The Distributions of Flow Rate and Mixing Ratio of Two Impinging Jets*

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The distributions of flow rate and mixing ratio are studied about a spray generated by two impinging jets which are generally used for bipropellant liquid rocket systems using hypergol.

The propellant system was simulated by a water model. When two jets impinge together, the total mixing efficiency varies with the impinging angle; it has a minimum value when the impinging angle is nearly 90° . When jets impinge together with different injection pressures from orifices of same sizes, the total mixing efficiency decreases as the difference of the pressure increases.

When the injection pressure is same and the dimensions of orifices are different, the total mixing efficiency varies with the increase of diameters, but the variation is small. When two jets are composed of immiscible liquids, the state of mixing is basically the same as that of miscible liquids.

1. Introduction

In order to get perfect reaction of a great deal of propellants in a small combustion chamber and to get high combustion performance on a bipropellant liquid rocket engine, it is sufficient to keep moderate control of their condition from the state of injection of propellants. So it must be decided whether mixing is prior to moisturing and vaporizing or conversely moisturing and vaporization are prior to mixing in accordance with the nature and combination of propellants.

Especially for those rockets which use hypergolic propellants the reaction of liquid phase⁽¹⁾ is important and the state of mixing of the earlier period of injection of fuel and oxydizer affects the condition of subsequent combustion.

In this report, we studied the distribution of flow rate and mixing ratio of two impinging jets using a water model instead of real propellants. And we measured the influences of pressure, difference of diameters of orifices etc., on their mixing.

In order to evaluate the mixing we introduced a conception of total mixing efficiency. Moreover the characteristics of mixing of immiscible materials were compared with those of miscible materials.

rials.

2. Testing equipment and procedure

2.1 Equipment for injecting water

The equipment for injecting water consists of two parts pressurizing part and injecting part. Fig.1 shows the equipment schematically.

The pressurizing part contains two water tanks pressurized by compressed air. The two tanks are filled with two kinds of water, one of which is pure water and the other is dyed water or water containing NaCl or other material, in order to measure the mixing ratio corresponding to each

Fig. 1 Schematic diagram of the equipment

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method. The injecting part consists of a face plate and a receiving block. The face plate is set vertical and has two injection cylinders, on which injection pieces with round orifices are fixed. The receiving block has a horizontal plane which holds copper tubes of different diameters on the top. Diameters of tubes are so selected as to keep the quantity of water entering the tubes nearly constant. Water falling into the tubes is led to test tubes under the receiving block through pipes of vinyl chloride. Water collected in test tubes is measured by a mess-cylinder of 0.1 cc scale.

2.2 Equipment for measuring the mixing ratio

We employed two methods to measure the mixing ratio of two kinds of water falling on each place. One method is to measure the depth of colored water which is a mixture of pure water and dyed water.

To measure the density of water a colorimeter with photo-electric tube was used. The other is to measure the electric resistance of salt water which is a mixture of pure water and salt water which contains about 3 g of NaCl per 1 litre of pure water.

In order to measure the electric resistance of salt water a bar of synthetic resin with electrodes of stainless steel and an A.C. bridge were used. This method was simple but the electric resistance of solution was appreciably varied with temperature, so that the measurement was done in a room with constant temperature. Calibration of density was done by comparing the sample with a standard solution which was prepared by weighing the two liquids.

2.3 Inclined angle of jet spray

When sizes or injection pressures of two jets are not the same, the center line of the spray produced by impingement had some angle to the line that divided the injection angle into equal parts. This angle ε is calculated from the relation of reservation of momentum:

$$\tan \varepsilon = \frac{\rho_1 A_1 v_1^2 - \rho_2 A_2 v_2^2}{\rho_1 A_1 v_1^2 + \rho_2 A_2 v_2^2} \tan \alpha \quad \dots\dots\dots (1)$$

where ρ_1, ρ_2 are densities of two kinds of liquid, A_1, A_2 are areas of section of orifices, v_1, v_2 are their injection velocities and α is half the impinging angle. When injection pressures of two jets are p_1 and p_2 under the assumption that discharge coefficients are equal, we get

$$\tan \varepsilon = \frac{A_1 p_1 - A_2 p_2}{A_1 p_1 + A_2 p_2} \tan \alpha \quad \dots\dots\dots (2)$$

3. Definition of mixing ratio

The distributions of flow rate and mixing ratio of spray are affected greatly by the differences in

impinging angle, impinging pressure and other factors. Mixing ratio of the mist scattered by impingement is peculiar depending on the situation and its value sometimes much deviates from the injection mixing ratio in some kinds of injection system. When such injection system is used for a rocket engine, the combustion of the engine becomes poor and it causes combustion instability. We selected a certain range where the mixing ratio of propellants was suitable for combustion; this may be called suitable mixing range. Total mixing efficiency of the injection system was defined as the ratio of the weight of suitable mixing range to the total weight of mixture. For the injection system with two equal jets the total mixing efficiency is defined as follows:

$$\eta = \frac{\sum_{n=0}^n \left[\frac{\Delta q}{\Delta n} / \frac{q}{50} \Delta n \right]}{\sum_{n=0}^{50} \left[\frac{\Delta q}{\Delta n} / \frac{q}{50} \Delta n \right]} \times 100 \quad \dots\dots\dots (3)$$

where q is total water flow rate, Δq is water flow rate at some point, n and $n + \Delta n$ is the range of deviation of mixing ratio from the injection mixing ratio about the quantity of Δq and suitable mixing range is between 0 and n . For the case of an injection system with two different jets we selected the suitable mixing range from the equivalence ratio corresponding to that of two equal jets.

The total mixing efficiency in this case was calculated as follows. Define ϕ as the mixing ratio of two jets at some point, ϕ_s as injection mixing ratio and ϕ^* as equivalence ratio, then $\phi^* = \phi / \phi_s$. Now m_a and m_b are masses of two kinds of liquid at that point, then the deviation of mixing ratio n is as follows:

$$n = \frac{m_a - m_b}{2(m_a + m_b)} \times 100 \quad \dots\dots\dots (4)$$

combine with $\phi = m_a / m_b$ and we get

$$n = \frac{\phi - 1}{\phi + 1} \times 50 = \frac{\phi^* \phi_s - 1}{\phi^* \phi_s + 1} \times 50 \quad \dots\dots\dots (5)$$

If the suitable mixing range is from ϕ_1^* to ϕ_2^* , values of n_1 and n_2 corresponding to these equivalence ratios are calculated by Eq. (5). Then the total mixing efficiency is given by the equation.

$$\eta = \frac{\sum_{n=n_1}^{n_2} \left[\frac{\Delta q}{\Delta n} / \frac{q}{100} \Delta n \right]}{\sum_{n=0}^{100} \left[\frac{\Delta q}{\Delta n} / \frac{q}{100} \Delta n \right]} \times 100 \quad \dots\dots\dots (6)$$

If we assume the suitable mixing range for the case of two equal jets as 50%~10%, ϕ^* becomes 1.5~0.67.

4. Experimental result and consideration

4.1 Mechanism of mixing of jets

When two jets impinge at some angle and if they have considerable speeds, they have a tendency of penetrating each other⁽²⁾⁽⁸⁾. In order to observe the behavior of these sprays, the appearance of jets from orifices whose inner diameters are 2 mm ϕ and 1.4 mm ϕ , was taken by camera with a flash of 3 μ sec using "micro flash" apparatus. Fig. 2(a) shows the state of small injection pressure, in this case a jet is a "smooth flow" and there is no perturbation on the surface. Near the point of impingement two jets join together and spread outward in a shape of disc, and become thinner and thinner until they resolve into fine particles.

(a) $p_1 = p_2 = 0.01$ atg (b) $p_1 = p_2 = 0.8$ atg
Fig. 2 Two impinging jets

If two jets are coloured with different dyes, streams do not penetrate and the colour of one side is the same as that of jet of the same side. (b) shows the state of 0.8 atg of injection pressure; on the surface of jets there is seen a perturbation. Spray produces rings of turbulence, thick and thin, just after impingement⁽⁴⁾. Rings produced near the impinging point spread radially outward and become thinner and thinner until they are broken into fine particles. When two jets impinge, they change their direction by pushing off each other.

Especially when a slender jet at high velocity impinges with a fat jet at low velocity, the former does not mix with the latter immediately, but runs straight forward, splitting the latter sidewise, and slightly changes the direction by receiving momentum from the latter. If a turbulence of streams is large enough compared with the relative velocity of two jets, rugged parts of the turbulence eat into the opposite jet and penetrate to the other side, but if the turbulence is small, this phenomenon will not occur and it will run skirting around it. Therefore a phenomenon of penetration scarcely occurs on a thin boundary layer as in cross

Fig. 3 Distribution patterns of flow rate and mixing ratio (impinging angle varied)

passage in closed pipes.

4.2 Effect of impinging angle in the case of two equal jets

In the case of same orifices and same injection pressure ε becomes zero as may be shown by Eq. (2). In this case distributions are on the receiving plate symmetric about two axes which are shown on Fig. 4 as OX and OY. Equi-flow lines and equi-mixing lines on the receiving plate which was calculated from mean values by the two symmetrical lines are shown on Fig. 3. Full lines show equi-quantity lines and broken lines show equi-mixing lines. Equi-mixing lines are equi-density lines calculated from ratio of partial quantity of one jet (in direction Y) to total quantity (in two jets) which were collected at each point. When the impinging angle is small, the equi-flow line assumes a shape of ellipse whose short axis is in the direction of injection, and as the impinging angle increase, corners spread toward the direction of injection, so the shape becomes diamondlike. When the impinging angle increases more than about 90° , the equi-flow line moves toward the line of injection, taking a flat shape again.

Distributions of flow rate on the line of two symmetrical lines varying from 70° to 110° are shown on Fig. 4. In the case of $2\alpha_0 = 70^\circ$ much flow concentrates on center but as $2\alpha_0$ increases, the area of center decreases; when $2\alpha_0$ is nearly equal to the flow at center, it becomes minimum; and as $2\alpha_0$ increases further, it begins to increase

Fig. 4 Distribution of flow rate on OX and OY axis

again. Distributions of mixing ratio on the OY axis are shown on Fig. 5. Total mixing efficiency calculated from these data by varying the injection angle is shown on Fig. 6. It is indicated that the total mixing efficiency reaches a minimum in the range of $80^\circ \sim 90^\circ$ injection angle.

4.3 Effect of injection pressure on two jets of same dimensions

We studied the effect of impinging pressure on two jets having same dimensions i.e. $\varepsilon = 0$. Distribution curves of same orifices i.e. $d_1 = d_2 = 1$ mm under varying injection pressure from 1 atg to 4 atg are shown on Fig. 7(a), (b). Distribution of flow rate on Y-Y' axis is shown on Fig. 9 on such scale as to make the total flow equal to standard state with injection pressure 2 atg. Distribution of mixing ratio on Y-Y' axis is shown on Fig. 9. On Fig. 7(b) the equi-flow line is nearly ellipse on center area but it extends toward four corners and becomes similar to a diamond shape on periphery.

A point of inflection occurs on the part where

Fig. 5 Distributions of mixing ratio on Y-Y' axis

Fig. 6 Total mixing efficiency versus injection angle

the ellipse changes to a diamond on Fig. 8, and as the injection pressure increases, the point of inflection seems to become more distinct for the flow rate of center area decreases. The part of main mist which collects at the center where momentums of both jets cancel each other and accordingly their mixing ratio is equal to that of injection, and the part of inclined mist which runs penetrating the other are separated distinctly. For

these reasons the total mixing efficiency becomes worse as the injection pressure increases. Several curves on Fig. 9 are similar in their inclination except at 0.7 atg. When the injection pressure is 2 atg, the axis of X-X' direction is longer than that of Y-Y' direction, but when the injection pressure is 1 atg, the axis of X-X' direction becomes shorter than that of Y-Y' direction.

Through these phenomena the total mixing

Fig. 7 Distribution patterns of flow rate and mixing ratio (injection pressure varied)

Fig. 8 Distribution of flow rate on Y-Y' axis

Fig. 9 Distribution of mixing ratio on Y-Y' axis

efficiency becomes worse again because a greater portion gets outside of the proper mixing range. In such state the distinction is lost between main mist and inclined mist and there is no longer any such point of inflection on the distribution curve as on Fig. 8. For this reason a maximum point appears near the injection pressure of 2 atg.

4.4 Effect of ratio of injection pressure

Effect of ratio of injection pressure was studied, changing the ratio of pressures of two jets with

orifices of same dimensions.

ε was changed according to Eq. (2). Patterns of distributions are shown on Fig. 10. Chain lines indicate suitable mixing ranges whose equivalence ratio is between $\phi^*=0.67$ and $\phi^*=1.5$.

When $\varepsilon=0$ i.e. both injection pressures are equal, the pattern is symmetrical to X-X' axis as on Fig. 3 but as ε becomes greater, the equi-flow lines become flat on higher pressure side. On the contrary, the equi-mixing lines become convex toward high pressure side and their curvature becomes sharper on lower pressure side.

Some equi-mixing lines near 10%

Fig. 10 Distribution patterns of flow rate and mixing ratio (ratio of injection pressure varied)

Fig. 11 Distribution of flow rate on Y-Y' axis

Fig. 12 Distribution of mixing ratio on Y-Y' axis

make a loop as in the figure.

As ε becomes greater, the shape of equi-flow lines is changed gradually and the shape of equi-mixing lines becomes more and more convex toward high pressure side so that suitable mixing range moves out of the center, namely the concentration of the district of maximum flow rate becomes lean. On Fig.11 the scale is so defined as to make the flow rate of center of symmetrical jets i.e. $\varepsilon=0$ equal to unity. Distribution of mixing ratio is shown on Fig.12 which indicates that inclinations of the curves hardly change and the proper mixing range falls outside of center. A jet with lower velocity spreads easier but a jet with higher velocity cannot spread at once.

The forward portion of a jet near the plane of impingement spreads sidewise, but the backward portion of it cannot spread at once and changes its direction slowly under the effect of the former portion so that extent of changing direction is small. For this reason, as ε increases, much flow concentrates on one district.

From the above we know that the value of total mixing efficiency decreases rapidly as ε becomes larger. Relation between ε and η is shown on Fig.13.

4.5 When ratio of injection pressuers is constant but their values are varied

Cases with changing values of injection pressures and with keeping constant of ratio of them were studied. Fig.14 shows equi-mixing ratio lines drawn from distribution of flow for each changing value of injection pressures with same ratio of $p_1/p_2=2.25$ i.e. $\varepsilon=21^\circ 5'$.

Distributions of flow rate on Y-Y' axis are shown on Fig.15.

On this figure the flow rate is so converted as to make the total flow equal in each case. From these figures it is clear that the shapes

Fig.13 Total mixing efficiency versus inclined angle of jet

of distribution curves are almost similar but the flow rate at center points decreases as the injection pressure increases. This phenomenon is the same as on two equal impinging jets mentioned before.

It is because the main jet of center part is split out as the velocity increases i.e. the injection pressure becomes high. Thus at the central part where much flow is concentrated, the equi-flow rate lines are triangular shape spreading toward both shoulders as on Fig.14(a), but as the injection pressure increases, these shoulders drop gradually

Fig.14 Distribution patterns of flow rate and mixing ratio (ratio of injection pressure not varied)

as on Fig.14(b). In this way the proper mixing range decreases gradually as the velocity of jets increases, so that the total mixing efficiency becomes rapidly worse.

4.6 Effect of difference in diameters of orifices

The equi-flow lines and equi-mixing lines with two injection pressure being equal and diameters of two orifices different are shown on Fig.16.

In this case the equi-mixing lines and equi-flow lines are curved toward same side, so that the total mixing efficiency does not become so poor as when the injection pressure is varied. In this state the jet speeds of both sides are equal, so that both flows change their direction and mix with each other under same condition. For this reason there does not occur any state of splitting that is observed when the jet speeds are different. Flow distribution on Y-Y' axis is shown on Fig.17. Distribution of mixing ratio on Y-Y' axis is shown on

Fig.15 Distribution of flow rate on Y-Y' axis

Fig.17 Distribution of flow rate on Y-Y' axis

Fig.18. Proper mixing range is narrow when the difference of diameters is great. The relation of total mixing efficiency versus diameter ratio is shown on Fig.19. The efficiency decreases as the difference of diameters increases, but the rate of decrease is not large.

4.7 Two insoluble jets

As working liquid we used water for both jets until now, but actual propellants may be combinations of insoluble materials. For this reason

(a)

(b)

Fig.16 Distribution patterns of flow rate and mixing ratio (area of diameters of orifices are varied)

water and kerosene were used as two jets. The specific weight of kerosene was 0.79. Mixture of water and kerosene collecting in test tubes by injection apparatus was separated into two phases in a short time, and each volume was measured by a mess-cylinder. From Eq.(2) angle ε is zero although specific weight is not equal when the injection pressure is controlled to same value and diameters of orifices are equal. Distribution curves under conditions of $2\alpha_0=90^\circ$, $p_1=p_2=2$ atg and $d_1=d_2=1$ mm ϕ are shown on Fig.20. This pattern is a little unsymmetric but it is not so much different from the pattern when water was used for both jets. The total mixing efficiency was calculated as 54%. On account of lack of data under the same condition about miscible liquid, we can not make direct comparison between the two states, but there is only a little difference between those states whose conditions are not much different.

Therefore it can be concluded that there

Fig.18 Distribution of mixing ratio Y-Y' axis

Fig.19 Total mixing efficiency versus ratio of diameters

will be any basic difference in mechanism and performance of mixing between miscible and immiscible liquids.

5. Conclusions

Mixing state of two impinging jets was compared in terms of total mixing efficiency with the following conclusions.

(1) In the case of two equal jets, the total mixing efficiency varied with the impinging angle. It has a minimum value near 90° .

(2) In the case of two same jets, when the injection pressure is varied, the total mixing efficiency is maximum when the pressure is about 2 atg.

(3) When diameters of orifices are same, with an increasing ratio of injection pressure, the total mixing efficiency decreases.

(4) When diameters of orifices are same and injection pressure ratio is constant, the total mixing efficiency decreases as the injection pressure increases.

(5) With same injection pressure and with different diameters of orifices the total mixing efficiency decreases as the diameters of orifices increase, but the rate of decrease is small.

(6) There is no basic difference in mechanism of mixing of impinging jets between miscible liquid and immiscible ones.

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Fig.20 Distribution patterns of flow rate and mixing ratio of immiscible materials

References

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Discussion

G. T. SATO: (1) In obtaining Eq. (2) from Eq. (1) it is necessary to consider the discharge coefficient or the velocity coefficient which is a function of R_e , namely a function of viscosity. So I think the statement that "there is no influence of ρ " is unreasonable.

(2) In section 4.4 you made the experiment under the condition of constant flow rate, but there must be other methods as for instance, under the condition of constant pressure.

(3) As a whole it might be more generalised, if you used the expression of R_e , S_b (Stability number), J_e (Jet number) and so on.

T. KURABAYASHI: (4) It has been shown that the total mixing ratio η decreases with increased impinging velocities of the jets. In high speed impinging of the jets, however, the contact area, which may have a major role in combustion phenomena, generally becomes large.

How does the author consider the relation between the effects of weight mixing ratio η and such contact area on combustion?

(5) In section 4.4 where the impinging jets with different flow rates are dealt with, the value of 1.5~0.67 is used as the equivalent flow ratio ϕ^* as is the same with the case of equal flow rates.

Here, however, ϕ^* should be newly defined corresponding to weight mixing ratio $\phi_s = m_1/m_2$

(6) From Eqs. (1) and (2), we may write for the injection pressure drop p in the following form:

$$p \propto \rho A (=1) v \cdot v$$

which shows p is proportional to the momentum of flowing liquid in unit area. Since, in section 4.7, liquids with different densities ($\rho_1 \neq \rho_2$) are impinged together under the same pressure $p_1 = p_2 = 2$ atg, v_1 and v_2 should be different.

(a) Are the values of v_1 and v_2 presented in Fig. 20 defined by the above relation?

(b) If the experiment is performed under $v_1 = v_2$, the deflection angle does not become zero from Eq. (2). Because p_1 is equal to p_2 .

It seems that the slight shift of the equi-

tions on the following points which would clarify the relations between experiments of this report and practical combustion.

(a) What is the optimum range of mixing ratio of two liquids in actual combustion? And what are the jet pressures? Do they fall in the range of these experiments?

(b) Is it necessary that the jet pressures of two liquids be equal in actual combustion? Are they controlled separately?

(c) Which is preferable and more important: to have good atomization or to have high mixing efficiency η ? According to one conclusion of this report, the jet pressure seems to be quite low (lower than 0.7 atg) in order to have high value of η , but in my opinion, it would be more important to have good atomization for good combustion. So I think the jet pressure should be high enough, although η may be low.

(d) What is the optimum value of angle ϵ for actual combustors?

(e) Is there any experiment on the case of $\epsilon = 0$, with difference in flow rate and jet pressure between two liquid?

(8) What is the mechanism of cross penetration of two liquids?

(9) For combustion of two liquid fuels, there should be other methods; for instance, to have a separate swirl nozzle atomizer for each fuel, or to have a pre-mixed swirl nozzle atomizer, etc.

Even by the atomizing method using collision of two liquid jets, there should be other jet types; for instance, plate type.

Does the method of this report which uses collision of two cylindrical jets has any superiority?

(10) Give us some informations about the spray size adopted in this experiment reported here.

Author's closure

(1) In the process of reducing Eq. (2) from Eq. (1) there appear terms containing the discharge coefficient which is a function of R_e , as in your opinion. But concerning the mixing of impinging

velocity under careful mechanical finish of inner diameters of orifices.

For these reason the discharge coefficient is assumed to be constant.

The statement that ε is independent of $\rho_1\rho_2$ is not mood in strict sense but in relative sense.

(2) Reason for using constant flow rate in section 4.4 is to make it easy to compare their distributions with each other on Fig.11. State of jets just after orifices may be a waving flow on account of $R_e \cong 1.3 \times 10^4$ from the data under $d_1 = 1$ mm, $d_2 = 1$ mm and $p_2 = 0.93$ atg.

(3) Jets injected from orifices of liquid rockets are almost in the state of wavy flow, and we did not study the states of smooth flow and transition flow. When the back pressure is considerable, it is convenient to use the expression of J_e (Jet number), and to explain phenomena of mixing there is only a little influence of S_b (Stability number) because surface tension and viscosity have little effects compared with other factors. When we get much more data we intend to use R_e number to arrange them.

(4) In combustion of the propellants of hypergol, liquid phase reaction has a great influence on the state of combustion. For this reason, mixing of liquid phase is a problem prior to evaporation.

From the point of view that the extent of contact area is important, the total mixing efficiency does not indicate the effect for combustion directly, but there must be some interval on liquid phase mixing so that the total mixing efficiency defined here seems to have much greater influence on subsequent combustion than the area contacted instantly.

(5) For the case of different injection pressures the mixing ratio is defined, corresponding to injection mixing ratio $\phi_s = m_1/m_2$ as in your opinion, and the equivalence ratio of proper mixing range is selected as $\phi^* = 1.5 \sim 0.67$ which is the same as in the case of equal flow rates.

(6) Injection pressure p shows the reading of the pressure gauge just ahead of the injection equipment on Fig. 1. Pressure drop between the pressure gauge and entrance of orifice is negligible as the leading pipe is big enough. So p may be considered as a magnitude of your opinion, if the discharge coefficient is assumed to be constant.

(a) On Fig. 20 v_1 and v_2 have different values corresponding to the difference of ρ .

(b) In this case ε is set as zero, since momentums of both sides are equal. The distribution areas are a little unsymmetrical. There would be an expected effect of difference of velocity

on v_1 and v_2 as occurred in the case of Fig.10.

(7) (a) For actual hypergolic propellants the optimum range of injection mixing ratio (Oxidizer/Fuel) is ordinarily 4~1 by volume, and the injection pressure drop may be 2~8 atg generally. There may be no clear-cut optimum range of proper mixing ratio, but we think it will be reasonable to use the range referred to in this paper.

(b) It is desirable to minimize the pressure difference of two liquids in order to make the mechanism simple. It is possible to control two pressures independently but this method is not desirable as it complicates the construction.

(c) It depends upon the combination of propellants whether evaporation is prior to mixing or not. For the former case good atomization of spray is preferable but for the case of hypergolic propellants good mixing is much more important. There will be some optimum range of the dropsize of spray which gives good condition of combustion. We have some experimental results showing that too small drops do not give good condition of combustion, but too big one is not good, either. For the reason mentioned above and others the range of injection pressure should not be too low in spite of high value of η .

(d) In the actual combustor the center line of spray is so designed as to point to the center of exhaust nozzle by angle ε which is calculated from the injection mixing ratio, injection pressures and so on.

(e) The experimental results where diameters of orifices are $2\phi \times 1\phi$ and injection pres-

Append-Fig. 1 Distribution patterns of flow rate and mixing ratio (two jets of same flow rates)

tures are $1 \text{ atg} \times 4 \text{ atg}$ are shown on Append-Fig. 1 where the total mixing efficiency is calculated as $\eta \cong 29\%$.

(8) Liquids are pushed out from impinging part as rings of liquid at first and then these rings spread into droplets. The cross penetration is due to eddy turbulence before atomization because there is not seen any aspect of sticking again after atomization in the observation of high speed camera.

(9) There are other types of injector in liquid rockets i.e. pre-mixing type, plate type, swirl type and so on. It is said that much risk of explosion is present with pre-mixing type. Combustion of liquid rocket is very violent so injectors used for rockets have rather simple structure now-a-days; but when the problem of

combustion instability is settled, such nozzles may become useful. Jets of plate type were studied before but there was no particular merit in considering its complexity of structure.

(10) Diameters of droplets of spray have been studied for a long time by many investigators and these diameters can be expected roughly from the environment. [e. g. Y. Tanasawa, *Trans Japan Soc. Mech. Engrs.*, Vol 8, No. 33 (1942), p. II-87, II-100]

It is expected that droplets of too large size or too small size both produce worse results of mixing and combustion. For practical injectors, the sizes of orifices are usually $0.8 \text{ mm} \sim 2.5 \text{ mm}$, and injection pressures fall in a certain range, so that the diameters of droplets of spray may be within some fixed range also.