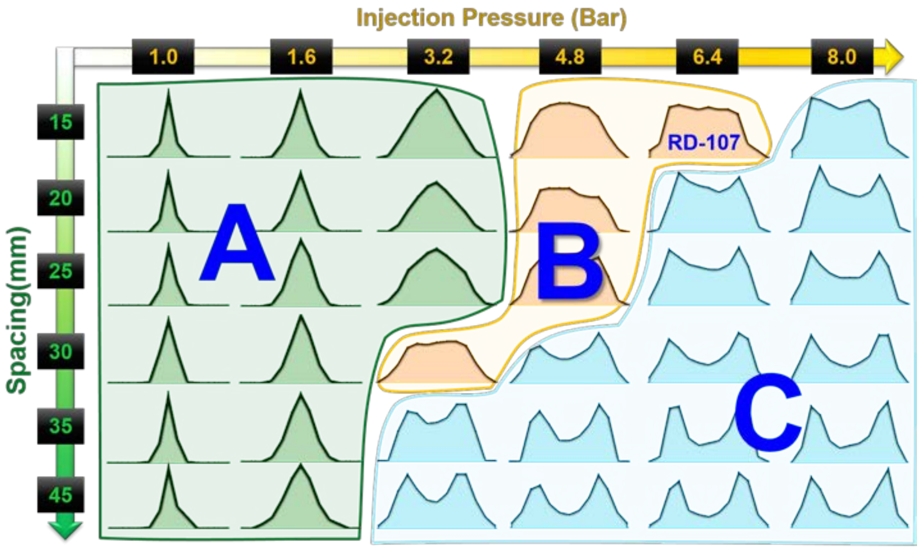

Figure 3.7 Mass flux distribution Result of Mechanical Patternator

To investigate the inside mass flux distribution, mechanical patternator was used to get the quantitative measurement of liquid flux with varing injection pressure and spacing. Mass flux distribution show clear tendency.

First, as injection pressure increase mass flux distribution of interacting spray at downstream of the colliding point is getting wide. At low pressure, almost all mass go in the narrow area shaping thick liquid sheet. Clear and big peak of mass distribution is observed. At high injection pressure Clear two peack of mass distribution are observed showing relatively low mass distributions.

Between two clear tendency, flat and homogenous mass distribution are found in the mid time.

Secondly, as longer spacing between two nozzles centers are set, same tendency are again happen. When two nozzles are close, sharp and clear one peak of mass distribution graph is made as the same case of low injection pressure case. While, spacing is getting larger, again, two clear and sharp peaks of mass distributions are captured.

By adjusting injection pressure and spacing between two nozzles we can make flat and homogeneous mass flux distribution. Considering RD-107 was operated in this condition, we can conclude that this shape of mass distribution is ideal condition.

Three distinct tendency was observed, so we can group their mass distribution graph. Group A is low injection pressure and close spacing case; one clear and sharp mass distribution. Group B is flat and homogenous mass distribution. Group C is two clear peak of mass distribution case.

3.7 Mechanism of liquid collision

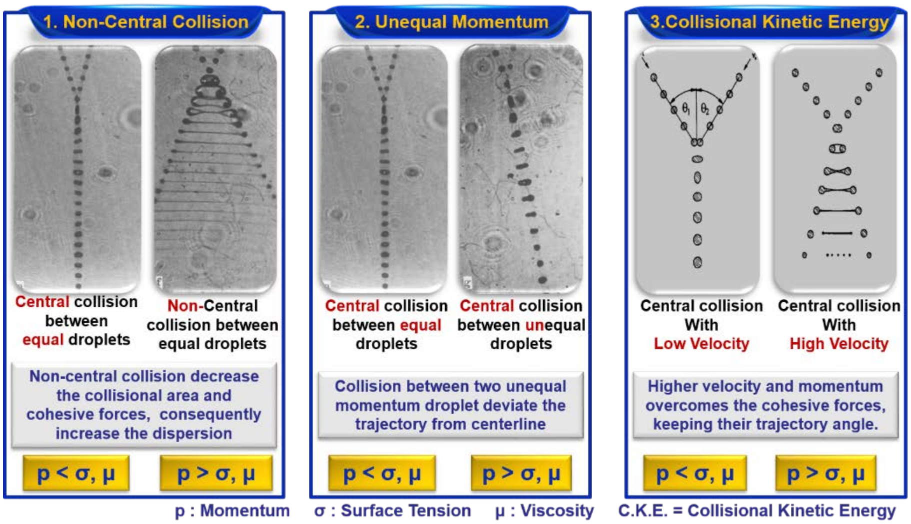

Figure 3.8 Three factor of liquid collision.

There are three factors that make mass distribution wide and divergent other than make one clear peak in the downstream of collision point. First one is 'Non-central collision'. When two same magnitude and speed of droplets collide, there are two cases. First one is central collision, and second one is non central collision. When they collide at central condition state, two droplets make one stable bigger droplet. And they go along the centerline of two trajectory lines. If it is the 'Non-central' collision state they keep their trajectory line so they divert again.

Second factor is unequal momentum. It is most straight forward mechanism.

Dynamics based analysis leads to interpreting result of mass distribution. When one side droplet is larger than the other side, sum of two momentum of two droplets will not be zero and divert again from the centerline of two trajectory.

Thirdly, ‘higher collisional kinetic energy’ makes mass flux distribution wide and divert. Even if their colliding condition is central, they separate again and go keeping their trajectory if they have high C.K.E.. Because C.K.E. is bigger than cohesive forces like surface tension and viscosity. It gives driving force that integrated two droplets break up again.

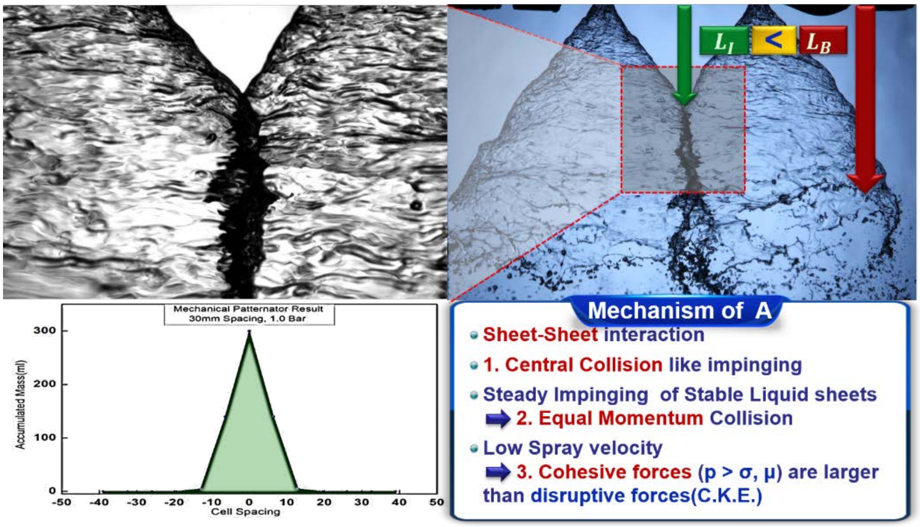

Figure 3.9 Characteristics of Group A.

Two sum up, as shown above Fig. 3.13, group A can be explained as follows. Sheet-Sheet interaction is dominant so, central collision like impinging happens and they collide with relatively equal momentum of liquid dump. Low spray velocity is last characteristics of this group. Therefore, cohesive forces are larger than disruptive forces. So, none of three diverting mechanisms are found on this case.

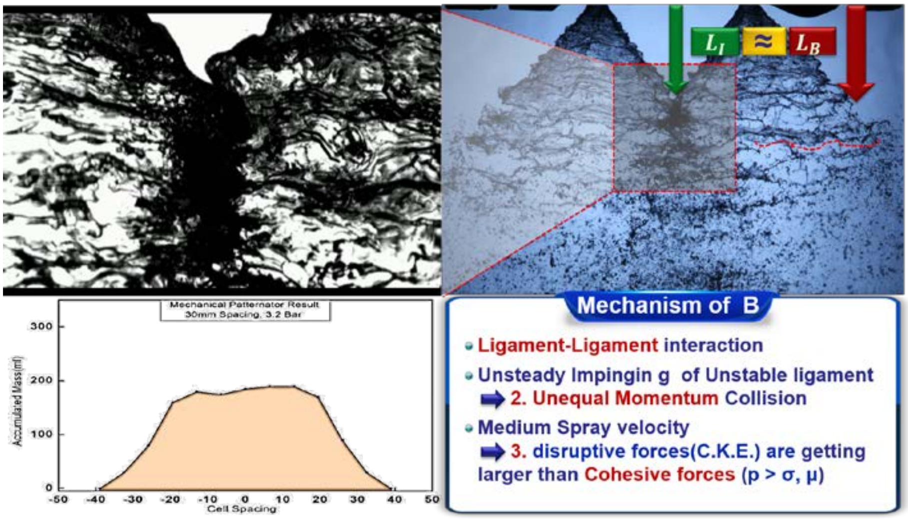

Figure 10 Characteristics of Group B.

Group B is characterized as ligament-ligament based interaction. Accordingly, unsteady impinging of and un-stable ligaments are made. C.K.E. of spray is nearly same with cohesive forces. So they make ligament again after they collides.

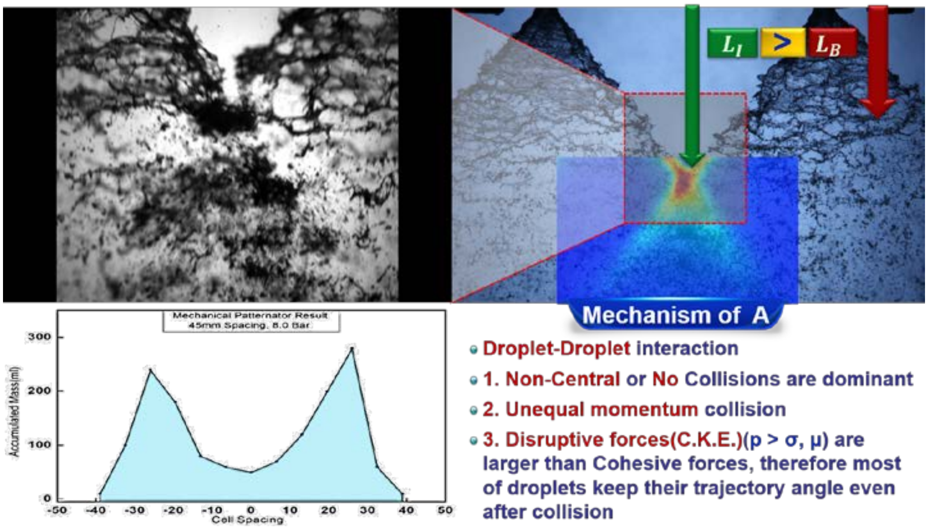

Figure 3.11 Characteristics of Group C.

Finally, group C is characterized as droplet-droplet interaction. All of the three mechanism of diverting mechanism are dominant in all most all colliding. Non-central or no collisions are dominant. Therefore, central collision seldom happens and relatively high injection pressure make high C.K.E. Accordingly, Almost of integrated droplets divert again right after their collision making clear and sharp two peaks of mass distribution graph.

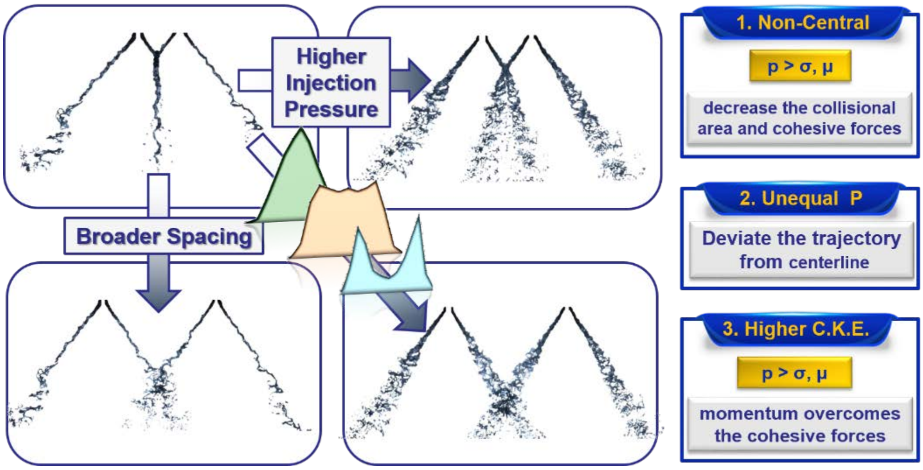

Figure 3.12 Effect of Injection Pressure and Spacing

Finally, we can conclude that both ‘higher injection pressure’ and ‘larger spacing’ contribute to making mass distribution divert and two clear peaks of mass distribution.

Adjusting properly ‘injection pressure’ and ‘spacing’, the most ideal mass distribution are reached; flat and homogeneous. There are three diverting mechanism; non-central collision, unequal momentum, higher collisional kinetic energy. How much these three mechanism happen decide their mass distribution shape; group A, B and C.

Yegorychev’s equation is only valid in ‘Group A’ like region within limited spacing boundary. Co/Counter-Rotating effect should be considered, and mass flux distribution is governed not only by ‘Spacing’ but also ‘Injection Pressure’, ‘Type of fuel and Oxidizer’ and ‘Spray angle’.

Chapter 4. CONCLUSION

Static Characteristics of two interacting sprays are analyzed with varying spacing and injection pressure (using two open type swirl injector). To investigate the mass distribution of the inside interacting spray, optical and mechanical patternator were used. As a result, three distinct mass distribution groups are found and three diverting mechanism are suggested to explain these three tendency. Most important founds are the effect of spacing and injection pressure on mass distribution of the interacting sprays downstream.

This means that liquid rocket engine engineer can get ideal mass flux distribution by adjusting injection pressure and spacing between to center of nozzles. Flat and homogeneous mass distribution is ideal and it can be reached considering these mechanisms.

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초 록

액체로켓 개발에 있어서 가장 중요한 부분 중 하나는 바로 연소실의 설계이다. 연소실, 특히 혼합 헤드의 여러 파라미터들이 연료의 유량 분포에 영향을 주고, 이는 곳 비 추력, 연소 불안정, 효율 등의 로켓 성능의 대부분에 아주 직접적인 영향을 준다. 질유량 분포도는 대부분 각 분무들이 서로 충돌하며 어떻게 상호작용 하냐가 결정한다. 그럼으로 이 현상에 대해 규명하고 분석하는 것은 결국 로켓 개발에 매우 중요한 것이다. 많은 연구자들이 가스터빈이나 디젤엔진에서는 이런 멀티 분사 시스템에서의 상호작용에 대한 연구를 많이 진행하였지만, 소수의 연구자들만이 공식적으로 이 연구를 로켓엔지니어링 분야에서 다루었다.

예고르체프가 그런 소수 중의 한명으로서 수학적 모델링을 통해 연료와 산화제가 충돌 이후 어떤 유량분포를 가지게 될 것인가에 대해서 연구를 하였다. 그는 두 분무 사이에 평면 제트가 형성되고 그 평면 제트들이 모여 4개 이상이 인접하게 되면 그

사이에 액주가 형성되는데 그 액주의 유량을 정규분포함수로 근사하고자 하였다. 그의 유량부포공식과 실제 유량은 매우 일치한 결과를 보여줌을 주장하긴 했지만, 그 수학적 모델링의 제한 조건이나, 실제값과의 괴리가 얼마나, 왜 큰지에 대한 상세한 서술을 하지 않았다. 그리고 결정적으로 가시화를 하지 못함으로써 그 현상 자체를 깊이 분석 하는데 좋은 정보를 제공하지 못했다. 이 모델의 단점을 보완하여 정확한 제한범위를 제시하고 무엇보다 레이저 장비들을 통해 유량 단면을 가시화하며 그 현상을 분석하고 또한 그런 현상이 일어나는 메커니즘에 대해서 서술하고자 했다. 분석 결과, 유량 단면이 세가지 그룹으로 나누어 짐을 확인 할 수 있었다. 그룹 A, B, 그리고 C로 나누게 하는 분리 매커니즘에 대해서도 서술 하였다.

주요어: 액체 로켓 엔진, 멀티 분사 시스템, 분무 간섭, 유량 분포, 충돌 에너지, 기계식 패터네이터, 광학 패터네이터

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