ARMY RESEARCH LABORATORY

Droplet Entrainment of Breakup by Shear Flow

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ARL-CR-276 October 1995

prepared by

Combustion Propulsion and Ballistic Technology Corporation
1217 Smithfield Street
State College, PA 16801

under contract

DAAA15-92-D0001

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1995	Progress, Sep 1992 - Aug 1993

4. TITLE AND SUBTITLE
Droplet Entrainment and Breakup by Shear Flow

5. FUNDING NUMBERS
C: DAAA15-92-D-0001

6. AUTHOR(S)
Kenneth K. Kuo and F. Bill Cheung

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Combustion Propulsion and Ballistic Technology Corporation
1217 Smithfield Street
State College, PA 16801

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-WT-PA
Aberdeen Proving Ground, MD 21005-5066

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

ARL-CR-276

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The combustion processes of an electrothermal chemical (ETC) gun depend strongly upon the entrainment and breakup of liquid propellant droplets into the Taylor cavity occupied mostly by high-temperature plasma, combustion product gases, and dispersed fine droplets. This report summarizes the existing empirical correlations for entrainment rates. The critical review of these correlations and their applicability to ETC gun environments is given. The required work for future development of a more adequate entrainment correlation, excluding the effect of droplet deposition to the liquid propellant, is proposed.

14. SUBJECT TERMS
electrothermal chemical (ETC) gun, droplet entrainment rate, roll wave, droplet breakup, Kelvin-Helmholtz instability, plasma/liquid propellant interaction, entrainment correlation

15. NUMBER OF PAGES
46

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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ACKNOWLEDGEMENT

This work is being sponsored by the Army Research Laboratory under the management of Ms. Gloria P. Wren. Her encouragement and support are greatly appreciated.

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1. Introduction

A considerable amount of research effort has been initiated in the past few years in the electrothermal chemical (ETC) gun area. An ETC gun makes use of the electrical energy from an external power supply as well as the chemical energy from liquid propellants to generate the thrust for driving a projectile. By tailoring the electrical power input, it is possible to control the energy transfer, from electrical energy to thermal energy and finally to projectile energy, in the gun system. With this arrangement, a non-abrasive working fluid with low molecular weight gaseous products can be chosen to increase the impetus and reduce gun barrel erosion, as the selectivity of the type of liquid propellants is much less restrictive in an ETC gun than in conventional liquid propellant gun. Thus, the projectile kinetic energy of an ETC gun is not limited by the size of the gun. Higher muzzle velocities on the order of 2,000 m/s and smaller gun sizes can be accomplished by tailoring the electrical power source and selecting an appropriate working fluid.

Though an ETC gun provides considerable improvements in gun performance over conventional guns, the feasibility of the ETC gun concept has yet to be demonstrated. The major uncertainties that hinder the development and field application of ETC guns are ballistic repeatability and controllability. To remove these uncertainties, it is necessary to address the issue of plasma/liquid propellants interaction during the interior ballistic processes in ETC guns. The rate of burning of liquid propellants and the processes of energy conversion from electrical/chemical energies to thermal/projectile kinetic energies, depend strongly upon the plasma/liquid propellants interaction in the gun chamber. Until a clear understanding of the phenomena of mixing of plasma and liquid propellants is achieved, it is not possible to optimize the design of ETC guns and predict the actual gun performance.

The primary goal of Task Order #1 is to obtain a better understanding of the phenomena of mixing of plasma and liquid propellants in ETG gun chambers and to assess the extent of usefulness of existing empirical correlations for predicting the entrainment and subsequent breakup of the liquid propellant droplets resulting from the discharge of a plasma jet from the plasma cartridge. Hence the major objectives of this work are: (i) to evaluate the applicabiltiy of existing empirical correlations for liquid entrainment and drop size distribution, (ii) to identify the key elements of plasma/liquid propellants interaction that are not fully understood, and (iii) to perform a theoretical analysis to provide guidance in the development of a suitable correlation applicable to ETC gun conditions. This report summarizes the finding of a critical review of information available in the literature and thereby define basic research needs for future modeling and diagnostic activities that should be pursued in order to acquire the essential information required to accurately predict the ETC gun behavior.

2. Entrainment Mechanisms

From a theoretical point of view, the mixing of plasma and liquid propellants in an ETC gun resembles to the phenomena of droplet entrainment in two-phase annular mist flow, which have been observed and investigated quite extensively in the past. Physically, when two immiscible fluids flow over each other, the interface of the two fluids is inherently unstable. As the relative velocity between the two fluids exceeds a certain critical value, which depends upon the properties of the two fluids, instabilities would set in and grow in the interfacial region, resulting in the formation of wavy interface and large amplitude roll wave. This so-called Kelvin-Helmholtz instability is responsible for the entrainment of liquid droplets from a wavy liquid film into a gas flow. According to this entrainment mechanism, the interface between the plasma and the liquid propellants in an ETC gun can be torn off into fine droplets through interface dynamic interactions caused by the high veliocity plasma jet. Subsequent burning of these entrained droplets provides an important energy transferring process from chemical energy to propulsive energy in the ETC gun (Chen, Kuo and Cheung 1992; Chen, Cheung and Kuo 1992).

Detailed studies of entrainment mechanism have been performed by Newitt et al. (1954), Hinze (1955), Hanratty and Hershman (1961), Chung and Murgatroyd (1965), and Ishii and Grolmes (1975) . In general, entrainment may take place in a number of different ways, depending on the flow situation. Hydrodynamic and surface tension forces govern the motion and deformation of the wave crests. Under certain conditions, these forces lead to an extreme deformation of the interface that results in breakup of a portion of a wave into several liquid droplets. The forces acting on the wave crests depend on the flow pattern around them as well as on the shape of the interface. There are five basic types of entrainment mechanisms for two-phase annular mist flow (Ishii and Grolmes 1975). They are: roll wave, wave undercut, liquid impingement, bubble bursting, and liquid bulge disintegration. A schematic diagram of these five types of entrainment mechanisms is shown in Figure 1.

In the first type of entrainment, roll wave, the drag force acting on the wave tops deforms the interface against the retaining force of the liquid surface tension. The tops of large amplitude roll waves are sheared off from the wave crest by the gas flow and then broken into small droplets. The second type of entrainment, wave undercut, is caused by the undercutting of the liquid film by the gas flow. This mechanism is similar to droplet disintegration by a gas stream. The third type of entrainment, bubble bursting, is associated with the bursting of gas bubbles. The droplets may be generated by the bubble rising to the surface of a liquid. Large droplets can also be formed by the collapse of liquid film between the liquid film and the bubbles. The fourth type of entrainment, liquid

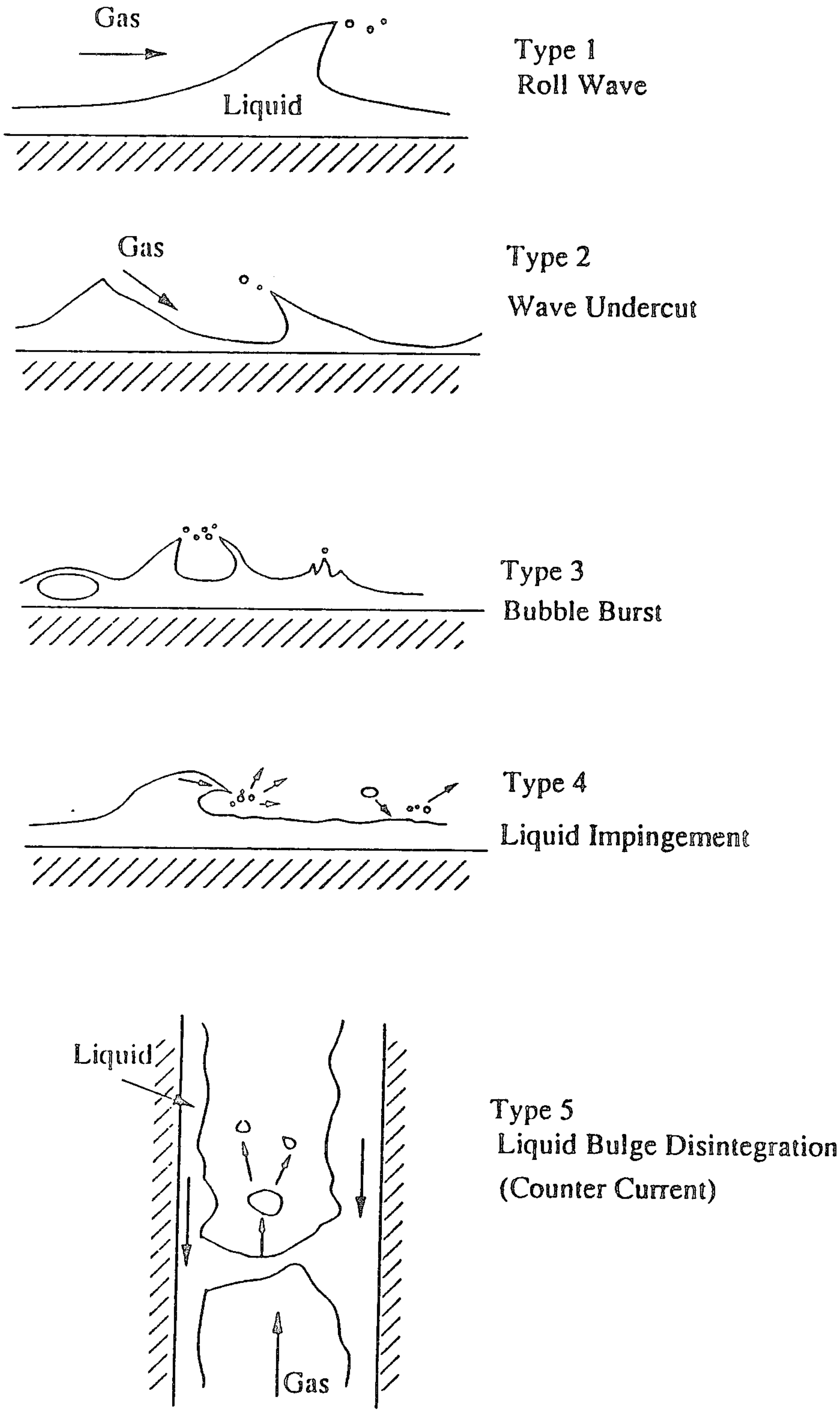

Figure 1. A Schematic Diagram Showing the Five Types of Entrainment Mechanisms

impingement, is caused by the impingement of relatively large liquid droplets to the film interface for production of small droplets. An advancing roll-wave front may also produce small size droplets by this mechanism. The fifth type of entrainment, liquid bulge disintegration, is associated with the flooding phenomena. When a counter-current flow reaches the flooding condition, large amplitude waves can be separated from the film to form a bulge. The bulge then disintegrates into small droplets due to the gas dynamics.

.It is believed that the first four entrainment mechanisms, namely, roll wave, wave undercut, droplet impingement, and bubble bursting could occur in an ETC gun system. However, the roll wave type of mechanism dominates the other types and contributes most of the entrained droplets.

3. Onset of Entrainment

When a gas phase is flowing over a liquid film, the gas-liquid interface may become unstable depending on the magnitude of the gas velocity. For a very small gas velocity, the interface is relatively stable. However, as the gas velocity increases, the interfacial wave appears as a result of Kelvin-Helmholtz instability. The amplitude and irregularity of the waves become more and more pronounced as the gas velocity is further increased. At a sufficiently high gas flow, the interfacial waves transform into large amplitude roll waves. Beyond this point, the interfacial shear forces become greater than the surface tension forces, and the onset of entrainment occurs. The critical condition for entrainment to take place depends on the film Reynolds number, which is defined by

$$Re_f = \rho_f \, j_f \, d_h / \mu_f \tag{1}$$

where ρ_f and μ_f are the density and viscosity of the liquid, d_h the hydraulic diameter of the chamber, and j_f the superficial velocity of the total liquid. The latter quantity includes both the liquid film at the wall and the liquid droplets in the gas core. At high film Reynolds numbers, the mechanism of entrainment is basically due to the shearing-off of roll wave crests by the highly turbulent gas flow. This is deemed to be the case for the plasma/liquid propellants interaction in the interior ballistic processes of an ETC gun.

Inception criteria for the onset of entrainment in annular two-phase flow have been based largely upon experimental data, as reported by Wallis (1962), Zuber (1962), Jensen (1972), Kutateladze (1972), and Ishii and Grolmes (1975a, b). Among others, the criterion developed by Ishii and Grolmes (1975b) appears to be most complete and well tested against a large number of experimental data. They investigated the onset of liquid entrainment by performing a force balance at the crest of roll waves. Droplet entrainment was considered to occur when the retaining force of surface tension, F_σ , is exceeded by the interfacial shear force, τ_i , exerted by the streaming gas flow (see Figure 2). The critical superficial gas velocity at the onset of entrainment was found to depend on the film Reynolds number and the viscosity number of the fluids. The latter quantity is defined by

$$N_\mu = \mu_f \Big/ \left[\rho_f \, \sigma \, (\sigma / g \Delta\rho)^{1/2}\right]^{1/2} \tag{2}$$

where σ is the surface tension and $\Delta\rho$ the density difference between the two fluids. For a horizontal two-phase annular flow with $160 < Re_f < 1635$, the criterion of Ishii and Grolmes (1975b) gives

$$\frac{\mu_f \, j_g}{\sigma} \left(\frac{\rho_g}{\rho_f}\right)^{1/2} \geq 11.78 \, N_\mu^{0.8} \, Re_f^{-1/3} \text{ for } N_\mu \leq \frac{1}{15} \tag{3}$$

and

$$\frac{\mu_f \, j_g}{\sigma} \left(\frac{\rho_g}{\rho_f}\right)^{1/2} \geq 1.35 \, Re_f^{-1/3} \text{ for } N_\mu > \frac{1}{15} \tag{4}$$

where ρ_g and j_g are the density and the superficial velocity of the gas phase. For values of Re_f that are above 1635, a so-called completely rough turbulent regime occurs in which the critical superficial gas velocity becomes independent of the film Reynolds number. This is believed to be the prevailing regime of plasma/liquid propellants interaction in an

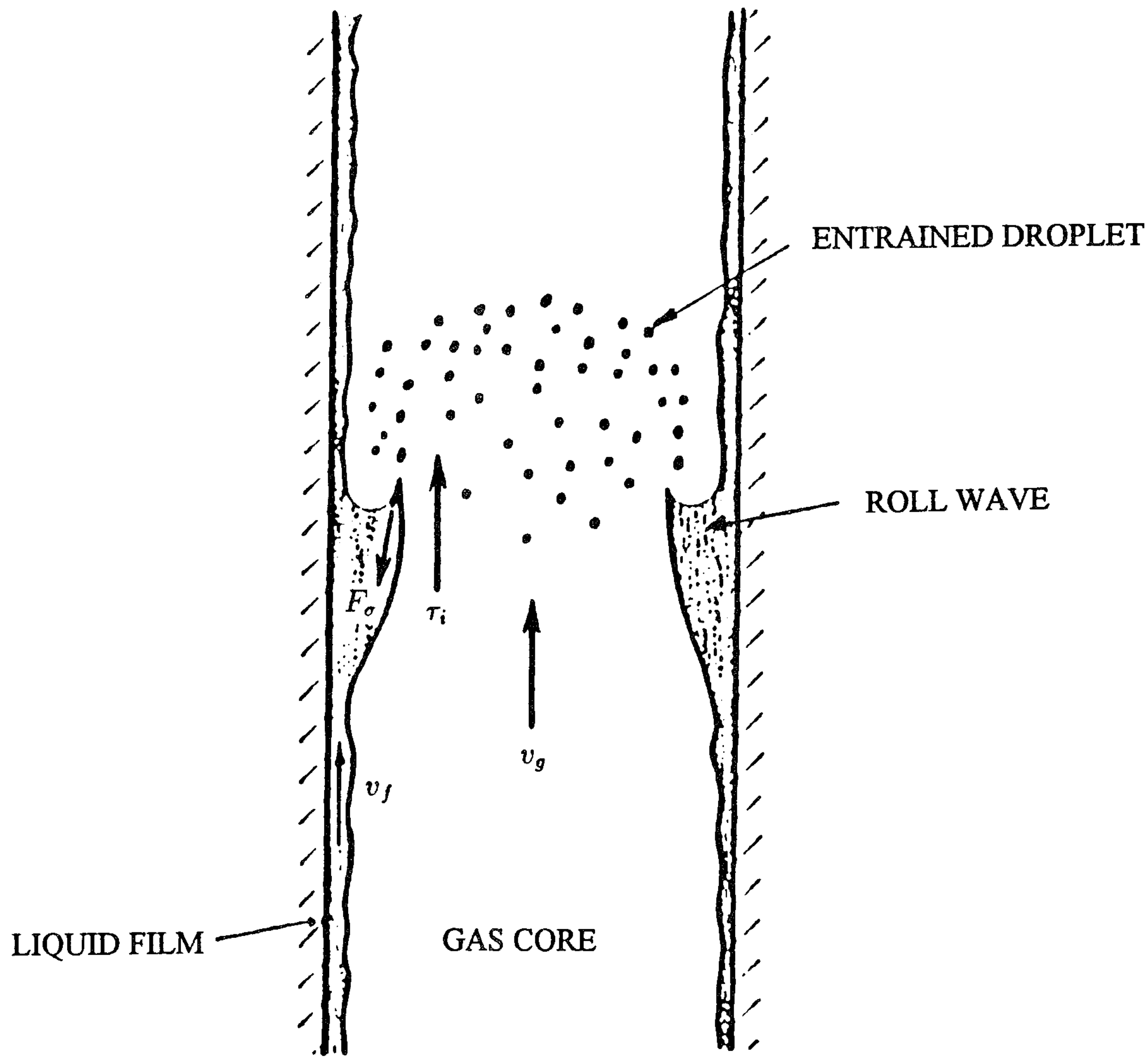

Figure 2. A Schematic Diagram Showing the Forces at the Crest of Roll Waves

ETC gun. According to Ishii and Grolmes (1975b), the inception criterion for this flow regime is given by

$$\frac{\mu_f j_g}{\sigma}\left(\frac{\rho_g}{\rho_f}\right)^{1/2} \geq N_\mu^{0.8} \text{ for } N_\mu \leq \frac{1}{15} \tag{5}$$

and

$$\frac{\mu_f j_g}{\sigma}\left(\frac{\rho_g}{\rho_f}\right)^{1/2} \geq 0.1146 \text{ for } N_\mu > \frac{1}{15} \tag{6}$$

The above inception criterion has been shown by Ishii and Grolmes (1975b) to compare favorably with a large number of experimental data for various types of fluids covering a wide range of the film Reynolds numbers and the viscosity numbers, as illustrated in Figure 3. The inception criterion of Ishii and Grolmes should be applicable to the case of plasma/liquid propellants interaction provided that adequate fluid properties are used.

4. Entrainment Correlations

Empirical correlations for entrainment have been obtained by a number of investigators based upon measured data. There are basically two different techniques for measuring the fraction of liquid flux that is entrained into the gas phase as droplets. The first technique is based on local probe measurements. The measuring device is usually a sampling probe that determines the axial liquid mass flux at the location of the probe. Normally, measurement is made only along the centerline with the assumption that the mass flux is radially uniform. This technique has been used with limited success by Wicks and Dukler (1960), Magiros and Dukler (1961), Wallis (1962), Steen and Wallis (1964), Cousins et. al. (1965), Gill and Hewitt (1968), and Yablonik and Khaimov (1972). The second technique is based on the measurement of the liquid film flow by removing it completely from the test section. This method, which eliminates those uncertainties associated with the local probe measurement, is probably a more accurate measurement

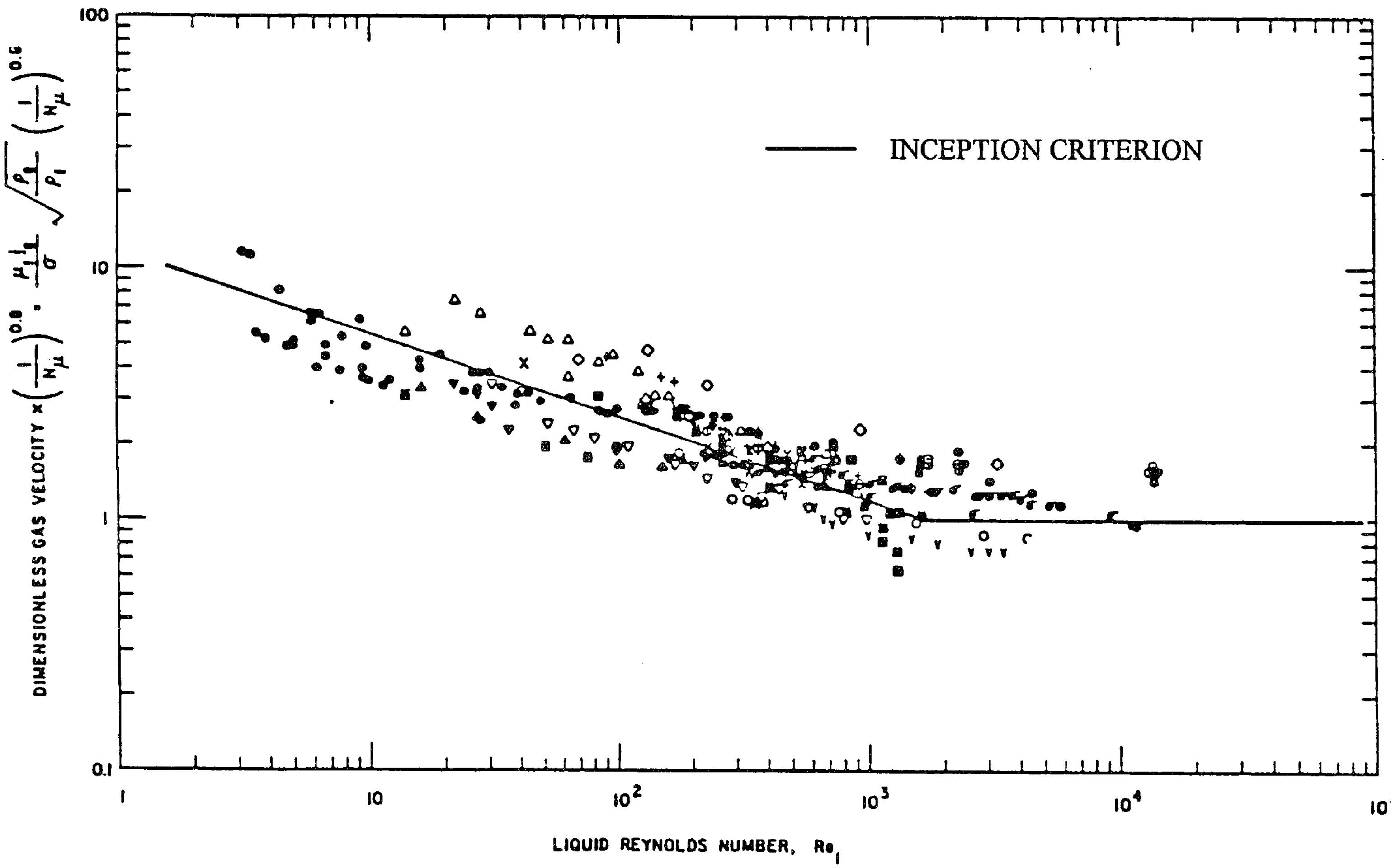

Figure 3. Comparison of the Inception Criterion of Ishii and Grolmes with Data

technique. The liquid film removal method has been employed by a number of investigators including Paleev and co-workers (1962, 1966), Cousins and Hewitt (1968), Petrovichev et. al. (1971), and Ishii and Mishima (1981).

4.1 Correlations for Entrained Fraction

In the interior ballistic processes of an ETC gun, the liquid entrainment that occurs at the interface between the gas core (i.e., the Taylor cavity) and the liquid film, represents one of the key elements responsible for facilitating the transfer of chemical energy to propulsive energy. The entrainment rate governs the droplet formation rate which in turn controls the rate of energy release associated with burning of the entrained droplets. To realistically evaluate the performance of an ETC gun, it is necessary to predict the liquid entrainment rate as a function of the parameters of the gun system.

In the previous studies of droplet entrainment, the rate of entrainment is usually measured in terms of the so-called entrained fraction. This quantity is defined as the fraction of liquid flux flowing as droplets in the two-phase flow system. Many experiments have been carried out for the measurements of the entrained fraction. Correlations of the entrainment data have been performed by a number of investigators based upon various model with limited success. The most relevant entrainment correlations include those reported by Wicks and Dukler (1960), Minh and Huyghe (1965), Paleev and Filipovich (1966), Wallis (1968), Hutchinson and Whalley (1973), Dallman et. al. (1984), and Ishii and Mishima (1989). A brief review and evaluation of each is given below.

(i) Wicks and Dukler Correlation

One of the earlier efforts on entrainment studies was the work of Wicks and Duklers (1960). They reported a correlation that relates the entrainment parameter to the Martinelli parameter X defined by

$$X = \left[(dP/dz)_f \Big/ (dP/dz)_g \right]^{1/2} \tag{7}$$

where the subscripts f and g refer to the liquid and gas phases, respectively, and the quantities in the numerator and denominator represent the single phase pressure drops which would exist if each phase flowed alone. The entrainment parameter, R, is defined by

$$R = \frac{We_c(j_f/j_g)}{(dP/dz)_g} W_d \tag{8}$$

where W_d is the liquid droplet mass flow rate, and We_c the critical Weber number. The latter quantity is defined in terms of the film thickness δ by

$$We_c = \rho_g v_g^2 \delta \Big/ \sigma \tag{9}$$

where v_g is the velocity of the gas phase. The critical Weber number has the value of 22 for smooth entry and the value of about 14 for abrupt entry. Wicks and Dukler (1960) presented their correlation graphically by plotting the entrainment parameter against the Martinelli parameter. Although a reasonable agreement between the correlation and the entrainment data was found, the Wicks and Dukler correlation has two major drawbacks. First, the dependence of the entrainment on various controlling factors is hidden by the use of the Martinelli parameter. Second, the correlation is dimensional which severely limits the range of applicabiltiy.

(ii) Minh and Huyghe Correlation

An empirical correlation was proposed by Minh and Huyghe (1965) that relates the fraction of liquid entrained to the gas core momentum. The entrained fraction, E, was defined as the ratio between the volumetric flux of the droplets, j_d , and the superficial velocity of the total liquid flow, j_f ,i.e.,

$$E = W_d/W_f = j_d/j_f \tag{10}$$

where W_d is the mass flow rate of the droplets and W_f the total liquid mass flow rate including both the liquid film and the droplets. The gas core momentum was defined as the product of the homogeneous density of the gas core and the square of the superficial gas velocity, i.e., $\overline{\rho}_g j_g^2$, where the homogeneous density of the gas core is given by

$$\overline{\rho}_g = \rho_g \left(1 + \rho_f j_d / \rho_g j_g\right) \tag{11}$$

Minh and Huyghe (1965) presented their correlation by plotting E against the gas core momentum. This correlation has very limited application due to two major drawbacks. First, the use of the dimensional parameter results in uncertainties regarding the dependence of the correlation on the fluid properties. Second, the range of applicability is virtually unknown as the effects of many important factors such as the liquid Reynolds number are not included.

(iii) Paleev and Filipovich Correlation

The shortcoming in the Minh and Huyghe correlation (1965) was eliminated by Paleev and Filipovich (1966) by introducing a dimensionless gas flux in correlating the entrained fraction. The dimensionless gas flux is defined in terms of two dimensionless quantities. These are (a) the ratio between the homogeneous density and the liquid density and (b) the product of the liquid viscosity and the superficial gas velocity divided by the surface tension. Based on data fitting, they presented the following empirical correlation:

$$\frac{W_{ff}}{W_f} = 0.985 - 0.44 \log \left[\frac{\overline{\rho}}{\rho_f} \left(\frac{\mu_f j_g}{\sigma}\right)^2 \times 10^4\right] \tag{12}$$

where W_{ff} is the mass flow rate of the film and W_f the total liquid flow rate including the film and the droplets. This correlation showed fairly good agreement with a limited number of data. However, its range of applicability is not well defined as the important effects of the hydraulic diameter and the liquid Reynolds number were not included. Thus the correlation can be employed only under certain specific conditions.

(iv) Wallis Correlation

In an effort to improve the correlation of Paleev and Filipovich (1966), Wallis (1968) introduced a modified dimensionless gas flux by replacing the liquid viscosity by the gas viscosity in the Paleev and Filipovich correlation. He employed a new parameter defined by the following expression:

$$\pi = \left(v_g\,\mu_g/\sigma\right)\left(\rho_g/\rho_f\right)^{1/2} \tag{13}$$

where μ_g is the viscosity of the gas. He then presented his correlation by plotting E against this new parameter. Unfortunately, the range of applicability is not well defined and the dimensionless gas flux used in either correlation is not general enough to account for the effect of fluid properties. The dimensionless gas flux appearing in the correlations for the onset of entrainment (Kutateladze 1972, Ishii and Grolmes 1975b), for example, has indicated that the viscosity dependence is more complicated than those predicted by Paleev and Filipovich correlation and Wallis correlation.

(v) Hutchinson and Whalley Correlation

Hutchinson and Whalley (1973) proposed a mechanistic model to correlate the rates of entrainment and deposition of droplets rather than the equilibrium amount of entrainment used by others. The deposition rate is taken to be a linear function of the droplet concentraion in the gas core, i.e.,

$$\dot{D} = k\,C \tag{14}$$

where k is the mass transfer coefficient. On the other hand, the entrainment rate is considered proportional to the equilibrium concentration, i.e.

$$\dot{E} = k\,C_e \tag{15}$$

The problem then boils down to estimating the equilibrium concentration. Hutchinson and Whalley (1973) presented their results by correlating the equilibrium concentration in a functional form given by

$$C_e = C_e(\tau_i\delta/\sigma) \tag{16}$$

where τ_i is the interfacial shear of the two phase flow and δ the liquid film thickness. Although this correlation method is conceptually more advanced than the previous approach, it has two major drawbacks. First, it is difficult to accurately determine the equilibrium concentration. The data for this quantity showed considerable scattering. Second, the entrainment rate should not be dictated by the equilibruim concentration. Third, in order to estimate the entrainment, two separate correlations, i.e., one for the entrainment rate and the other for the deposition rate, need to be employed. Any error in determining the deposition would add to the error associated with the entrainment rate.

(vi) Dallman, Laurinat and Hanratty Correlation

Dallman, Launrinat, and Hanratty (1984) conducted an experimental study of horizontal annular two-phase flow. They performed measurements of entrainment for air and water flowing in horizontal 25.4mm and 50.4mm pipelines. An entrainment correlation was derived from their experimental data by assuming that the amount of liquid entrained in the gas flow is governed by a dynamic balance between the rate of atomization of the liquid film at the wall and the rate of deposition of droplets from the gas core. The rate of deposition of liquid droplets on the liquid film at the wall was considered to vary linearly with the concentration of the droplets whereas the rate of atomization of the liquid film was assumed to vary linearly with the film flow rate. Under fully developed conditions, the entrainment fraction was found to correlate very well with the gas velocity, v_g , and the hydraulic diameter, d_h , by the following expression:

$$\frac{E}{E_m} = \frac{A\left[(d_h - 2\delta)\,\rho_g^{1/2}\,\rho_f^{1/2}\,v_g^3\right]^{1.5}}{1 + A\left[(d_h - 2\delta)\,\rho_g^{1/2}\,\rho_f^{1/2}\,v_g^3\right]^{1.5}} \tag{17}$$

where A is a dimensional constant having the value of 3.6×10^{-8} in SI unit and E_m the maximun entrainment fraction. The latter quantity is given by

$$E_m = 1 - (W_{ff})_c / W_f \tag{18}$$

where $(W_{ff})_c$ is the so-called critical film flow rate. Physically, this represents the critical thickness of the liquid film below which no further atomization occurs. The critical film flow rate has been determined by Dallman et al. (1984) as a function of the ratio between the droplet mass flow rate and the mass flow rate of the gas. Their results are shown in Figure 4 along with the value of critical flow ratio reported by Woodmansee and Hanratty (1969) for comparison.

The above entrainment correlation indicates that the entrained fraction increases very quickly with increasing gas velocity once the inception criterion is met. At moderate gas velocities, the entrainment rate increases with the third power of the gas velocity. At high gas velocities, a limiting condition is reached where the flow in the liquid film equals to the critical film flow rate. This limiting condition was referred to as the "fully entrained atomization region". Beyond this limit, the entrainment does not increase with increasing gas velocity. Rather, it assumes an asymptotic value equal to the maximum entrainment fraction.

The Dallman, Laurinat, and Hanratty correlation was shown to compare satisfactorily with experimental data obtained at different fluid velocities, gas densities, and pipe diameters. Unfortunately, the applicability of the correlation is rather limited due to (i) the dimensional form of the correlation and (ii) the dependence of the entrainment fraction on the critical film flow rate. The assumption of fully developed conditions, i.e., a dynamic balance between deposition and atomization, also renders the correlation invalid when applied to the case of mixing of plasma and liquid propellants in an ETC gun.

(vii) Ishii and Mishima Correlation

Recently, Ishii and Mishima (1989) developed an advanced mechanistic model based upon the mechanism of roll wave entrainment. They considered the shearing-off of roll wave crests to be the dominant mechanism of liquid entrainment into the gas core in annular two-phase flow. Droplet entrainment would result whenever the retaining force of surface tension is exceeded by the interfacial shear force exerted by the streaming gas flow. They postulated that the same forces considered for the onset of entrainment also

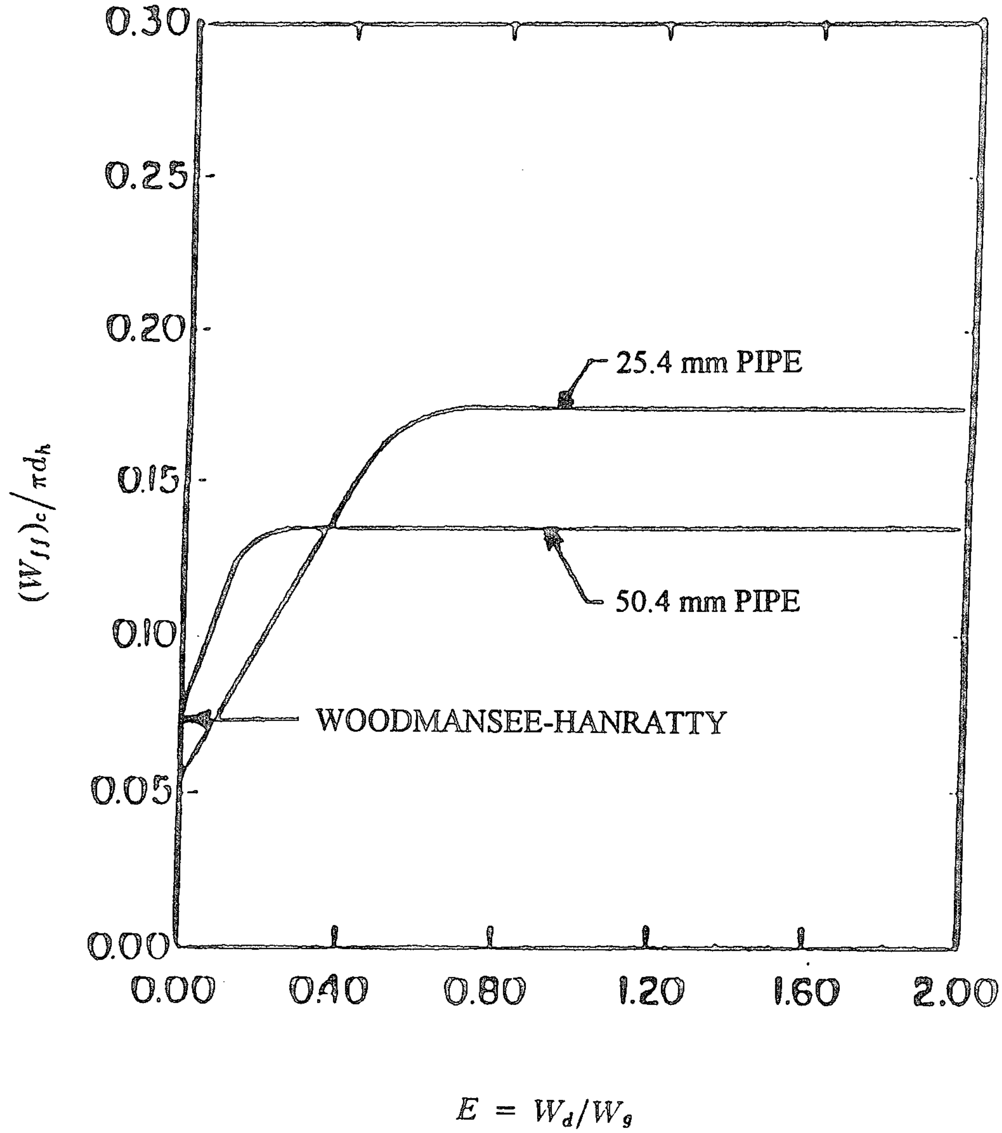

Figure 4. Variation of the Critical Film Flow Rate with the Mass-Flow-Rate Ratio

control the process of entrainment itself. However, a modification of the inertia of the gas core flow is required in order to account for the effect of droplet inertia. This modification was deemed necessary as there are many droplets flowing in the gas core along the liquid-gas interface. Based upon their mechanistic model and the available entrainment data, they successfully developed a correlation for the fraction of liquid flux flowing as droplets. Under an equilibrium condition in which the deposition rate exactly balances the atomization rate, the entrainment fraction was correlated in the following form:

$$E = \tan h(7.25 \times 10^{-7}\eta) \tag{19a}$$

$$\eta = \widetilde{We}^{1.25} Re_f^{0.25} \tag{19b}$$

where Re_f is the liquid film Reynolds number and $\widetilde{We}$ an effective Weber number. The latter quantity is defined in terms of a dimensionless gas flux, j_g^* , and a dimensionless diameter, D^*, as follows:

$$\widetilde{W}_e = j_g^{*2} D^* \tag{20}$$

where the dimensionless gas flux and the dimensionless diameter are given by

$$j^* = j_g \Big/ \left[\frac{\sigma g \Delta\rho}{\rho_g^2}\left(\frac{\rho_g}{\Delta\rho}\right)^{2/3}\right]^{1/4} \tag{21}$$

and

$$D^* = d_h(g\Delta\rho/\sigma)^{1/2} \tag{22}$$

Note that the dimensionless diameter is simply the hydraulic diameter of the channel scaled by the Taylor wavelength.

The Ishii and Mishima correlation, which compares favorably with a large number of data (see Figure 5), is probably the best correlation available today. Unfortunately, the entrained fraction represents the equilibrium value that includes the contribution due to droplet deposition. Thus, the Ishii and Mishima correlation would tend to underestimate the actual entrainment rate in a ETC gun environment as the deposition mechanism has

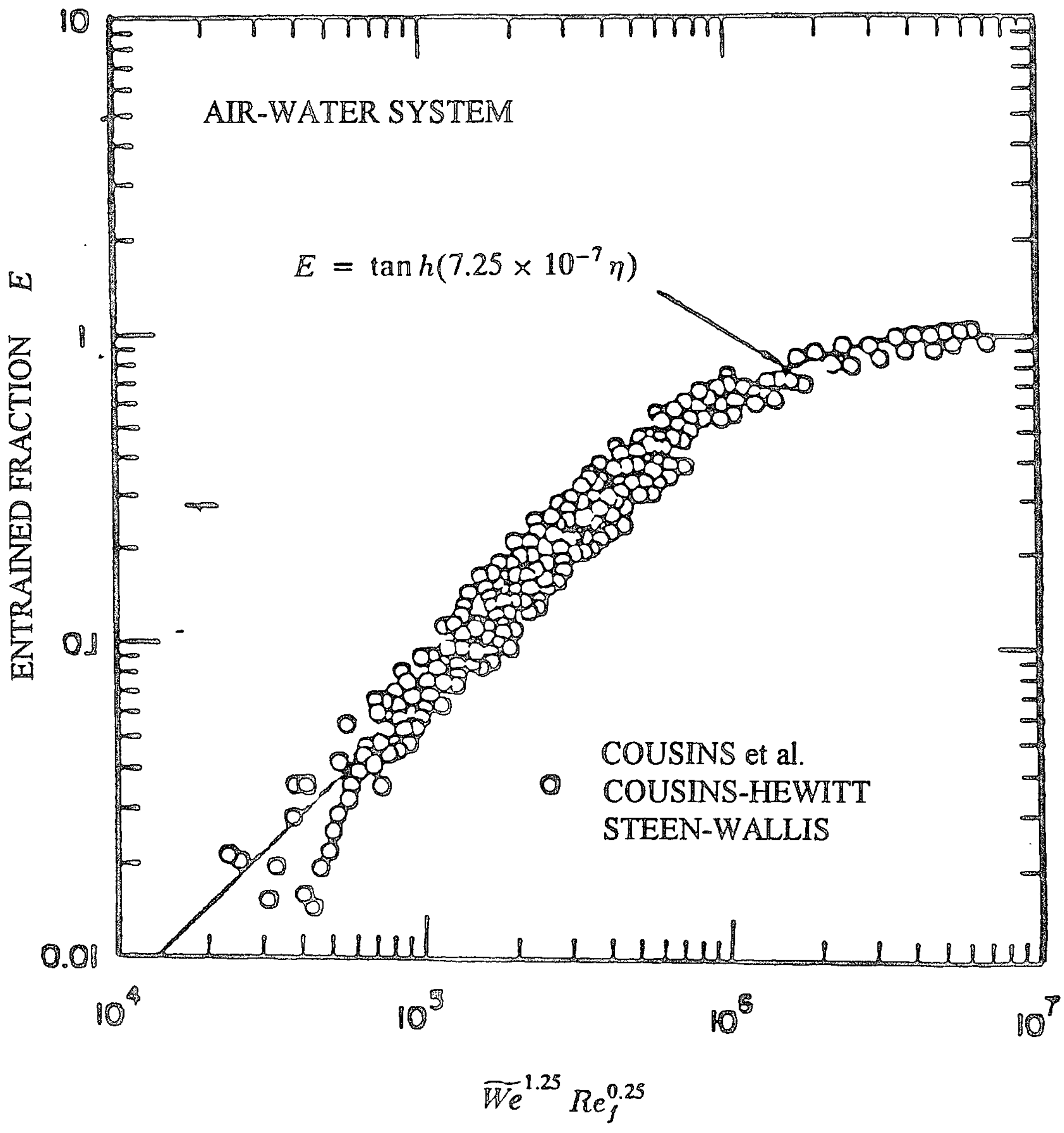

Figure 5. Comparison of the Entrainment Correlation of Ishii and Mishima with Data

virtually no contribution to the overall entrainment process. In fact, this same issue exists in all the available entrainment correlations.

4.2 Correlations of the Entrained Droplet Size Distribution

In an ETC gun environment, the chemical reactions that are directly responsible for the transfer of chemical energy to propulsive energy, are controlled not only by the entrainment rate but also by the entrained droplet size distribution. Thus, it is important to determine the sizes of the entrained droplets in addition to the rates at which they are being entrained. As in the general case of annular two-phase flow, most droplets in the ETC gun chamber are produced by entrainment at the gas-liquid interface. A large number of experimental data indicate that the liquid droplets are too small to be generated by the standard droplet disintegration mechanism. In other words, the critical Weber number based upon the relative velocity between the droplets and the gas flow gives rise to much larger droplet sizes than experimentally observed. This implies that the majority of the droplets would be generated at the time of entrainment and not by the secondary breakup mechanism during the flight as droplets in the gas flow. Thus the relative velocity between the gas core flow and liquid film flow is the governing factor in determining the droplet sizes. Furthermore, the size distribution should be the direct reflection of the droplet entrainment based on shearing off of the roll waves. Studies of droplet sizes have been performed by Hinze (1955), Hass (1964), Wicks and Dukler (1966), Cousins and Hewitt (1968), Tatterson et. al. (1977), and Kataoka, Ishii, and Mishima (1983). Correlations of droplet size distribution, that may find application to the interior ballistic processes of an ETC gun, have been obtained by Tatterson et al. (1977) and Kataoka, Ishii, and Mishima (1983).

Tatterson et al. (1977) performed an experimental study to measure the entrained droplet size in an annular two-phase flow. They employed a log normal function to simulate the droplet size distribution for a thin film flow. They presented a correlation in the form

$$We(d_{vm}) = 0.106\, Re_g^{1.1} \left(\mu_g^2 / d_h\, \sigma\, \rho_g\right)^{1/2} \tag{23}$$

where μ_g is the gas viscosity, Re_g the gas Reynolds number, and $We(d_{vm})$ the characteristic Weber number based on the volume median diameter. The gas Reynolds number and the characteristic Weber number are defined respectively by

$$Re_g = \rho_g\, j_g\, d_h / \mu_g \quad \text{and} \quad We(d_{vm}) = \rho_g\, j_g^2\, d_{vm} / \sigma \tag{24}$$

where d_{vm} is the volume median diameter. Physically, d_{vm} is defined such that droplets having diameters greater than the volume median diameter would occupy exactly half of the total droplet volume in the gas core.

The correlation of Tatterson et al. (1977) was based largely on the Kelvin-Helmholtz instability at the top of a liquid ligament in an inviscid flow. However, the assumption of a potential flow is not strictly valid for two-phase annular-mist flow with a highly turbulent gas core. As a result, the correlation of Tatterson et al. does not compare favorably with experimental data over a wide range of gas Reynolds number.

A mechanistic model was proposed by Kataoka, Ishii, and Mishima (1983) to determine the drop size distribution in annular gas-liquid two-phase flow. The model was based on the mechanism of shearing off of the roll-wave crests for generation of liquid droplets by a viscous shear flow. The potential flow assumption employed in the standard Weber number criterion was eliminated in developing the mechanistic model. By collaborating the mechanistic model with experimental data, Kataoka, Ishii, and Mishima (1983) successfully derived a correlation for the volume median diameter in the form

$$We(d_{vm}) = 0.028\, Re_f^{-1/6}\, Re_g^{2/3} \left(\frac{\rho_g}{\rho_f}\right)^{-1/3} \left(\frac{\mu_g}{\mu_f}\right)^{2/3} \tag{25}$$

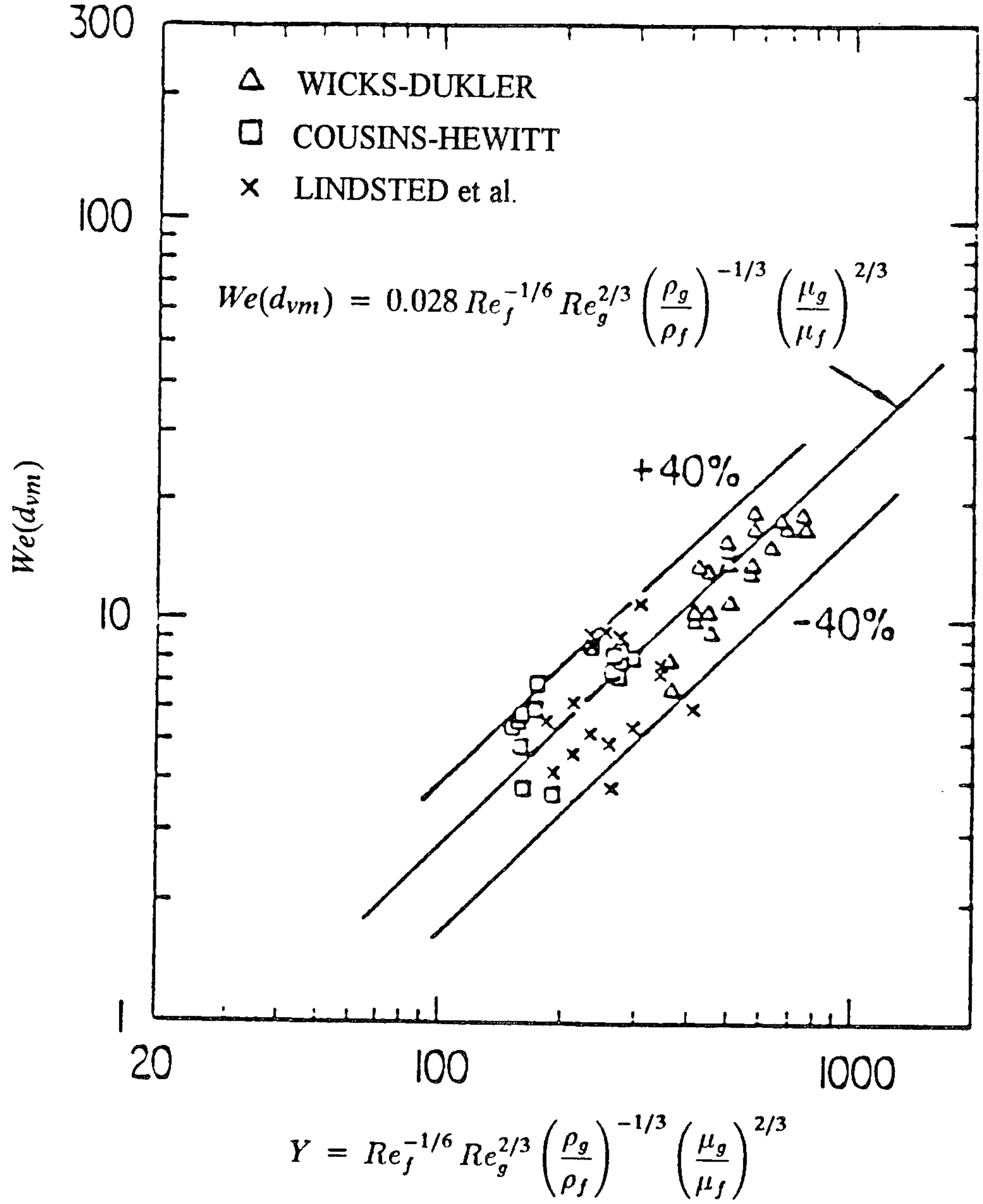

Figure 6. Correlation of the Volume Median Diameter by Kataoka, Ishii and Mishima

where $We(d_{vm})$ is the characteristic Weber number having the same definition as the one used by Tatterson et al. (1977). In terms of the characteristic Weber number, the volume median diameter is given by

$$d_{vm} = \sigma\, We(d_{vm})/\rho_g j_g^2 \tag{26}$$

The above expression correlates the experimental data of volume median diameter within $\pm$ 40% errors as illustrated in Figure 6. The volume-median-diameter data shown in the figure were obtained by Wicks and Dukler (1966), Cousins and Hewitt (1968), and Lindsted et al. (1978).

Kataoka, Ishii, and Mishima (1983) further postulated that the droplet size distribution for annular two-phase flow can be correlated in terms of the same dimensionless parameters as those for the volume-median-diameter correlation. They introduced a new dimensionless parameter Y as

$$Y = Re_f^{-1/6}\, Re_g^{2/3} \left(\frac{\rho_g}{\rho_f}\right)^{-1/3} \left(\frac{\mu_g}{\mu_f}\right)^{2/3} \tag{27}$$

The experimental data on drop size distribution were then correlated by plotting We/Y versus the volume fraction oversize, Δ . The diameter of droplet was given in terms of the Weber number, We, which was treated as a dependent variable in the plot. The volume fraction oversize, Δ , was defined as the volume fraction of droplets whose diameters are larger than the droplet diameter indicated by the Weber number. Their results showed that the drop size distribution correlated in this manner lie within $\pm$ 40% of the mean values of all the data.

The mean values of the data were fitted by Kataoka, Ishii, and Mishma (1983) to the upper limit log-normal distribution proposed by Mugele and Evans (1951) as

$$\frac{d\Delta}{dy} = -\frac{\xi}{\sqrt{\pi}} \exp\left[-(\xi y)^2\right] \tag{28}$$

In the above equation, ξ is a distribution parameter and y is defined in terms of the maximum diameter d_m and volume median diameter d_{vm} as

$$y = \ln\left[kd/(d_m - d)\right] \quad \text{and} \quad k = (d_m - d_{vm})\big/ d_{vm} \tag{29}$$

Based upon the experimental results, the values of ξ and k were found to be $\xi = 0.884$ and $k = 2.13$ whereas using the upper limit log-normal distribution, the maximum diameter was related to the volume median diameter by

$$d_m = 3.13\, d_{vm} \tag{30}$$

From the above expressions, the drop size distribution can be correlated in the form

$$\frac{d\Delta}{dy} = -\frac{0.884}{\sqrt{\pi}} \exp\left(-0.781 y^2\right) \tag{31}$$

with

$$y = \ln\left[2.13\, d\big/(3.13\, d_{vm} - d)\right] \tag{32}$$

where the volume median diameter is given by equation (25). Note that once the volume median diameter is known, the drop size distribution can be uniquely determined by the above correlation.

The correlation of drop size distribution developed by Kataoka, Ishii, and Mishima (1983) is probably the most suitable one among the existing correlations for use in simulating the phenomena of mixing of plasma and liquid propellants in the ETC gun envirnoment. It is recommended that the correlation be used in future modeling. The reasons are: (i) the correlation is based upon a sound physical model, taking full account of the key elements involved in the droplet formation process, (ii) the use of the upper limit log-normal distribution function is evidently appropriate for annular-mist flow, (iii) the correlation compares very well with available experimental data on drop size distribution covering a wide range of conditions, and (iv) the correlation is easy to use since the primary quantity that needs to be determined is the volume median diameter.

5. Research Needs

In the past three years or so, rather intensive and focused efforts have been made in the U.S. towards obtaining a detailed understanding of the ETC interior ballistic processes (Wren 1991, Oberle and Morelli 1991). A number of ETC models have been proposed which show promising potential (Sinha, Hosangadi, and Dash 1991, Chen, Kuo, and Cheung 1992). Among the various fundamental processes considered in these models, the process of mixing of plasma and liquid propellants is probably the most important one. Unlike solid propellant guns, interior ballistic events in ETC guns are dominated by the plasma/liquid propellant interaction (see Table 1). In an ETC gun utilizing liquid propellants, a plasma jet is discharged from the plasma generating cartridge, and it interacts with the liquid propellant in the gun chamber to create a Taylor cavity (Kuo et al. 1990). As the Taylor cavity expands along with the projectile motion, the relative motion between the plasma and the liquid propellant entrains a large number of propellant droplets into the cavity. Subsequent burning of these droplets in the cavity result in the transfer of chemical energy into propulsive energy. Thus the performance of an ETC gun depends strongly on the process of entrainment of propellant droplets by the plasma jet.

One key element that has important impact on the mixing process of plasma and liquid propellants but are not fully understood is the rate of entrainment in the ETC gun environment. Information on the rate of entrainment during the interaction of plasma and liquid propellants in an ETC gun needs to be sought by considering two types of injector configurations. These are a rear plasma capillary configuration venting axially (axial injection type) and a centerline plasma capillary configuration venting radially (piccolo type). In the axial injection type, a single Taylor cavity would develop as a result of the interaction between the plasma jet and the liquid propellants. On the other hand, in the piccolo type, a large number of small Taylor cavities would develop in the vicninity of the injector during the initial stage of the plasma/liquid propellant interaction. These small

Table 1 Comparison of the Dynamic Events Inside Solid Propellant and ETC Guns

Solid Propellant Gun	ETC Gun
• Combustion of solid propellant grains	• Combustion of liquid propellant and droplets
• Flamespread along solid propellant surfaces	• Flamespread to liquid/gas interfaces and droplet surfaces
• High-pressure real gas	• Ionized gas and high-pressure real gas
• Basepad and/or centercore ignition system	• High-energy plasma generation in and discharge from PGC
• Dispersed propellant grains with known initial configurations	• Dispersed droplets generated continuously as a result of plasma/liquid interaction
• Combustion chamber partially loaded with solid propellant grains	• Combustion chamber fully loaded with liquid propellant

cavities would subsequently expand and merge together to form a single Taylor cavity in the late stage of the interior ballistic cycle. While the dynamic behavior of the Taylor cavity in the axial injection type has been simulated and observed by previous investigators (Chen 1990, Kuo et al. 1990, Arensburg, Wald, and Goldsmith 1992), the dynamic behavior of the Taylor cavities in the piccolo type has never been studied heretofore.

From the above discussion and the results of the state-of-the-art review, it is evident that two important tasks need to be performed in order to obtain a clear understanding of the phenomena of mixing of plasma and liquid propellants in ETC guns. These tasks are: (i) development of a suitable entrainment correlation for ETC gun application, and (ii) simulation of the mixing phenomena in the piccolo type of an ETC gun. Unit problems involved in these two tasks have been identified along with the solution methodology as described below.

5.1 Development of Entrainment Correlation for ETC Gun Applications

From the literature survey, it can be seen that none of the available entrainment correlation is applicable to the ETC gun environment. This is because the liquid entrainment determined by previous investigators represents the net or equilibrium amount of liquid film that is entrained as liquid droplets in the gas phase. This quantity refers to the amount entrained into the gas flow minus the amount of entrained droplets that returns to the liquid film in the deposition process. However, in an ETC gun environment, the droplet life times are very short due to high rates of heat transfer, evaporation, thermal decomposition, and combustion. Hence the droplets would have very little chance to return to the liquid film before they are totally consumed by burning. This means that the deposition rate is negligible in the interior ballistic processes of an ETC gun. The insignificance of the deposition process in an ETC gun represents a unique feature that is absent in most annular two-phase flows studied by previous researchers. As a result, the available entrainment correlations can not be applied directly to the case of mixing of plasma and liquid propellants in an ETC gun.

To develop a suitable entrainment correlation for ETC gun applications, liquid entrainment due to the primary atomization process must be separated from the deposition process. It is proposed in the following sections that an experimental study be conducted for measuring the rate of entrainment for the case in which the effect of deposition is negligible. The experimental data so obtained may then be analyzed and correlated with the help of theoretical considerations.

5.2 Theoretical Considerations of Droplet Entrainment

As explained above, the deposition process is rather insignificance during the mixing of plasma and liquid propellants in the ETC envirnoment. Thus, to estimate the rate of entrainment, it is necessary to separate the contribution due to the primary atomization process taking place at the gas-liquid interface of the Taylor cavity from the deposition process. This can be done by considering the conditions leading to the onset of entrainment. Before the onset of entrainment, there is no droplets in the gas core and therefore, no deposition of droplets would take place. By assuming that the same forces considered for the onset of entrainment also control the process of entrainment itself, as suggested by Ishii and Mishima (1989), a functional form for the entrained fraction contributed solely by the primary atomization process can be derived. A detailed description of the derivation is given below.

The starting point of the analysis is an appropriate inception criterion. As presented in section 3, the criterion developed by Ishii and Grolmes (1975b) appears to be most complete and well tested agsinst a large number of experimental data. The criterion has a sound theoretical basis as it was derived by considering a detailed force balance at the crest of roll waves. Since the roll wave mechanism is also the prevailent mechanism of entrainment during plasma/liquid propellant interaction in an ETC gun, it is deemed appropriate to adopt the inception criterion of Ishii and Grolmes (1975b) in the present analysis. Accordingly, the superficial gas velocity must satisfy the relationship given by either equation (3) or equation (5) as the viscosity number for the plasma/liquid propellant system should be considerably smaller than 1/15. Since equation (5) can be viewed as an asymptotic expression for equation (3), it would be more general to start the present analysis with equation (3). This is considered most adequate (Ishii 1993) as the objective of the analysis is to derive a functional form for the entrained fraction under the condition that there is no deposition of the entrained droplets.

Owing to the relatively high velocity of the plasma jet, the plasma/liquid propellant system in an ETC gun is likely to be well above the lines representing the inception criterion (see Figure 3). However, there is a potential for the liquid film Reynolds number to be reduced to a critical value given by the inception criterion as the liquid film thickness decreases.. Below this critical Reynolds number , no furhter entrainment is possible. An upper theoretical limit for the entrained fraction may thus be determined by assuming that the liquid film flow rate is given by the critical condition of equation (3), e.g.,

$$(Re_f)_c^{1/3} = 11.78\, N_\mu^{0.8} \left(\frac{\sigma}{\mu_f j_g}\right) \left(\frac{\rho_f}{\rho_g}\right)^{1/2} \tag{33}$$

where $(Re_f)_c$ is now the critical Reynolds number based on the critical film flow rate. The critical Reynolds number is defined by

$$(Re_f)_c = \rho_f \, (j_{ff})_c \, d_h / \mu_f \tag{34}$$

where $(j_{ff})_c$ is the critical superficial velocity of the liquid film. The use of this definition in equation (33) is equivalent to ignoring the effect of droplets in determining the critical condition. Now, in terms of the film Reynolds number given by equation (1), the critical superficial velocity of the liquid film is given by

$$(j_{ff})_c = \frac{j_f}{Re_f}\left[11.78\,N_\mu^{0.8}\left(\frac{\sigma}{\mu_f j_g}\right)\left(\frac{\rho_f}{\rho_g}\right)^{1/2}\right]^3 \tag{35}$$

The above expression will now be used to determine the entrained fraction, E.

Following the conventional definition, the entrained fraction E can be expressed in terms of the superficial velocities of the total liquid (including the liquid film and the entrained droplets) and the liquid film alone, i.e., j_f and j_{ff}, respectively. This is given by

$$E = \frac{j_d}{j_f} = \frac{j_f - j_{ff}}{j_f} = 1 - \frac{j_{ff}}{j_f} \tag{36}$$

where the total liquid flow rate is

$$j_f = j_{ff} + j_d \tag{37}$$

Substitution of equation (35) into equation (36) gives

$$E_{up} = 1 - \frac{1}{Re_f}\left[11.78\,N_\mu^{0.8}\left(\frac{\sigma}{\mu_f j_g}\right)\left(\frac{\rho_f}{\rho_g}\right)^{1/2}\right]^3 \tag{38}$$

where the subscript "up" refers to the upper limit of the entrained fraction, e.g.,

$$E_{up} = 1 - \frac{(j_{ff})_c}{j_f} \tag{39}$$

In reality, the plasma/liquid propellant system would never be able to reach a dynamic equilibrium condition. This is particularly true as the interior ballistic processes of an ETC gun are highly transient. Thus the entrainment given by equation (38) could considerably over-estimate the actual amount of droplets entrained in the Taylor cavity during mixing of the plasma and liquid propellant. Nevertheless, the functional dependence of E on the various controlling parameters should be similar to (if not the same as) those given by equation (38).

Theoretically, the actual entrainment during the mixing of plasma and liquid propellants in an ETC gun should be bounded by the lower limit given by equation (19) and the upper limit given by equation (38), i.e.,

$$(E)_{IM} < E < E_{up} \tag{40}$$

where $(E)_{IM}$ is the entrained fraction predicted by the correlation of Ishii and Mishima (1989). Note that the quantitiy $(E)_{IM}$ includes the effect of deposition and thus it should represent the lower limit of entrainment in the ETC gun environment. From equations (35), (36), and (38), a functional form can be postulated for the actual entrained fraction as

$$E = 1 - B\, Re_f^{-1}\, N_\mu^{2.4} \left(\frac{\sigma}{\mu_f\, j_g}\right)^3 \left(\frac{\rho_f}{\rho_g}\right)^{3/2} \tag{41}$$

where B is a coefficient that needs to be determined experimentally. However, in view of the fact that the critical superficial velocity of the liquid film represents the lower limit of the liquid film flow, the value of B should be bounded by

$$B \geq 1.635 \times 10^3 \tag{42}$$

Introducing a dimensionless characteristic gas velocity as

$$\tilde{j}_g = j_g \left(\mu_f / \sigma \sqrt{\rho_f/\rho_g}\right) \tag{43}$$

a more general expression for the entrained fraction can be postulated. This is

$$E = 1 - B\, N_\mu^a\, Re_f^b\, \tilde{j}_g^c \tag{44}$$

where the indices a, b, and c need to be determined experimentally. However, if the preceding physical arguments are correct, the values of these indices should be approximately equal to: a = 2.4, b = -1, and c = -3. Note from equation (44) that for a given plasma/liquid propellant system, the viscosity number is a constant. Hence, the entrained fraction should vary only with the liquid Reynolds number, Re_f , and the dimensionless characteristic gas velocity, $\tilde{j}_g$.

Using equation (44) as a theoretical basis, correlation of entrainment data for the case without the effect of deposition may be performed over appropriate ranges of the liquid Reynolds numbers and the dimensionless characteristic gas velocities. The required entrainment data may be obtained using suitable simulant materials that cover the range of viscosity numbers anticipated for the plasma/liquid propellant system. A brief description of some essential features that need to be acheived in the proposed experimental work is given in next section.

5.3 Measurements of Droplet Entrainment in the Absence of Deposition

An experimental study should be conducted to obtain the required database for evaluating the empirical constants (i.e., a, b, c, and B) appearing in the correlation for droplet entrainment proposed in the preceding section. The experimental conditions should be such that the entrained droplets would be removed from the gas phase and would not return to the liquid film. This represents one major task that needs to to performed in the subsequent phase of the project.

5.4 Simulation of Mixing Phenomena in the Piccolo Type of an ETC Gun

The phenomena of mixing of plasma and liquid propellants in an ETC gun utilizing a piccolo injector can be quite different than those utilizing an axial injector. For the axial injection type, there is only one Taylor cavity developed during the plasma/liquid propellants interaction. This is not the case for the piccolo type. The phenomena of mixing of plasma and liquid propellants for the piccolo type must be studied in two sequential stages. In the initial stage of the plasma/fluid interaction, a large number of small plasma jets or mini-Taylor cavities would develop in the vicinity of the injector. These small cavities would subsequently expand and eventually merge together to form a single Taylor cavity in the later stage, i.e., the fully developed stage, of the interior ballistic cycle. The correlations described above for entrainment and for entrained droplets size distribution could be useful only for predicting the liquid entrainment in the fully developed stage. However, these correlation can not be applied to the initial stage during which the gaseous jets or mini-Taylor cavities are not flowing over thin liquid films as in the annular two-phase flow studied by previous investigators. Rather, the gas core flow is penetrating through a relatively large body of liquid. In fact, this two-phase flow behavior resembles the class of external gas-liquid flow in which the two-phase motion is not bounded by solid walls (Hanratty and Engen 1957, Ricou and Spalding 1961, Hussain and Siegel 1976). Evidently, different forms of entrainment correlations needed to be developed.

It should be noted that for the piccolo type of an ETC gun, the interfacial areas of the mini-Taylor cavities could play an important role in the energy transferring process from chemical energy to propulsive energy. Unlike the axial injection type where only a single Taylor cavity would be created in the gun chamber, a large number of mini-Taylor cavities could be generated in the early stage of the interior ballistic processes for the piccolo injection type . The energy release associated with burning of liquid propellants at the gas-liquid interfaces of the mini-Taylor cavities could be as important as the energy release associated with burning of the liquid propellant droplets inside the mini-Taylor cavities. Therefore, in addition to the droplet entrainment, it is important to determine the interfacial area of the mini-Taylor cavities in the early stage of the interior ballistic processes in the piccolo type of an ETC gun. In view of this, two important subtasks need to be conducted. The first subtask, entitled "Air-Water Simulation Using a Single-Line Piccolo Injector," should aim at discerning the characteristic features of the gaseous jets or mini-Taylor cavities issuing from a piccolo injector. The second subtask, entitled "Measurement of the Interfacial Area of the Mini-Taylor Cavities," should aim at obtaining quantitative information on the mini-Taylor cavities.

5.4.1 Air-Water Simulation Using a Single-Line Piccolo Injector

This simulation experiment will shed light on the dynamic behavior of the mini-Taylor cavities issuing from a piccolo injector. The experimental variables for this subtask should include the injector diameter, injection rate, liquid pool height, and number of liquid jets.

5.4.2 Measurement of the Interfacial Area of Individual Taylor Cavity

Owing to the fact that there are a large number of mini-Taylor cavities developing in the early stage of the interior ballistic processes, the available burning surface area represented by the gas-liquid interfaces of the mini-Taylors cavities could be larger than the burning surface area of the dispersed droplet inside the cavities. Thus it is necessary to determine the interfacial area of individual Taylor cavities in the early stage of the interior ballistic cycle. This can be done experimentally by measuring the interfacial area using the advanced technique by Ishii and Revankar (1992).

6. Conclusions

The key elements of plasma/liquid propellants interaction that are not fully understood have been identified and the applicability of existing correlations for describing the entrainment and subsequent breakup of the liquid propellant droplets caused by the discharge of a plasma jet from a plasma generating cartridge has been critically evaluated. Based upon the results of this study, the following conclusions can be made:

1. The single most important element in accurate prediction of the performance of ETC guns is the droplet entrainment rate, since it controls the rate of conversion of chemical energy into propulsive energy.
2. A suitable entrainment correlation, excluding the effect of droplet deposition, should be developed for ETC gun application. This can be accomplished by performing an experimental study to measure the rate of entrainment for the case without the effect of deposition.

3. The theoretical analysis performed in this study provides a useful guidance for future experimental work in the development of a suitable entrainment correlation applicable to ETC gun conditions.
4. In order to develop a realistic model for simulating the mixing phenomena of plasma jets and liquid propellants in ETC guns using piccolo igniters, it is useful to conduct detailed observations of the evolution of mini-Taylor cavities.

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