Introduction

The aims of injector are similar to those of a carburetor in an internal combustion engine. The injector has to introduce and meter the flow to the combustion chamber, to atomized and mix the propellants in such a manner that correctly proportioned, homogeneous fuel-oxidizer mixture will result, one that can readily be vaporized and burned.

Injector design like many engineering tasks entails many compromises. For any new engine application, there are almost several different approaches that could produce a satisfactory injector design and perhaps more than one approach which provide an outstanding injector design. The proper design starting point considers the particular application, engine size, propellant combustion, and design priorities. Of course, the initial approach invokes complete optimization of all features: light weight, high performance, low cost, reliability, etc.

The pintle injector is distinguished by its unique geometry and injection characteristics compared to the impinging or coaxial distributed-element injectors typically used on liquid bipropellant rocket engines. The pintle injector design can deliver high combustion efficiency (typically 96-99%) and enables implementing some unique operating features, such as deep throttling and injector face shutoff. Its design simplicity makes it ideally suited for use on low cost engines significantly lower development and qualification costs are realized with pintle engines because their injectors can be easily adjusted and optimized by changing only two simple parts.

The TRW pintle engine has a demonstrated heritage of being low cost, highly reliable and safe to operate. The origins of the pintle injector were early laboratory experimental apparatus, used by JPL in the mid-1950's, to study propellant mixing and combustion reaction times of hypergolic liquid propellants. The pintle injector was reduced to practice and developed by TRW starting in 1960; however, it was not until 1972 that the pintle injector design patent was publicly released. Over the last 40 years, TRW has developed over 60 different pintle engine designs at least to the point of hot fire characterization testing. Bipropellant pintle engines have encompassed a wide range of thrust: 5 lbf on a Brilliant Pebbles thruster, 100 lbf on liquid apogee engines for spacecraft, 1,000-10,000 lbf on the Apollo lunar module descent engine, 250,000 lbf on a

“Big Dumb Booster” engine, and 650,000 lbf on a development LOX/LH2 engine currently being readied for testing at NASA Stennis Space Center. Over 130 bipropellant engines using a pintle injector have flown successfully. Flight programs relying on TRW bipropellant engines have included Apollo LEMDE, Delta launch vehicle MMBPS, ISPS, ANIK E-1/E-2 and Intelsat-K, ERIS KKV stage, FMTI, and NASA Chandra. There has never been a flight failure of a TRW bipropellant engine.

Significantly, there has never been an instance of combustion instability in a pintle engine during any ground or flight operations, despite scaling over a range of 50,000:1 in thrust and 250:1 in chamber pressure and operation with 25 different propellant combinations. The pintle injector has demonstrated direct injection of near-normal boiling point LOX/LH2 propellants with high performance and proven dynamic combustion stability. “Bomb” stability testing has been performed on six different pintle engines with four different propellant combinations, including the physically large 250,000 lbf engine.

With its unique capabilities, the pintle injector has been used in very demanding application, such as an 8,200 lbf engine that could throttle over a 19:1 thrust range and perform 8 millisecond pulses. Also, with its ready adaptability to shut off propellants at the injector face, the pintle injector is ideally suited to operation with gelled propellants and has enabled the first successful flight of a gel propellant tactical missile.

The history of development and flight application of the pintle engine over the last forty years will be summarized. The features and performance characteristics of the TRW pintle injector and associated engine designs will be described. Features of the pintle injector will be compared to those of other injectors commonly used in rocket engines.

CHAPTER 1

LIQUID ROCKET ENGINE AND GENERALL PROCESSES IN ATOMIZATION

1.1 Liquid rocket engine

Liquid fueled rockets have better specific impulse than solid rockets and are capable of being throttled, shut down, and restarted. Only the combustion chamber of a liquid fueled rocket needs to withstand combustion pressures and temperatures. On vehicles employing turbo pump, the fuel tanks can be built with less material, permitting a larger mass fraction. For these reasons, most orbital launch vehicles and all first- and second-generation ICBMs use liquid fuels for most of their velocity gain. Most liquid propellants are also cheaper than solid propellants the main difficulties with liquid propellants are also with the oxidizers. These are generally difficult to store and handle. In a liquid propellant rocket, the fuel and oxidizer are stored in separate tanks, and are fed through a system of pipes, valves, and turbopumps to a combustion chamber where they are combined and burned to produce thrust. Liquid propellant engines are more complex then their solid propellant counterparts; however, they offer several advantages. By controlling the flow of propellant to the combustion chamber, the engine can be throttled, stopped, or restarted as shown in figure 1.1.

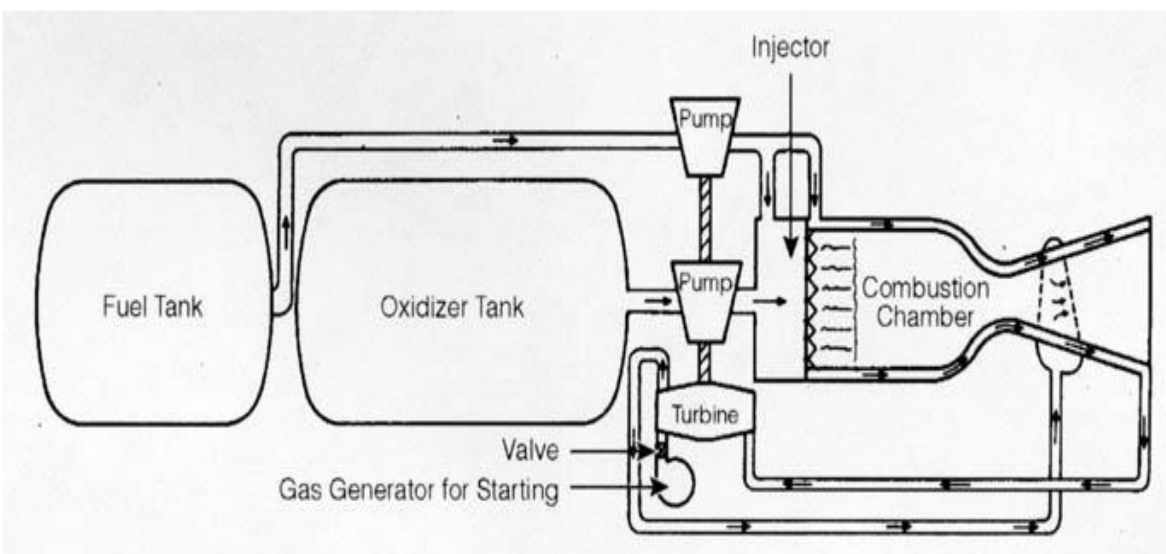

Fig.1.1 A simplified schematic diagram showing a liquid rocket engine.

A good liquid propellant is one with a high specific impulse or, stated another way, one with a high speed of exhaust gas ejection. This implies a high combustion temperature and exhaust gases with small molecular weights. However, there is another important factor which must be taken into consideration: the density of the propellant. Using low density propellants means that larger storage tanks will be required, thus increasing the mass of the launch vehicle. Storage temperature is also important. A propellant with a low storage temperature, i.e. a cryogenic, will require thermal insulation, thus further increasing the mass of the launcher. The toxicity of the propellant is likewise important. Safety hazards exist when handling, transporting, and storing highly toxic compounds. Also, some propellants are very corrosive.

1.2 Applications of liquid engines

The use of liquid propellant rocket engines in any specific application is based on selection among characteristics such as those listed in Table 1.1.

Table1.1 Desired characteristics of liquid propellant engines

Characteristics	Typical Applications
Random-variable thrust	Throttled aircraft rocket Trajectory control of large and small missiles
High performance (High-energy propellant)	High- performance research vehicles Space flight
Efficient thrust vector direction control	Gimbaled thrust chamber
Lightweight transportation (without propellants)	Mobile installation
Nonhazardous storage (no potentially explosive propellant mixture)	Stockpiling of missiles
Logistic availability of propellants	Any missile system that is not dependent on specialized propellant manufacturing facility
Known technology	System where use of available engines minimizes development effort
Long duration	Target drones
Checkout and calibration before use	Training, reliability
Gas generator control	Smaller, simpler missile
Wide temperature limits	Extreme climate
Restart capability	Flight path control

The selection of liquid propellant systems in preference to other propulsion systems for any specific application and the selection of a specific propellant combination is usually a compromise between the following typical factors.

1. Performance, such as maximum range, minimum weight.
2. Logistics, such as handling characteristics, availability in emergency.
3. Operational considerations, such as ease of troop training, adaptability of existing military bases.
4. Cost and time, such as for development effort; unit production price.

1.3 Basic systems and components

In a liquid propellant rocket engine there are five fundamental subsystems.

1. The feed system for transporting the liquids from the tanks to the thrust chamber, as shown in fig.1.2.
2. Propellant tanks (usually integral with the airframe). As shown in fig. 1.3.
3. The thrust chamber, where the propellants are mixed, burned, and expelled.
4. The control systems to start, stop, and regulate the operation of the engine.
5. Various supplementary and auxiliary devices such as gimbals and auxiliary power drives.

Fig 1.2 Classification of liquid propellant rocket feed systems.

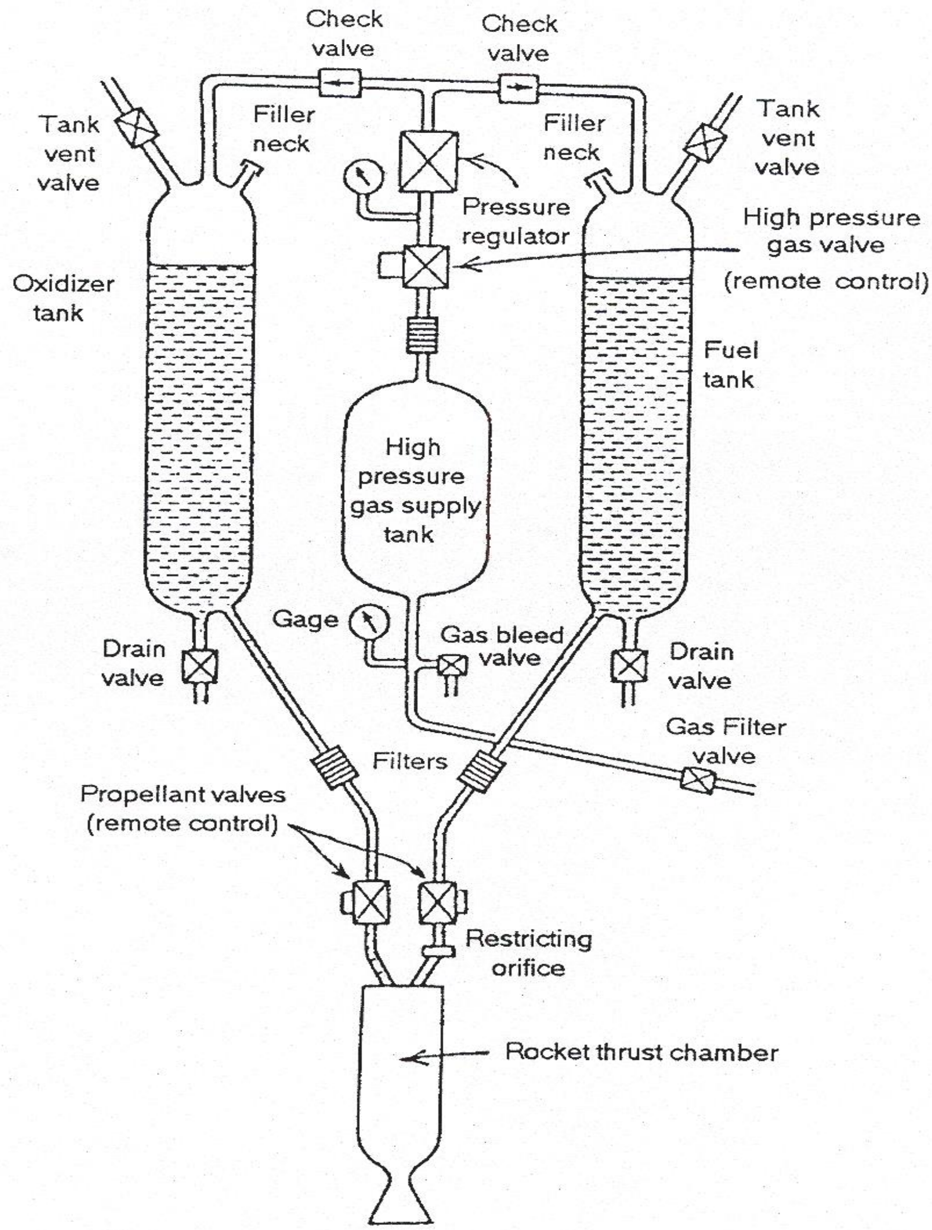

Figure 1.3 Simplified pressurized feed system

1.4 General processes in atomization

The process of atomization is one in which a liquid jet or sheet is disintegrated by the kinetic energy of the liquid it self, or by exposure to high-velocity air or gas, or as a result of mechanical energy applied externally through a rotating or vibrating device.

1.5 Liquid properties:

The most atomizers are strongly influenced by the liquid properties of density, viscosity, and surface tension. In theory, the mass flow rate through a pressure nozzle varies with the square root of liquid density. In practice it is seldom possible to change the density without affecting some other liquid property, so this relationship must be interpreted cautiously. The significance of density for atomization performance is diminished by the fact that most liquids exhibit only minor differences in this property. Moreover, the modest amount of available data on the effect of liquid density on mean drop size suggests that its influence is quite small.

One way of defining a spray is in terms of the increase in liquid surface area resulting from atomization. The surface area before breakup is simply that of the liquid cylinder as it emerges from the nozzle. After atomization, the area is the sum of the surface areas of all the individual droplets. This multiplication factor provides a direct indication of the level of atomization achieved and is useful in applications that emphasize surface phenomena such as evaporation and absorption. Surface tension is important in atomization because it represents the force that resists the formation of new surface area. The minimum energy required for atomization is equal to the surface tension multiplied by the increase in liquid in surface area.

In many respects, viscosity is the most important liquid property. Although in absolute sense its influence on atomization is no greater than that of surface tension, its importance stems from the fact that it affects not only the drop size distributions in the spray but also the nozzle flow rate and spray pattern. An increase in viscosity lowers the Reynolds number and also hinders the development of any natural instabilities in the jet or sheet. The combined effect is to delay disintegration and increase the size of the drops in the spray.

The effect of viscosity on flow within the nozzle is complex. In hollow-cone nozzles a modest increase in viscosity can actually increase the flow rate. It does this by thickening the liquid film in the discharge orifice, thereby raising the effective flow area. At high viscosity, however, the flow rate usually diminishes with increasing viscosity. With pressure-swirl nozzles an increase in viscosity generally produces a narrow spray angle. At very high viscosity the normal conical spray may collapse into a straight stream of relatively large ligaments and drops. An increase in liquid viscosity invariably has an adverse effect on atomization quality, because when viscous losses are large, less energy is available for atomization and a coarser spray results.

1.6 Spray properties:

In most applications the function of the atomizer is not merely to break the liquid down into small drops but also to discharge these drops into the surrounding gaseous medium in the form of a symmetrical uniform spray. The main properties of the spray are described down.

1.6.1 Dispersion

The dispersion of a spray may be expressed quantitatively if, at any given instant, the volume of liquid within the spray is known. According to one definition the degree of dispersion may be stated as the ratio of the volume of the spray to the volume of the liquid contained within it.

The advantage of good dispersion is that the liquid mixes rapidly with the surrounding gas, and the subsequent rates of evaporation are high. With stream atomizers of narrow spray angle, the dispersion is small. With centrifugal atomizers, dispersion is governed mainly by other spray characteristics, such as cone angle, mean drop size, and drop size distribution, and to lesser extent by the physical properties of the liquid and the surrounding medium. In general, the factors that increase the spray cone angle also tend to increase the spray dispersion.

1.6.2 Penetration

The penetration of a spray may be defined as the maximum distance it reaches when injected into stagnant air. It is governed by the relative magnitudes of two opposing forces: (1) the kinetic energy of the initial liquid jet and (2) the aerodynamic resistance of the surrounding gas. The initial jet velocity is usually high, but as atomization proceeds and the surface area of the spray increase, the kinetic energy of the liquid is gradually dissipated by frictional losses to the gas. When the drops have finally exhausted their kinetic energy, mainly gravity and the movement of the surrounding gas dictate their subsequent trajectory.

In generally, a compact narrow spray will have high penetration, while a well-atomized spray of wide cone angle, incurring more air resistance, will tend to have low penetration. In all cases, the penetration of a spray is much greater than that of a single drop. The first drops to be formed impart their energy to the surrounding gas, which begins to move with the spray, the gas therefore offers less resistance to the following drops, which consequently penetrate farther. Penetration is measured both radially and circumferentially to determine the distribution of liquid within a spray.

1.6.3 Cone angle

A major difficulty in the definition and measurement of cone angle is that the spray cone has curved boundaries, owing to the effects to the effects of air interaction with the spray. To overcome this problem, the cone angle is often given as the angle formed by two straight lines drawn from the discharge orifice to cut the spray contours at some specified distance from the atomizer face. A satisfactory method of measuring spray cone angle is to project a silhouette of the spray onto a ground-glass screen at two or three magnifications. Alternatively, measurement of spray width can be made at several axial locations to define the spray profile; one method is to use two probes equally spaced about the nozzle centerline that are moved until they contact the edges of the spray. The latest version for swirl nozzle employs linear variable displacement transducers to determine the probe positions, from which the spray angle and skew-ness of the spray about the nozzle axis are calculated.

Several workers have studied the characteristic of the flow in pressure atomizers. Their results show that spray angle is influenced by nozzle dimensions, liquid properties, and the density of the medium into which the liquid is sprayed.

1.7 Basic elements of the mixture formation and combustion processes in liquid rocket engine:

Effectiveness of combustion chamber of liquid propelled rocket engine depends a great deal on organization of the process of the mixture formation and combustion, which depends on fuel properties and a combustion chamber head construction.

Mixture formation represents a group of processes, which are performed from the moment of the fuel components injection into combustion chamber to the moment of the formation of the homogenous mixture. On that way, mixture formation process consists of next processes: fuel stream intake into the chamber through the injectors, breaking the stream to drops, vaporization and mixing.

Fuel transition into combustion product is summing process consisting of mixture formation and combustion.

Processes of the transition are schematically shown in the figure1.4 According to the type of fuel (self-igniting and non self-igniting).

Combustion process of the self-igniting fuel figure1.4.a when the components are already sprayed is performed on the following way. Parts of the fuel are vaporized before the mixing in the liquid phase. Mixing and combustion in the gaseous phase is done after that, leading to the formation of the combustion products.

Rest of the fuel is mixed in the liquid phase. In the contact of the fuel drops and oxidizer, combustion reaction starts in the liquid phase. A part of the fuel that is not mixed enough in the liquid phase vaporizes and the combustion cannot start, because of the sudden temperature increase. Further mixing and combustion that part of the fuel is performed in the gaseous phase.

Heterogeneous combustion can be done (accomplished) simultaneously with homogenous combustion, when liquid drops of one component burn into gaseous vapor of the other, i.e. combustion of the drops of the one component in the vapor of the other. Such combustion could be done in the case of the faster vaporization of the one component than the other, or in the case of the case of the formation very large drops after spraying which vaporize slower than others.

There are no combustion reactions in the liquid phase for the non self-igniting components. Transition process is shown in figure1.4.b Components are mixed in the liquid phase after spraying. Premixing is also possible (for instance, in the emulsion injectors). Then the components vaporize further mix and combust. Heterogeneous combustion of the drops is performed simultaneously.

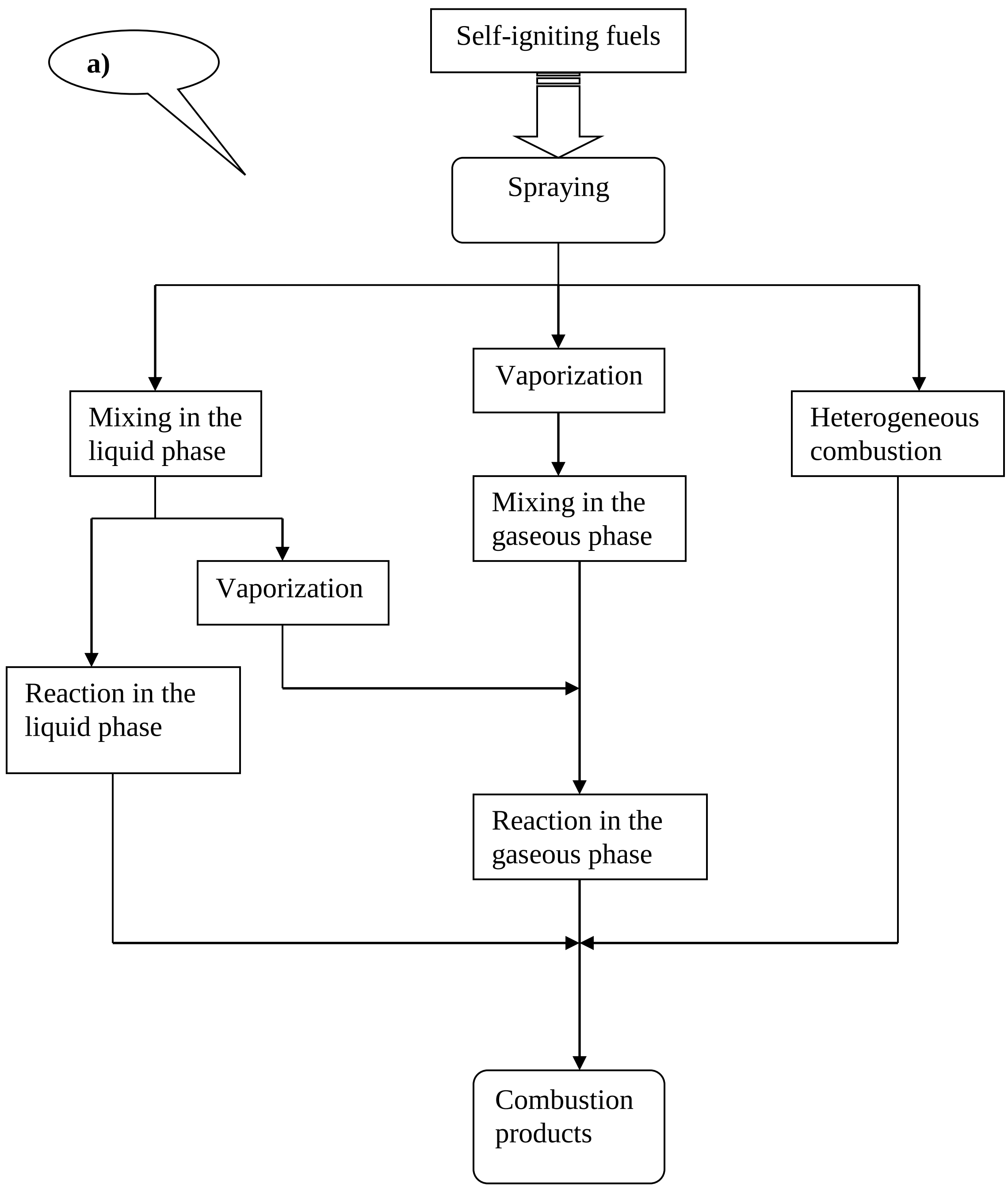

Figure1.4.a Scheme of the transition process for self-igniting

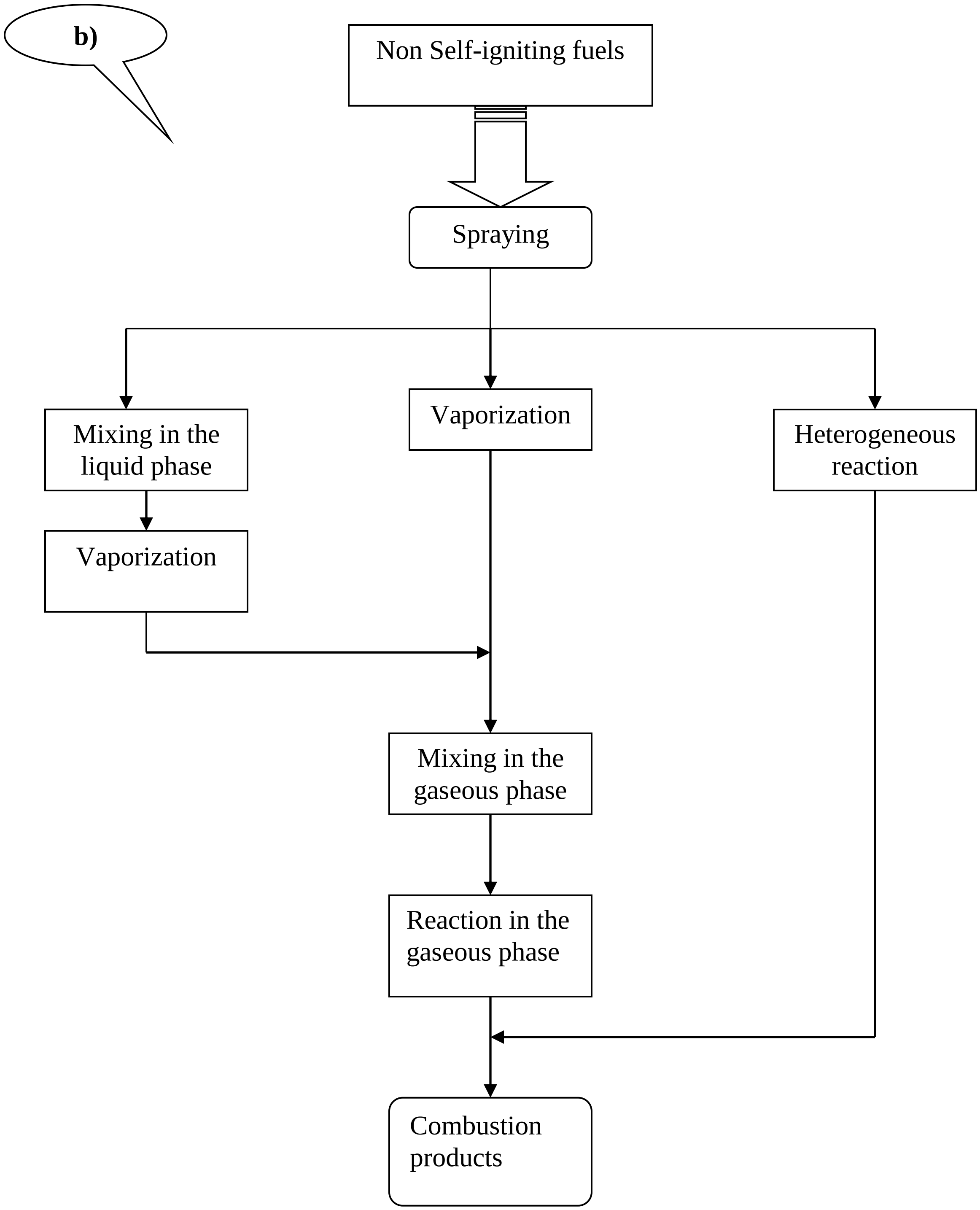

Figure1.4.b Scheme of the transition process for non self-igniting

According to the flow of the processes that the process of the fuel transition is made of combustion chamber of the liquid propelled rocket engine can be divided into following zones figure1.5:

I- Spraying zone.

II- Vaporization zone.

III- Mixing and combustion zone.

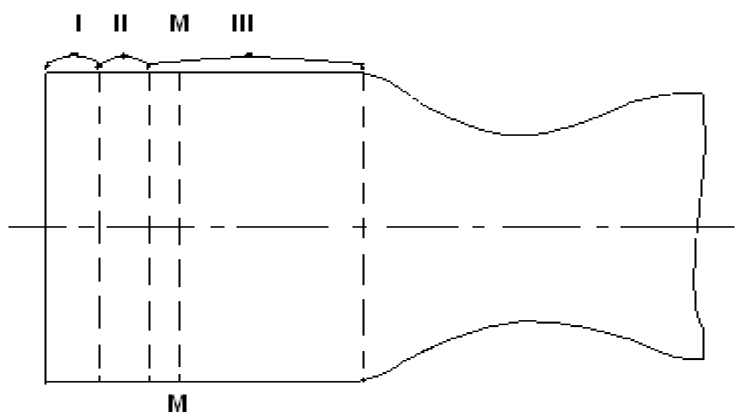

Figure1.5 Diagram of the combustion of the processes flow in the combustion chamber

Dividing of the combustion chamber into the mentioned zones is conditioned, because the processes of the spraying, vaporization, mixing and the combustion are not taking place necessary one after another. Two or more processes are intermixed in every zone. The most characteristic process determines every mentioned zone. Flow of the processes will be discussed.

1.7.1 Spraying

Quality of fuel spraying in the combustion chamber defines in some way the flow of following process: vaporization, mixing and combustion. Spraying quality is influenced by the fuel intake system, the injectors and combustion chamber. Type of the injectors (stream or centrifugal), their construction and distribution affect a process of fuel spraying.

After the stream injection through the injectors, stream crashing into the drops and drops breaking under the external and inner forces are taking place.

External forces (somewhere called aerodynamic) are forces of mutual interaction of the components and injection ambient. Their magnitudes depend on the ambient density, stream velocity and thickness of the stream jet. External forces are forces of mutual interaction of the intersected streams and forces of interaction between the streams and chamber wall. Increasing of the stream velocity in the injection ambient gives increase acting of the external forces and increase disturbances in the surface area of the stream, leading to the better stream crashing and higher spraying quality.

Crashing and breaking of the stream is possible without external forces. For instance, crashing is taking place under the influence of the inner forces as the components are injected into the vacuum.

Inner forces are forces of turbulence and molecular forces. There are components of the stream flows through injectors, and the turbulent pulsations are formed. Inside the stream heretical motion is present.

Intensity of turbulence depends on pressure on injectors, density and viscosity of the stream and injector construction. Pressure increase (i.e. increase of the velocity through the injectors) gives increase of turbulence intensity, accelerated crashing of stream, i.e. crashing quality is better. Molecular forces are forces of viscosity and forces of surface stresses.

External force and turbulent pulsation velocities inside the stream tend to crash the liquid into the drops, while the stream is passing through the injector exit. On the other hand, forces of surface stress and forces of viscosity are opposing to the external forces. Crashing of the stream and the drops formation is taking place on the following way.

During the injection of components through the injector, a liquid stream forms an envelope. Disturbances in the surface layer of the stream are formed and arise under the influence of the external forces and turbulent pulsations. As a result of further action of external and inner forces, envelope is crashing in small parts of various shape and size. Smaller parts get the shape of sphere and form drops under the influence of stress. Larger parts resume crashing into smaller. Figure1.6.

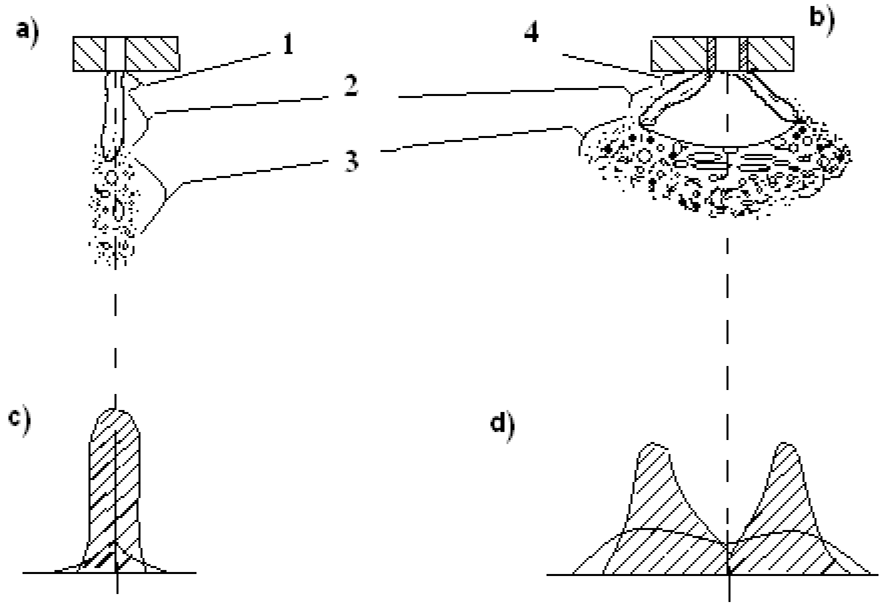

Figure1.6 Mechanism of the stream decompose

a) Linear injector. b) Centrifugal injector. c&d) is the stress distribution

1 stream. 2 surface disturbances and formation of envelope.

3 stream crashing to small parts. 4 envelope.

Fineness of spraying is defined by a value of average diameter of formed drops. Homogeneity of spraying is defined by a distribution curve of drops with known diameter and depends on component properties, injector construction, operating parameters of combustion chamber and density of combustion products. Density increasing in ambient where the spraying is taking place and pressure increasing in injectors give better fineness of spraying. An average drop size is in the range 25-250 µm. The stream piercing is determine by a stream velocity through the injector exit, i.e. by an injector pressure and direction and angle of spraying, but also by a density of spraying ambient. Increase of the piercing is undesirable because it demands a greater zone of spraying and greater combustion chamber.

Stress distribution over the cross section of the stream is determined by type of injector. Typical diagram of stress distribution for stream and centrifugal injectors. Two peaks in some distance from the axis are typical for the centrifugal injectors.

Peaks will become smaller at some distance between the stream and injector nozzle (dashed line on figure1.6d). Stress decrease is usually constant through the cross section of stream, although the stress decrease is uneven in reality.

1.7.2 Vaporization

Vaporization process is important part of fuel preparing for ignition and combustion, because the greatest part of fuel in the combustion chamber of the liquid propelled rocket engine is ignited and combusted in the gaseous phase. An overall time necessary for the formation of combustion product depends on vaporization velocity. Complication of the vaporization process in the combustion chamber is in simultaneous vaporization of the multi-component mixture with various physical and chemical properties. Vaporization process should be finished in a very small period, (0.002---0.008sec) Heat necessary for the vaporization of the drops in the combustion chamber of the liquid propelled rocket engine, is introduced from the combustion zone by convective heat transfer using recycled flows of burning gases. Recycled flows are formed because of ejection effect of the injected stream. Stream sucks gases between two or more streams. In that way diluted zones are formed and always come new burning gases there (which carry a heat and giving its heat by a convective transfer) figure1.7.

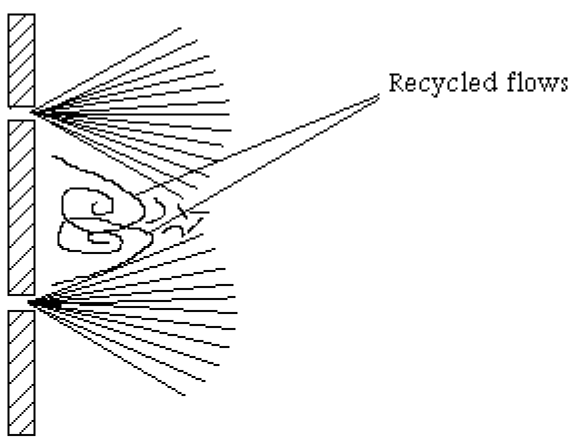

Figure1.7 Formation of recycled flows

A part of the heat in the drops originates from the radiation of the flame core. It is obvious that heat introduction is on the account of the combustion, which begins in the zone of vaporization.

Heating and vaporization rates, and thereby a length of a vaporization zone, depend on physical and chemical properties of drops matter.

Increase of the ambient temperature accelerates process of vaporization; pressure increase slows it down. Length of the drops size and increase of relative velocity of drops lead to faster vaporization. It is obvious, that the chamber length for drops heating to the boiling point increases as the drops size increase. So a finer spraying is desirable for shorting a zone of vaporization.

Uneven spraying leads to formation of greater amount of vapor in the beginning of vaporization, on account of faster vaporization of small drops. Further vaporization of larger drops is taking place during the whole period of vaporization. The uneven spraying leads to the longer process of vaporization.

During the vaporization, concentration of components drops with a high boiling temperature increases. Because of that, process of vaporization falls behind.

Besides the uneven spraying of multi-component liquid drops, a rate of fuel vaporization is affected by a chemical reaction in liquid phase. This is important only for the application of self-igniting fuels. It should be said that heat could accelerate the process of vaporization.

1.7.3 Mixing and combustion:

Mixing of fuel and oxidizer is taking place in both liquid and gaseous phase. The best fuel is one component or emulsion consisting of already mixed components in liquid phase. Characteristic of liquid propelled rocket engine is mixing of the components in the combustion chamber. Intensity of components mixing is determined by a turbulent diffusion.

Process of the mixing of the fuel components begins after the injection of components into combustion chamber and it finishes during the combustion. Mixing of components is taking place in the liquid and gaseous phase in the zones of spraying and vaporization. However, because of the uneven spraying and different rates of vaporization of the components, mixing is not completed in that zones and is resumed in the zones of mixing and combustion. Only a part of the fuel enters a zone of combustion as a completely prepared mixture for combustion.

Other part of the fuel enters the zone of combustion in a state of vapor, but not well mixed for combustion. Mixing of that fuel is resumed. Intensity of mixing is great because of the temperature difference between the flame and incoming components. Already mixed fuel is burning in the zones of the mixing and combustion. Because of the parallel mixing and burning processes, flame distinguishes a prepared fuel mixture from combustion products. Width of the flame is determined by a fineness and homogeneity of spraying, by vaporizing of the fuel components and by intensity of turbulent diffusion depends on rate of mixing.

Process of combustion of sprayed fuel can be divided into mixing of the components and chemical reactions.

Rate of reaction depends on temperature and energy of activation. With low temperature, rate of reaction is small and mixing is slower. Overall rate of the combustion is limited by chemical reactions. Such combustion, which rate is limited by a rate of chemical reaction is called kinetic combustion.

Kinetic combustion can take place at the beginning of the zones of combustion and mixing. That part of the zone is limited by a cross section M-M in the figure1.5, and is called area of kinetic combustion. Behind the cross section M-M a high temperature is developed. Chemical reactions are carried out instantaneously in this area. Rate of combustion is limited by a rate of mixing. Such combustion is called diffusion combustion. Area behind the cross section M-M is area of diffusion combustion. In the combustion chamber of liquid propelled rocket engine, area of kinetic combustion is small and diffusion combustion is more important. It is accepted that in the whole combustion chamber, only diffusion combustion is taking place.

CHAPTER 2

THE AIM OF INJECTOR AND TYPES

2.1 The aim of injector design:

The injector injects the propellants into the combustion chamber in the right proportions and the right condition to yield an efficient, stable combustion process. Placed at the forward or upper end of the combustion chamber, the injector also performs the structural task of closing off the top of the combustion chamber against the high pressure and temperature it contains. The injector located directly over the high-pressure combustion performs many other functions related to the combustion and cooling processes.

The four main injector functions are: Propellant atomization, Propellant dispersion and mixing following atomization, Flame front stabilization & Transmissions of thrust and pressure loads.

2.2 Injector requirements:

For an ideal atomizer would provide all the following characteristics:-

1. Ability to provide good atomization over a wide range of liquid flow rates.
2. Rapid response to changes in liquid flow rate.
3. Freedom from flow instabilities.
4. Low power requirement.
5. Low susceptibility to damage during manufacture and installation.
6. Low cost, light weight, ease of maintenance, and ease of removal for servicing.

Fuel nozzles should have all the above features, plus the following:

1. Low susceptibility to blockage by contaminants and to carbon buildup on the nozzle face.
2. Low susceptibility to gum formation by heat soakage.
3. Uniform radial and circumferential fuel distribution.

2.3 Types of the injectors:

The most common type of the injection elements are; Nonimpinging, Unlike-impinging, and Like-impinging.

2.3.1 Nonimpinging elements:

1. Coaxial. As shown in figure2.1.a. Injection element usually has slow-moving central stream of liquid oxidizer surrounded by a high-velocity concentric sheet of gaseous fuel.
2. Showerhead. As shown in figure2.1.b. gaseous propellants are generally referred to as “showerheads”. This type of element provides very little effective atomization or mixing, and is seldom used for primary injection. It is most frequently used for fuel-film-cooling streams at chamber wall.
3. Fan former. As shown in figure2.1.c. Is frequently used in various types of combustion systems. Generally, these units use internal geometry employing either swirl or impingement to provide a stream, which diverges in a predetermined pattern as finely atomized sprays. However, these systems have not been popular within rocket-injectors designers.
4. Slots and sheets. As shown in figure2.1.d. This type suggested to increase the surface area of propellant streams, but they have seldom been successful. Flow from slots usually has proven quite erratic, tending to ligament into large and irregular masses. Sheet flow of liquids generally requires swirl or impingement to provide the desired dispersal.

2.3.2 Unlike-impinging elements:

1. Unlike doublets. As shown in figure2.1.e. A straightforward way of mixing two different streams directs one against the other; this in essence describes the basic unlike-impinging doublet. The impact produces a fan-shaped spray made up mixture of the two impinging fluids.
2. Unlike triplets injectors have demonstrated high levels of mixing and resultant combustion efficiency, as shown in figure2.1.f. But they also tend to be sensitive to stability problems.
3. Pentads. Obviously there are many possible combinations of unlike-impinging streams; unlike-impinging stream configuration seldom exceeds the use of four streams of one propellant against a center stream of the other.

2.3.3 Like-impinging elements:

1. Like doublets. As shown in figure2.1.g. (or self-impinging), this type avoids most of the reactive-stream demixing of unlike-impinging designs and better maintains

patterns. Although the initial mixing provided by the element is poorer than for the unlike-impinging case.

2. Like-impinging triplets. Three streams of the same propellant can be directed to a common impingement point. The like impinging triplet usually produces narrower spray fans and larger drops than an equivalent doublet.

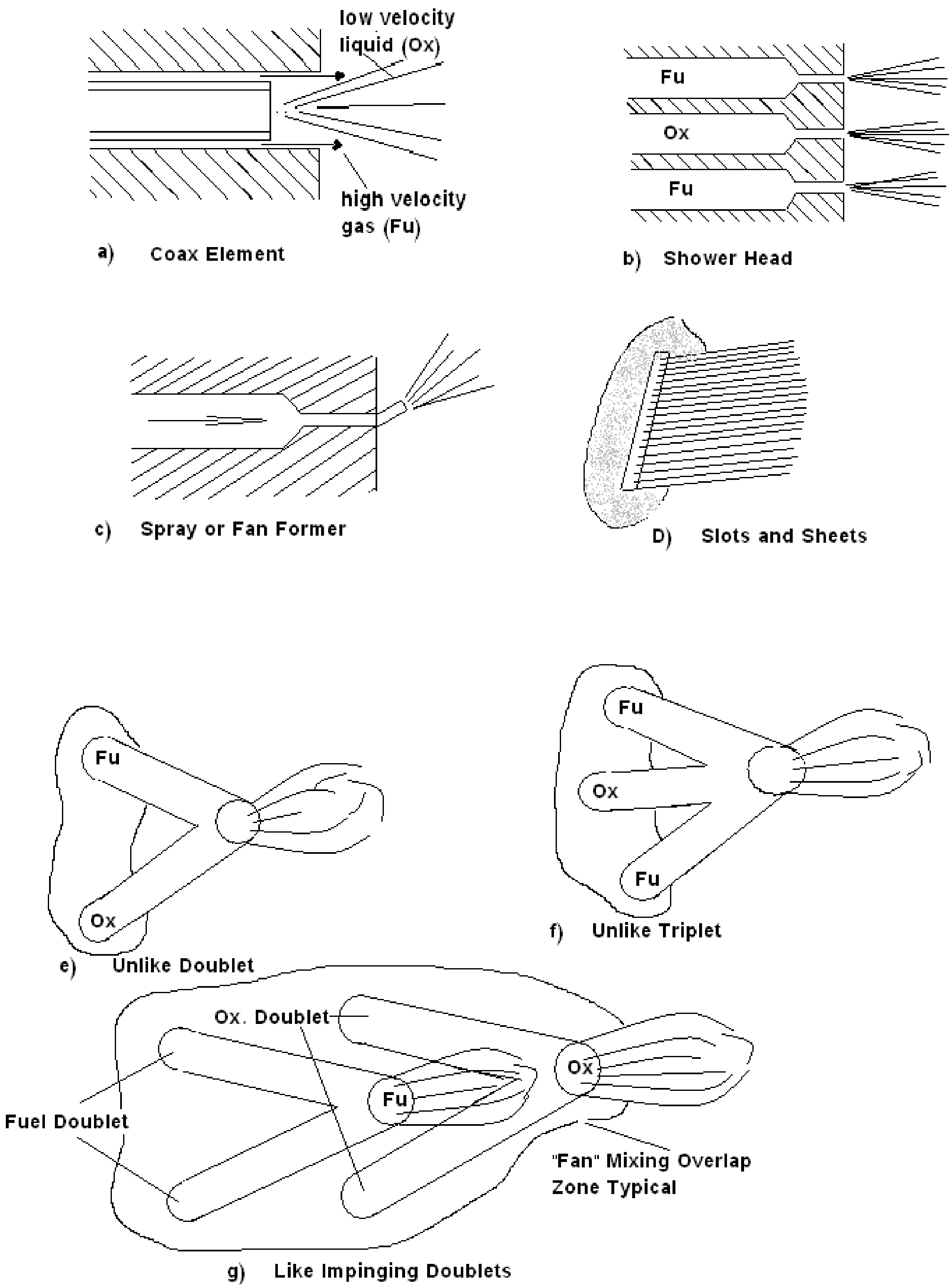

Figure2.1 Typical injector element types

2.3.4 Other element type pintle injector:

Pintle injectors also offer simple high-thrust-per-element design. Very little fundamental work on pintle injectors is available in the open literature, and the design process is highly empirical. More than the other injectors, the design of the pintle injector must be combined with the design of the combustion chamber to yield good results. Better understanding of the interactions between the pintle injector flow and the combustor could help reduce the combustor size. Figure2.2 photo for parts of pintle injector

Fig-2.2 Photo for parts of pintle injector.

CHAPTER 3

PINTLE INJECTOR DESIGN CONCEPTS

3.1 Pintle injector design concepts:

The basic concept of the bipropellant pintle injector is shown in figure 3.1.

One propellant (here shown as fuel) is fed through outer injector flow passage into a circumferential annulus-formed between the injector body “snout” and the central injector element which meters the flow into the combustion chamber. This propellant exits the injector as an axially flowing annular sheet that arrives at the impingement point with a circumferentially uniform velocity profile.

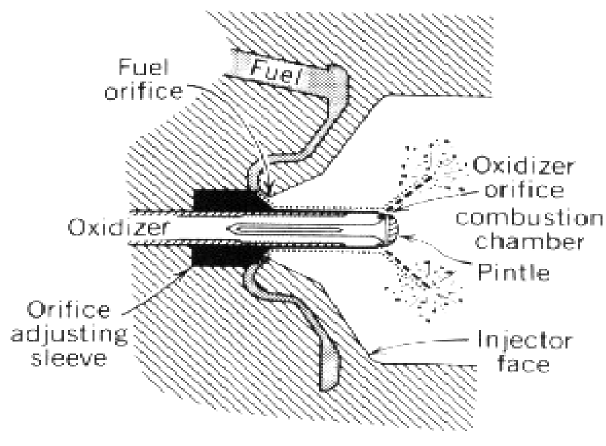

Figure 3.1.Pintle injector concept (continuous gap, fixed thrust or throttling designs)

The other propellant (here shown as oxidizer) enters the injector body via a separate centrally-located passage and flows axially through a central pintle sleeve toward the injector, where it is turned to uniform radial flow by the pintle tip’s internal contoured surface. This propellant is metered into the combustion chamber by passing through: (a) a continuous gap formed between the cylindrical sleeve and pintle tip, or (b) slots or holes of certain geometry machined into the end of the sleeve which may be integral with the tip, or (c) a combination of the above two designs. Thus, the pintle injector can meter the central propellant as a continuous radial sheet, a series of radially flowing “spokes”, or combination of both. Figure 3.2 shows the injection geometry of the slotted or “toothed” pintle injector with attached tip.

Experience has shown that the pintle injector can be designed to give high performance with either fuel or oxidizer being the centrally-metered propellant. Generally, fuel is chosen as the central propellant injector radiation-cooled engines because the radial injection momentum can be designed to persist to the wall, thus enabling a convenient means of “tuning” the injector to provide fuel film cooling of the combustion chamber. Ultimately, the decision to meter either fuel or oxidizer as the central propellant depends on many design trade-offs. TRW has successfully flown both ox-centered and fuel-centered pintle engines.

The 90°, axial-radial impingement of the two propellant streams combined with the specific geometry of the resulting atomization and mixing “fan” is fundamental to the pintle injector providing both high combustion efficiency and inherent combustion stability.

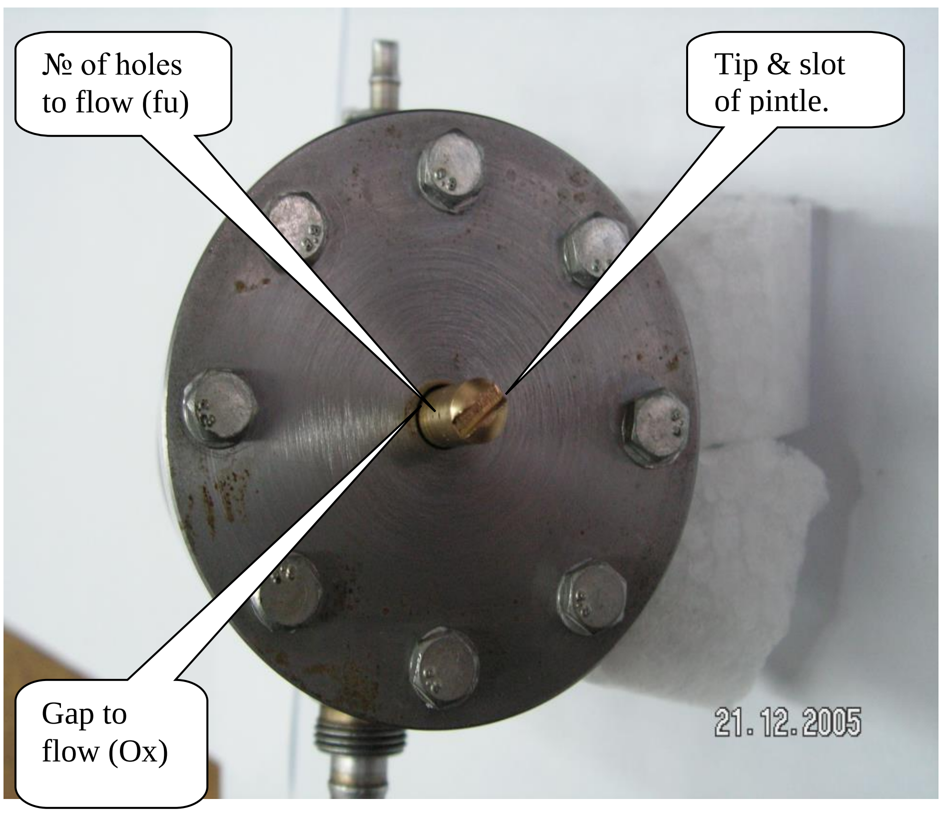

Figure 3.2 Photograph pintle injector concepts

(a) Outer flow only

(b) Inner flow only

(c) **Combined flows**

Figure 3.3 Photographs of injector water flows

Figure 3.3 is a series of photographs of water flow tests on a single pintle injector, looking back toward the injector element and headend dome. Figure 3.3(a) shows characteristic flow for the outer, annular injection; Figure 3.3(b) shows a wider-angle view of the inner passage flow being injected as a radial sheet; and Figure 3.3(c) shows the spray fan resulting form the combined injected, but non-reacting, flows.

The single central injector sleeve, shown injector Figure 3.1, is easily designed to be movable. This provides a convenient and reliable means of throttling the injector to maintain nearly constant injection velocities across a wide range of injected propellant flow rates. TRW has used this feature to great advantage, as discussed below, to produce deep (>10:1) throttling engines that maintain high combustion efficiency and insensitivity to chug instability across their operation range.

Where injectors employ a movable sleeve, a separate on-axis support rod (or tube) and cruciform guide vanes are used to support the pintle tip independent of the sleeve. It is seen that movement of the single sleeve can simultaneously meter both the fuel and the oxidizer at their immediate points of injection Furthermore, with proper design the sleeve can be made to fully shutoff both propellants at the injector face (hence, “face shutoff”), thereby eliminating all dribble volume from the injector. In face, TRW has implemented “face shutoff only” injector where this movable sleeve was the only “valving” locking off propellant supply pressures up to approximately 3000 psia.

The distance from the outer propellant’s annular entrance point into the combustion chamber to the point of contact with the injected central propellant stream is referred to as the injector’s “skip distance”. This parameter, together with others such as the pintle’s insertion depth into the chamber, it’s diameter relative to the chamber diameter and injection stream thicknesses, velocities and relative momentum, must be considered injector proper design of pintle injectors.

Careful design of the pintle injector ensures (a) good atomization and mixing of the two propellant streams for high combustion efficiency, (b) proper fuel film cooling at the chamber wall, and (c) evaporative cooling of the exposed headend dome for good thermal margin.

The momentum of the injector’s resultant spray “fan” of mixing and combusting propellants pump two major zones of recirculation within the combustion chamber, as indicated in Figure 3.4.

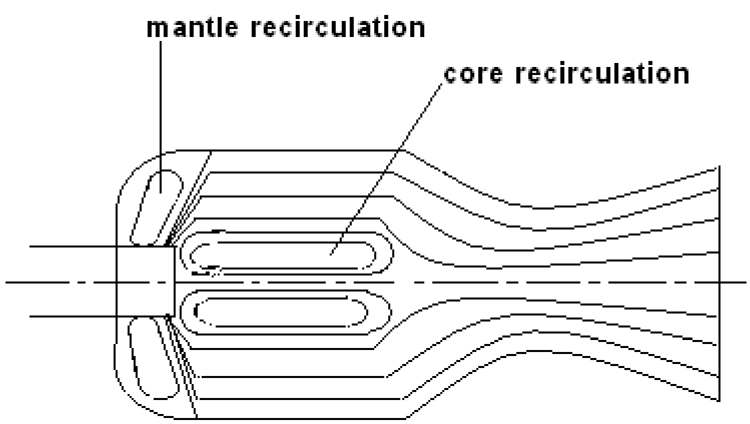

Fig-3.4. Combustion chamber flow field resulting from pintle injection of propellants

There is: (1) an upper torroidal zone that is predominantly outer propellant-rich and acts to cool the headend via evaporation of entrained and impinging droplets of liquid propellant, and (2) a lower torroidal zone that is predominately central propellant-rich and recirculates back on-axis toward the pintle, thereby acting as a deflector and mixer for any unburned droplets that would otherwise tend to travel directly from the injector to the nozzle throat.

3.2 Pintle engine design fundamentals:

Typical injectors for rocket engines consist of multiple, separate injection orifices distributed more or less uniformly across the diameter of the engine's headend. In comparison, the pintle injector injects propellants only at a relatively small area located at the center of the headend. And whereas conventional injectors create propellant mixing injector a planar zone immediately adjacent to the headend, the pintle injector creates a torroidal mixing zone that is significantly removed from the chamber headend. As was shown injector figure 3.4, the pintle injector therefore creates a combustion chamber flow field that is significantly different from that of conventional rocket engine injectors. This leads to operating characteristics favoring combustion stability and performance, which are summarized in Table 3.1.

One extraordinary benefit of such fundamental characteristics is that the pintle injector has been proven to be scalable over a wide rang of thrust level and different propellant combinations without any need for stability augmentation, such as acoustic cavities or baffles. There has never been an instance of acoustic instability observed in a TRW pintle injector rocket engine.

Another major benefit is that the pintle injector has demonstrated the ability to consistently deliver high performance (typically 96-99% of theoretical combustion performance, c*) with proper design and hardware buildup.

In comparison with conventional rocket engines operating at the same chamber pressure and thrust level, pintle rocket engines are generally longer in physical length and higher in chamber contraction ratio (both being required to support the chamber's major recirculation zones).

3.3 A comparison with typical rocket designs:

Table 3.1. Comparison of Key Engine Operating Parameters for Typical

Liquid Rocket Engines versus TRW's Pintle Rocket Engine

Parameter	Chamber Flow Pattern in Typical Liquid Rocket	Chamber Flow Pattern in TRW Pintle Rocket
Propellant injection	Distributed across injector face	Only at central location
Fuel and oxidizer injection geometry	Multiple intersecting or shearing propellant streams; intersecting streams are of like or unlike propellants	Single annular outer sheet of one propellant impinges on (a) multiple radial "spokes" of other propellant, or (b) thin radial fan of other propellant
Fuel and oxidizer collision geometry	In plane immediately adjacent to injector face	In torus significantly offset from injector face
Droplet trajectories	Approximately axial down chamber	Initially at large angle to chamber axis
Chamber recirculation	None	Two major recirculation zones in chamber
Droplet vaporization and combustion	Proceed in planar fashion down chamber length	Proceed along axially symmetric, but highly non-planar, contours in chamber
Secondary droplet breakup	Comparatively small due to axial flow and homogeneous distribution	Comparatively large due to wall impingement and recirculation zones
In passing through chamber, droplets see:	Little "relative wind" away from injector face (pressure perturbations thus cause large change injector energy release rate)	Large "relative wind" throughout chamber (pressure perturbations thus cause only small change in energy release rate)
Energy release zone geometry	Uniform and planar across chamber diameter (facilitates acoustically-coupled combustion instability)	Radially-varying and canted down and across chamber-together with stable zones having different gas properties (O/F,MW,gamma and T)-serve to prevent acoustic instabilities
Chamber for optimum combustion performance	Is relatively short and has relatively small contraction ratio	Is relatively long and has relatively high contraction ratio
Wall film cooling	Established by separate injection ports	Established by pintle injector "tuning", eliminating need for separate ports
Injection metering orifices	Relatively small and contamination sensitive	Relatively large and insensitive to contamination

3.4 Summary of TRW pintle injector rocket engines used on flight programs:

Table 3.2 summarizes TRW's flight experience with pintle engines, including those with thrust levels down to the 100 lbf class (i.e., Liquid Apogee Engine, LAE, class).

Table 3.2. Summary of TRW Pintle injector Rocket Engines Used on Flight Programs

Engine	Thrust(lbf)	Propellants	Pc(psia)	Duty Cycle	Development Funding Source	Number Produced	Cooling Method	Isp (sec)	Comments
LMDE	1000 to 9850	N2O4/A-50	100	*3 starts *10:1 throttling *1000 sec max single burn duration	NASA	84	Ablative	303	Perfect reliability record as LEM descent engine, saved Apollo 13 mission
TR201	9900	N2O4/A-50	100	*5 starts, 500 sec total *10 to 350 sec single burn duration	TRW	77	Ablative	303	Perfect reliability record as second stage Delta engine 77/77
ISPS	100 lbf class	HAD/USO	94	*300 pulses *1 to 570 sec. single burn duration	LMSC	28	Radiation, Columbium	272	Flown successfully on orbital Agena program 28/28
MMBPS	88	N2O4/MMH	90	*25,000sec. total burn time *130 starts *9000sec.max single burn time		21	Radiation, Columbium	305	Derived form TRW URSA 100R engine
DM/LAE	105	N2O4/N2H4	100	*25,000sec. total burn time *20 starts *6000 sec single burn time	Commercial G.E./TRW	10	Radiation, C-103	315	Six successful spacecraft flight engines (Anik,Intelsat)
AC/LAE	120	N2O4/N2H4	100	*24,000sec. total burn time *100 starts	Commercial G.E./TRW	6	Radiation, C-103	322	4 Engines flown successfully on NASA Chandra S/C-1999
ERIS Divert Thruster	910	N2O4/MMH	1600	*pulsing	Army	12	Ablative	284 (ε=16)	Flown successfully on two ERIS flights-4/flt
FMTI	1050	Gels:IRFNA/C-loaded MMH	1750	*pulsing	Army/AMCOM	6	Ablative	240 (S.I.)	Program on-going; 2 flight successes injector 2 launches

3.5 Rang of propellants tested:

Pintle injectors have successfully operated with 25 different combinations of propellant, which are summarized in Table 3.3.

Table 3.3 propellant combinations tested using pintle injectors

LOX/H2(1)	LOX/RP-1
LOX/C3H8	LOX/N2H4
LOX/ETHANOL	GOX/ETHANOL
FLOX/CH4(1)	FLOX/CH4(g)
FLOX/C3H8(1)	FLOX/CH4+C2H6(1)
N2O4-MON3/MIMH	N2O4-MON3/N2H4
N2O4/UDMH	N2O4/A-50
C1F3/N2H4	C1F3/NOTSGELA
F2(1)/N2H4	MON10/MMH
IRFNA/UDMH	IRFNA/JP4
IRFNA/NOTSGEL-A	HAD/USO
Gelled IRFNA/ Gelled MMH+60%AI	Gelled IRFNA/ Gelled MMH+60%C
Coal Dust/Air	---

3.6 Application and design guidelines:

Figure 3.5 highlights some of the major design features of a pintle injector. The most important design variable is total momentum ratio (TMR), defined as the ratio of radial-to-axial stream momentum:

$$TMR = \frac{\left(\dot{m}U\right)_r}{\left(\dot{m}U\right)_z}$$

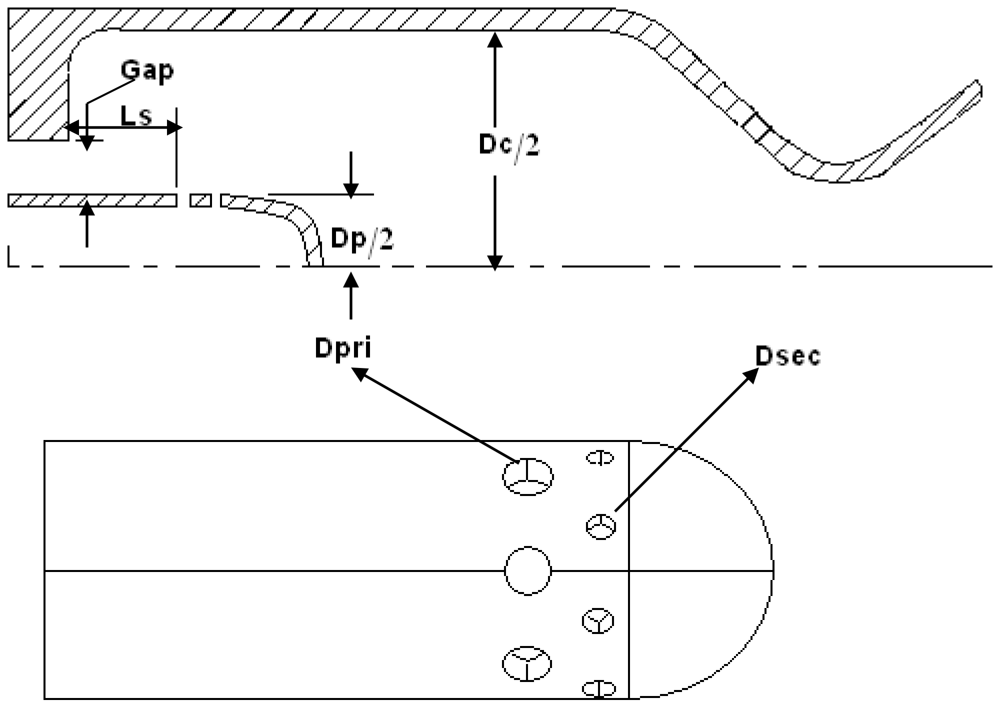

Fig-3.5 Key design variables for a pintle injector.

The cone angle formed by the propellant sprays increases with TMR; design experience shows that TMR values near unity provide optimal performance.

The cone angle of the spray scales as TMR, similar to the scaling of jet penetration in a cross flow with momentum ratio. Typical injection velocities for both axial and radial streams range from 10 to 50 m/s in most cases.

The blockage factor (BF), defined as the ratio of the total hole /slot circumferential length divided by the circumference of the pintle, is another important design variable:

$$BF = \frac{n \cdot dfu}{\pi \cdot d_p}$$

Where n is the number of holes/slots in the pintle tip (typically 20-36). In some designs, a set of secondary holes is placed just downstream of the primary holes in the pintle. These holes are placed circumferentially to lie in the gaps formed by the primary holes; they generally are smaller in size than the primary holes.

Another important dimensionless variable is the ratio of chamber-to-pintle diameters, dch/dp. Typical values for this quantity range from 3 to 5. Finally, the skip distance is defined as the length that the annular flow must travel before impacting the radial holes divided by the pintle diamet L_s / d_p .

A typical value for this parameter is around 1; larger skip distances are subject to substantial deceleration of the liquid because of friction against the pintle post, whereas very short skip distances may lead to spray impingement on the head end of the combustion chamber.

Increase TMR such that fuel jets actually penetrate the axial oxidizer annulus and impact on the wall to provide film cooling. Oxidizer-centered designs would operate best at lower TMR values to insure that oxidizer does not impact chamber walls and cause damage or compatibility issues.

In general, the combustion chambers that use pintle injectors tend to have a higher contraction ratio than face-type injectors to accommodate the radial flows induced by this injection scheme. However, the combustor lengths may actually be shorter because of this same phenomenon; the overall chamber characteristic length values are not dramatically different between the two designs. Pintle thrusters have demonstrated combustion efficiencies in the 96-99 % range for most of the engines that have been developed for flight programs. Because of the limited number of holes in the pintle, the thrust per element (thrust per hole) can be very large for high-thrust engine designs, and the combustion efficiency tends to be a bit lower on large engines for this reason. Of course, this difference in efficiency must be weighed against the inherent simplicity and cost of the injector.

The aforementioned design guidelines along with required propellant flow rates allow one to size the dimensions shown in Fig-3.5. Design changes are very easy to implement by simply machining another pintle tip. In general, it is difficult to manufacture very small thrust injectors (as in the case of all bipropellant engines) because both the orifice sizes and the annular gap become very small. Tight tolerances are required on the pintle outer surface to insure a uniform propellant gap under these conditions.

CHAPTER 4

MIXTURE FORMATION AND INJECTOR HEAD DESIGN

4.1 Stream injectors

Fuel intake into combustion chamber is accomplished by means of injectors. Basic purpose of the injectors is to provide finer and more homogeneous fuel spraying with low pressure acting on them.

Two types of the injectors are used in liquid propelled rocket engines; stream and centrifugal injectors. There are also injectors with slot, which can be regarded as stream injectors. They have an exit opening in a form of slot. There are injectors that have the characteristics of both types.

4.2 Calculation of stream injectors

Stream injectors can be calculated by means of the following equations. Theoretical velocity of the out flow of incompressible liquid through an opening is:

$$v = \sqrt{\frac{2\Delta P}{\rho}} \quad \textbf{.......... 1}$$

Where:

$\Delta P = P_2 - P_1$ = Injection pressure.

ρ = Liquid density

Flow of the liquid through injector is given by flow equation:

$$\dot{m} = \mu \cdot v \cdot A \cdot \rho \quad \textbf{............ 2}$$

Where:

A = surface area of the opening cross section.

μ = flow rate coefficient (discharge coeff-), takes into account contraction of the stream and decrease of real flow rate in comparison with theoretical.

From equation **1&2** we obtain:

$$\dot{m} = \mu \cdot A \cdot \sqrt{2\rho \cdot \Delta P} \quad \text{..............3}$$

From which it follows:

$$A = \frac{\dot{m}}{\mu\sqrt{2\rho \cdot \Delta P}} \quad \textbf{...................4}$$

The first calculation dealing with (Ox) flow used eq-4 with ρ=1000 kg/m³ of water, μox=0.75, m=0.3kg/s at 7 bar.
& ΔP= 5 — 10 bar.

By excel can get the values of area where Ox flow, at different values of pressure.

ΔP psi	Aox m²
500000	1.2649E-05
600000	1.1547E-05
700000	1.0690E-05
800000	1.0000E-05
900000	9.4281E-06
1000000	8.9443E-06

For this area of flow, the area equal

$$Aox = \frac{\pi}{4}\{D^2 - dp^2\}$$

$$where D = dp + 2\delta$$

$$final : .Aox = \pi.\delta.dp$$

Sub- the of D in to D² in the above eq- and because so small δ²<< δ dp cancel

And take the value of $\delta \equiv 0.1 \rightarrow 1mm$

To find out the value of dp use this eq- $Aox = \pi.\delta.dp$

Use excel to get dp at different value of (Aox, δ)

(δ) in m	**(dp)** in m at Aox1	**(dp)** in m at Aox2	**(dp)** in m at Aox3	**(dp)** in m at Aox4	**(dp)** in m at Aox5	**(dp)** in m at Aox6
1E-04	4.0263E-02	3.6755E-02	3.4029E-02	3.1831E-02	3.0011E-02	2.8471E-02
2E-04	2.0132E-02	1.8378E-02	1.7014E-02	1.5915E-02	1.5005E-02	1.4235E-02
3E-04	1.3421E-02	1.2252E-02	1.1343E-02	1.0610E-02	1.0004E-02	9.4902E-03
4E-04	1.0066E-02	9.1888E-03	8.5072E-03	7.9577E-03	7.5026E-03	7.1176E-03
5E-04	8.0527E-03	7.3511E-03	6.8058E-03	6.3662E-03	6.0021E-03	5.6941E-03
6E-04	6.7106E-03	6.1259E-03	5.6715E-03	5.3052E-03	5.0018E-03	4.7451E-03
7E-04	5.7519E-03	5.2508E-03	4.8613E-03	4.5473E-03	4.2872E-03	4.0672E-03
8E-04	5.0329E-03	4.5944E-03	4.2536E-03	3.9789E-03	3.7513E-03	3.5588E-03
9E-04	4.4737E-03	4.0839E-03	3.7810E-03	3.5368E-03	3.3345E-03	3.1634E-03
1E-03	4.0263E-03	3.6755E-03	3.4029E-03	3.1831E-03	3.0011E-03	2.8471E-03

And to get the value of dch (diameter of chamber) use this equation:

$$dch = 4.dp$$

dch.=4*dp1	dch.=4*dp2	dch.=4*dp3	dch.=4*dp4	dch.=4*dp5	dch.=4*dp6
1.6105E-01	1.4702E-01	1.3612E-01	1.2732E-01	1.2004E-01	1.1388E-01
8.0527E-02	7.3511E-02	6.8058E-02	6.3662E-02	6.0021E-02	5.6941E-02
5.3684E-02	4.9007E-02	4.5372E-02	4.2441E-02	4.0014E-02	3.7961E-02
4.0263E-02	3.6755E-02	3.4029E-02	3.1831E-02	3.0011E-02	2.8471E-02
3.2211E-02	2.9404E-02	2.7223E-02	2.5465E-02	2.4008E-02	2.2776E-02
2.6842E-02	2.4504E-02	2.2686E-02	2.1221E-02	2.0007E-02	1.8980E-02
2.3008E-02	2.1003E-02	1.9445E-02	1.8189E-02	1.7149E-02	1.6269E-02
2.0132E-02	1.8378E-02	1.7014E-02	1.5915E-02	1.5005E-02	1.4235E-02
1.7895E-02	1.6336E-02	1.5124E-02	1.4147E-02	1.3338E-02	1.2654E-02
1.6105E-02	1.4702E-02	1.3612E-02	1.2732E-02	1.2004E-02	1.1388E-02

The second calculation dealing with (fu) flow used eq-4 with ρ=1000 kg/m³ of water , μfu=0.70 , m=0.1kg/s at 7 bar

& ΔP= 5 — 10 bar

By excel can get the values of area where fu flow, at different values of pressure.

Afu m²	ΔP ps
4.51754E-06	500000
4.12393E-06	600000
3.81802E-06	700000
3.57143E-06	800000
3.36718E-06	900000
3.19438E-06	1000000

For this area of flow, the area equal

$$Afu = \frac{\pi}{4}.dfu^2.n$$

Where n is the number of holes around the pintle diameter in one row or two rows. And n = 2,4,6,8,10,12

From the above equation by using excel we can get the different value of dfu as change in Afu & n

dfu at fixed ΔP1&Af1 with different № of holes	n № of holes	dfu at fixed ΔP2&Af2 with different № of holes	dfu at fixed ΔP3&Af3 with different № of holes	dfu at fixed ΔP4&Af4 with different № of holes	dfu at fixed ΔP5&Af5 with different № of holes	dfu at fixed ΔP6&Af6 with different № of holes
0.001695864	2	0.001620301	0.001559046	0.00150786	0.001464107	0.001426046
0.001199157	4	0.001145726	0.001102412	0.001066218	0.00103528	0.001008367
0.000979108	6	0.000935481	0.000900116	0.000870563	0.000845303	0.000823328
0.000847932	8	0.000810151	0.000779523	0.00075393	0.000732054	0.000713023
0.000758413	10	0.000724621	0.000697227	0.000674336	0.000654769	0.000637747
0.000692334	12	0.000661485	0.000636478	0.000615581	0.000597719	0.000582181

4.3 Experimental work

This work is depended to above date and calculation, from that can be design and produce pintle injector head as shown in figure 4.1. With three different pintle diameter 6, 8, 12 mm and different gap to flow axial stream (δ=0.3, 0.4, 0.5) which is oxidizer flow.

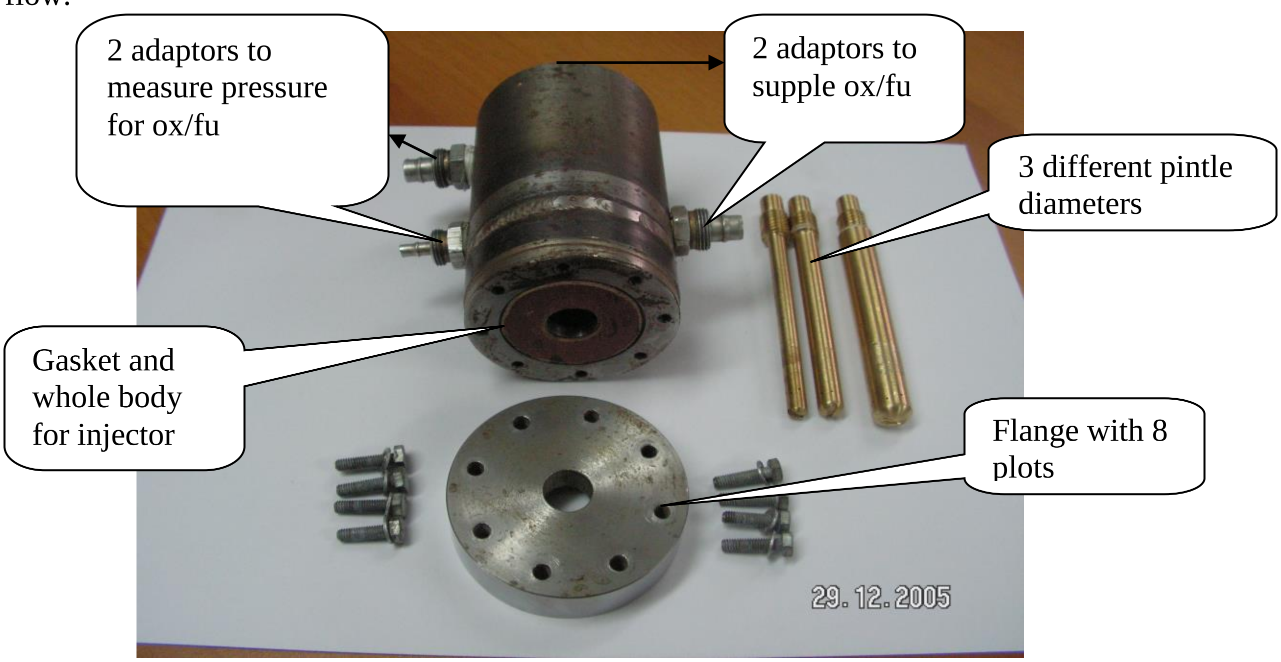

Figure 4.1 Photo for parts of pintle injector head

And also in this experimental work used three device of measuring pressure one for supple pressure fixed with 10 bars, and the author two to measure pressure in the pintle injector as flow for oxidizer and fuel, as shown in figure 4.2.

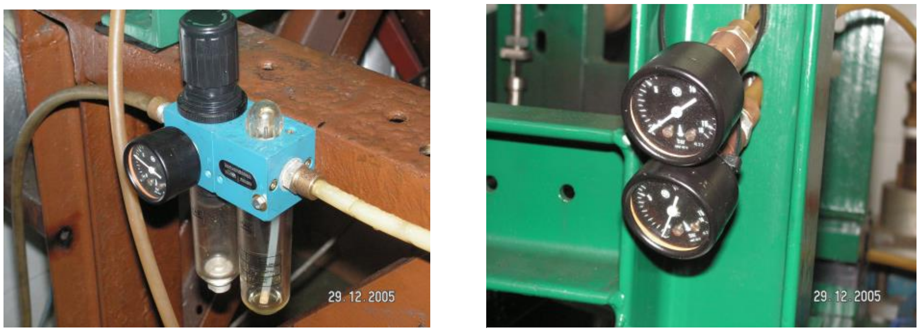

Figure 4.2 Two photos for pressure gage device

Counter weight gage device to collect the water flow from the pintle injector. Separate one for radial flow, and the anther for axial flow, with time gage to now mass flow rate. As shown in figure 4.3.

Figure 4.3 Photo for counter weight gage device

The first calculation to measure the mass flow rate with different pintle diameter and gab. Used this equation:

$$\dot{m} = \mu.\mathrm{A}.\sqrt{2\rho.\Delta\mathrm{P}}$$

Consider **C** as constant equal

$$C = \mu.\mathrm{A}.\sqrt{2\rho}$$

$$\therefore \quad \dot{m} = C.\sqrt{\Delta\mathrm{P}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. 5$$

From this equation can get the value of **C = Cox = Cfu =** $\frac{\dot{m}}{\sqrt{\Delta \mathrm{P}}}$.

For axial flow as (oxidizer) can get **Cox:**

dp= 6mm **δ= 0.3**	**ΔPox=4 bar**	**M=0.810kg**	**t = 10 sec**	**Cox= 1.2807e-4**
dp= 8mm **δ= 0.5**	**ΔPox=3 bar**	**M=3.626kg**	**t = 15 sec**	**Cox= 4.4134e-4**
dp= 12mm **δ= 0.4**	**ΔPox=2.8 bar**	**M=2.304kg**	**t = 10 sec**	**Cox= 4.3541e-4**

For radial flow as (fuel) can get **Cfu:**

dp= 6mm **δ= 0.3**	**ΔPfu=8 bar**	**M= 0.09kg**	**t =18 sec**	**Cfu=5.5901e-6**
dp= 8mm **δ= 0.5**	**ΔPfu=7 bar**	**M= 0.287kg**	**t = 10sec**	**Cfu=3.4303e-5**
dp= 12mm **δ= 0.4**	**ΔPfu=7.5 bar**	**M= 0.387kg**	**t = 12sec**	**Cfu=3.7239e-5**

The second calculation to calculate mass flow rate ($\dot{m}$), velocity stream injector (U), and total momentum ratio (TMR) with different measure values of ΔP using equation № 1 & 5.

$$TMR = \frac{(\dot{m}.U)r}{(\dot{m}.U)z}$$

1. For dp = 6mm , δ = 0.3 mm, density of water (ρ=1000kg/m³) , Cox= 1.2807e-4 & Cfu=5.5901e-6 by using excel program get:

ΔPox (Pa)	$\dot{m}$ ox (Kg/sec)	Uox (m/sec)	ΔPfu (Pa)	$\dot{m}$ fu (Kg/sec)	Ufu (m/sec)	TMR1	By visible
4.00E+05	8.10E-02	28.28427	6.00E+05	4.33E-03	34.64102	0.065474	good
3.50E+05	7.58E-02	26.45751	5.00E+05	3.95E-03	31.62278	0.062356	good
2.50E+05	6.40E-02	22.36068	5.50E+05	4.15E-03	33.16625	0.096029	bad
4.50E+05	8.59E-02	30	5.50E+05	4.15E-03	33.16625	0.053349	good
6.00E+05	9.92E-02	34.64102	5.50E+05	4.15E-03	33.16625	0.040012	good -
3.00E+05	7.01E-02	24.4949	6.50E+05	4.51E-03	36.05551	0.094574	bad
4.00E+05	8.10E-02	28.28427	6.50E+05	4.51E-03	36.05551	0.07093	bad
6.00E+05	9.92E-02	34.64102	6.50E+05	4.51E-03	36.05551	0.047287	good -
7.00E+05	1.07E-01	37.41657	5.00E+05	3.95E-03	31.62278	0.031178	good
8.00E+05	1.15E-01	40	5.00E+05	3.95E-03	31.62278	0.027281	good

For the above table can get three charts to see the relation between pressure and mass flow rate as shown in figure 4.4. And total momentum ratio TMR with visible test. As shown in figure 4.5.

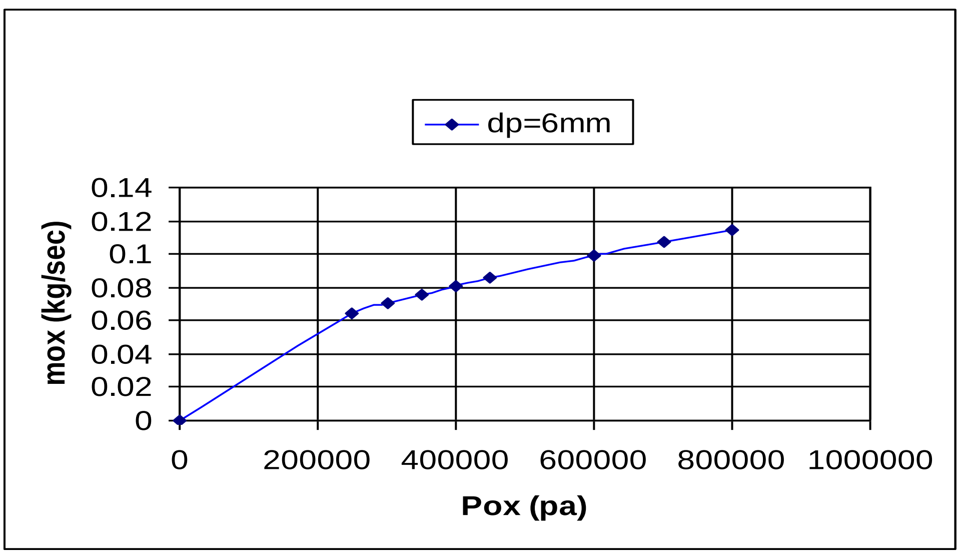

Figure (4.4a) Relation between pressure and mass flow rate at dp=6mm & δ=0.3 when flow is axial (ox).

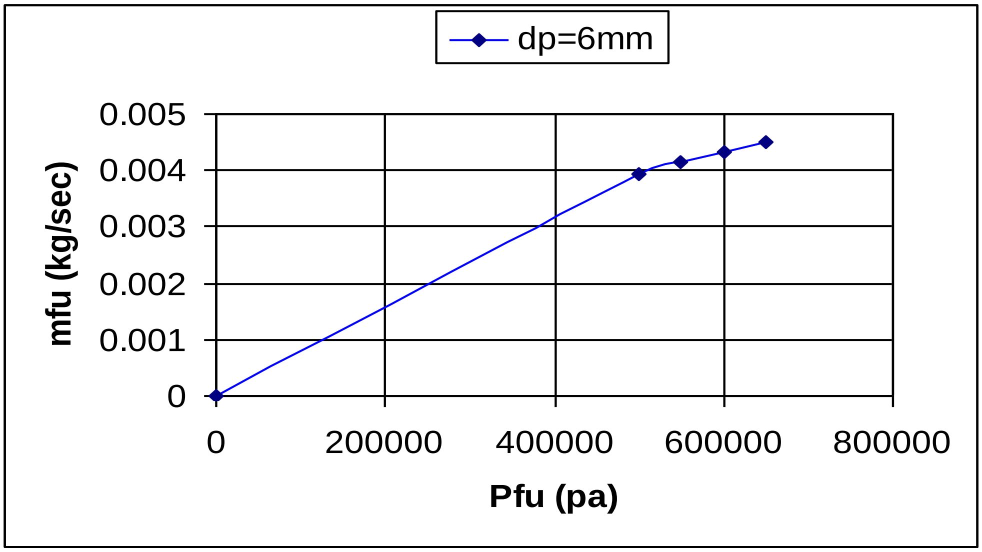

Figure (4.4b) Relation between pressure and mass flow rate at dp=6mm & δ=0.3 when flow is radial (fu).

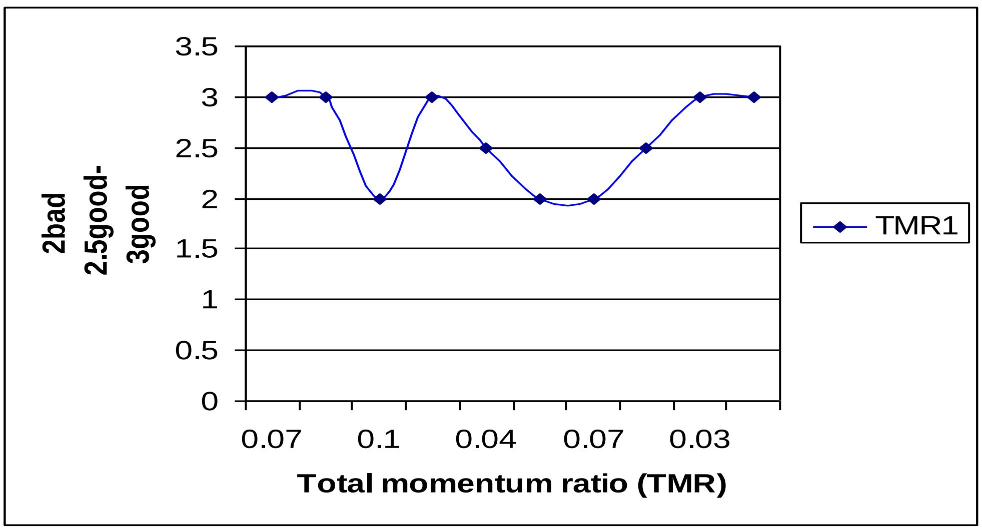

Figure (4.5) TMR with visible test

2. For dp = 8mm, δ = 0.5 mm, density of water (ρ=1000kg/m³), Cox= 4.4134e-4 & Cfu=3.4303e-5 by using excel program get:

ΔPox (Pa)	$\dot{m}$ ox (Kg/sec)	Uox (m/sec)	ΔPfu (Pa)	$\dot{m}$ fu (Kg/sec)	Ufu (m/sec)	TMR2	By visible
2.50E+05	2.21E-01	22.36068	4.50E+05	2.30E-02	30	0.139904	good
4.00E+05	2.79E-01	28.28427	4.50E+05	2.30E-02	30	0.08744	good
2.00E+05	1.97E-01	20	6.00E+05	2.66E-02	34.64102	0.233174	good
3.00E+05	2.42E-01	24.4949	6.00E+05	2.66E-02	34.64102	0.155449	very good
4.00E+05	2.79E-01	28.28427	6.00E+05	2.66E-02	34.64102	0.116587	very good
4.00E+05	2.79E-01	28.28427	7.00E+05	2.87E-02	37.41657	0.136018	very good
5.00E+05	3.12E-01	31.62278	7.00E+05	2.87E-02	37.41657	0.108815	good

For the above table can get three charts to see the relation between pressure and mass flow rate as shown in figure 4.6. And total momentum ratio TMR with visible test. As shown in figure 4.7.

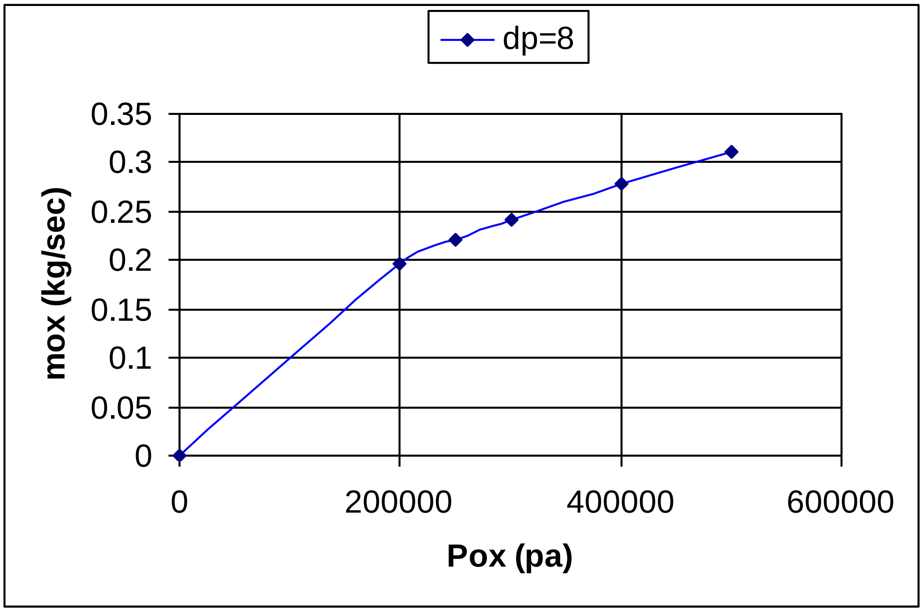

Figure (4.6a) Relation between pressure and mass flow rate at dp=8mm & δ=0.5 when flow is axial (ox).

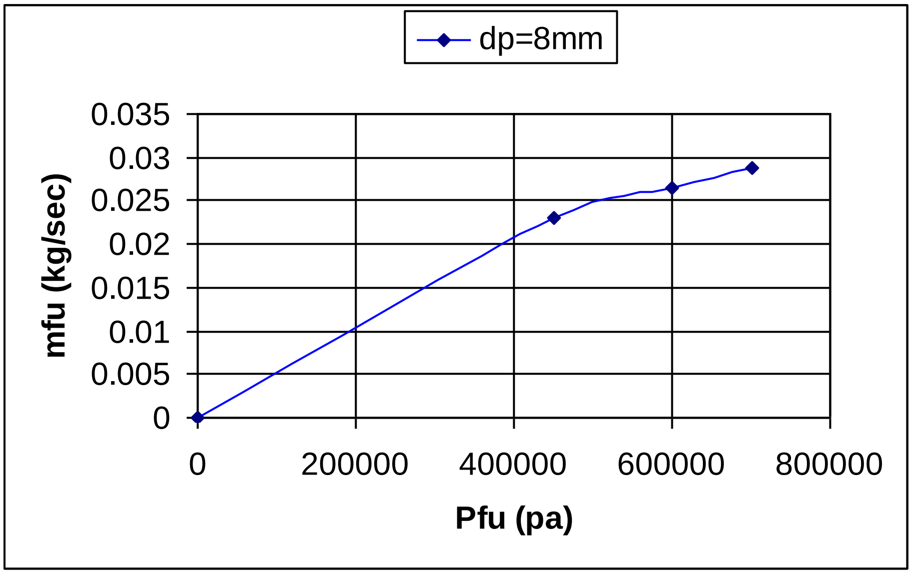

Figure (4.6b) Relation between pressure and mass flow rate at dp=8mm & δ=0.5 when flow is radial (fu).

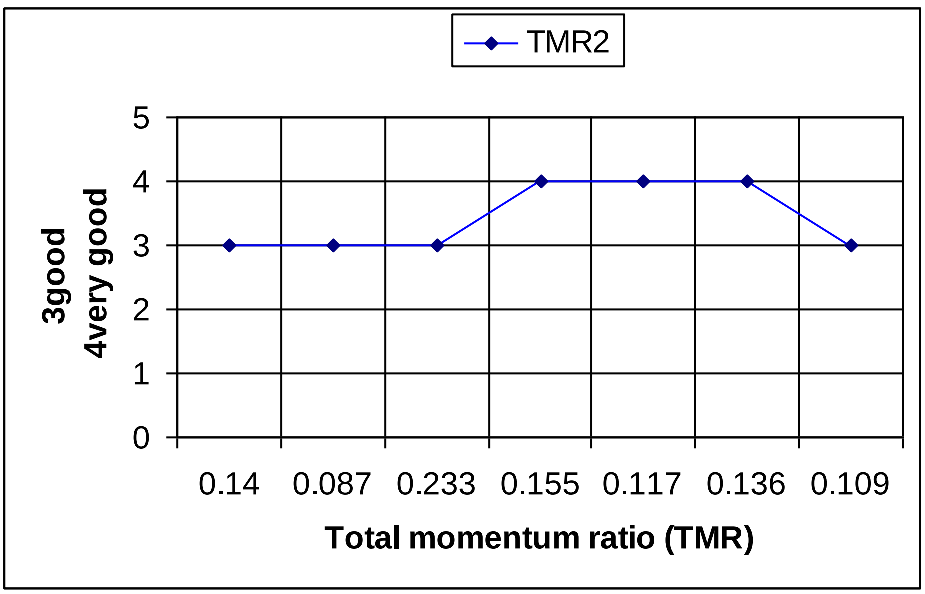

Figure (4.7) TMR with visible test.

3. For dp = 12mm , δ = 0.4 mm, density of water (ρ=1000kg/m³) , Cox= 4.3541e-4& Cfu=3.7239e-5 by using excel program get:

ΔPox (Pa)	$\dot{m}$ ox (Kg/sec)	Uox (m/sec)	ΔPfu (Pa)	$\dot{m}$ fu (Kg/sec)	Ufu (m/sec)	TMR3	By visible
2.00E+05	1.95E-01	20	4.00E+05	2.36E-02	28.28427	0.171051	bad
3.00E+05	2.38E-01	24.4949	4.00E+05	2.36E-02	28.28427	0.114034	bad
4.00E+05	2.75E-01	28.28427	4.00E+05	2.36E-02	28.28427	0.085525	good
2.00E+05	1.95E-01	20	5.50E+05	2.76E-02	33.16625	0.235195	bad
3.00E+05	2.38E-01	24.4949	5.50E+05	2.76E-02	33.16625	0.156796	good -
4.50E+05	2.92E-01	30	5.50E+05	2.76E-02	33.16625	0.104531	good
2.50E+05	2.18E-01	22.36068	7.00E+05	3.12E-02	37.41657	0.239471	bad
3.50E+05	2.58E-01	26.45751	7.00E+05	3.12E-02	37.41657	0.171051	good -
4.50E+05	2.92E-01	30	7.00E+05	3.12E-02	37.41657	0.133039	good

For the above table can get three charts to see the relation between pressure and mass flow rate as shown in figure 4.8. And total momentum ratio TMR with visible test. As shown in figure 4.9.

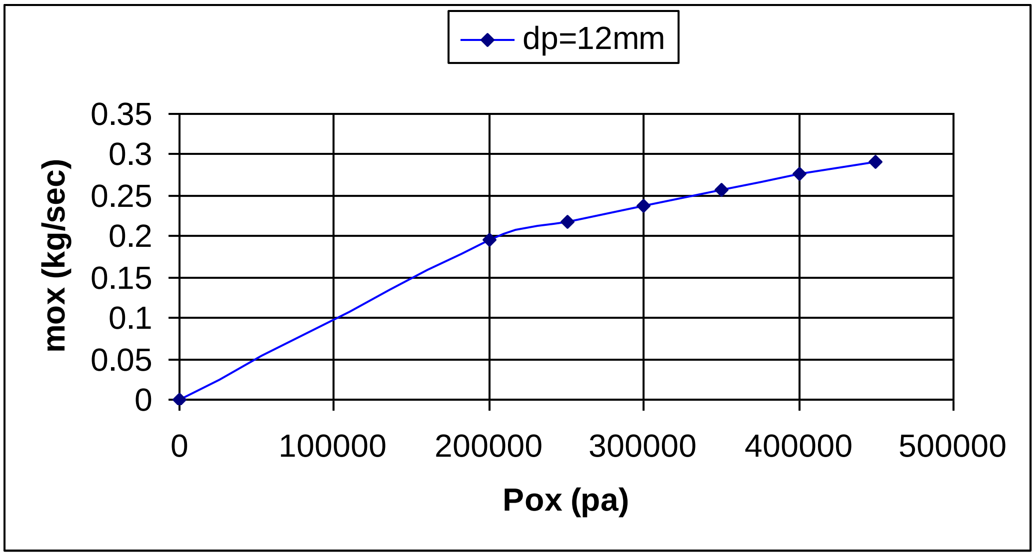

Figure (4.8a) Relation between pressure and mass flow rate at dp=12mm & δ=0.4 when flow is axial (ox).

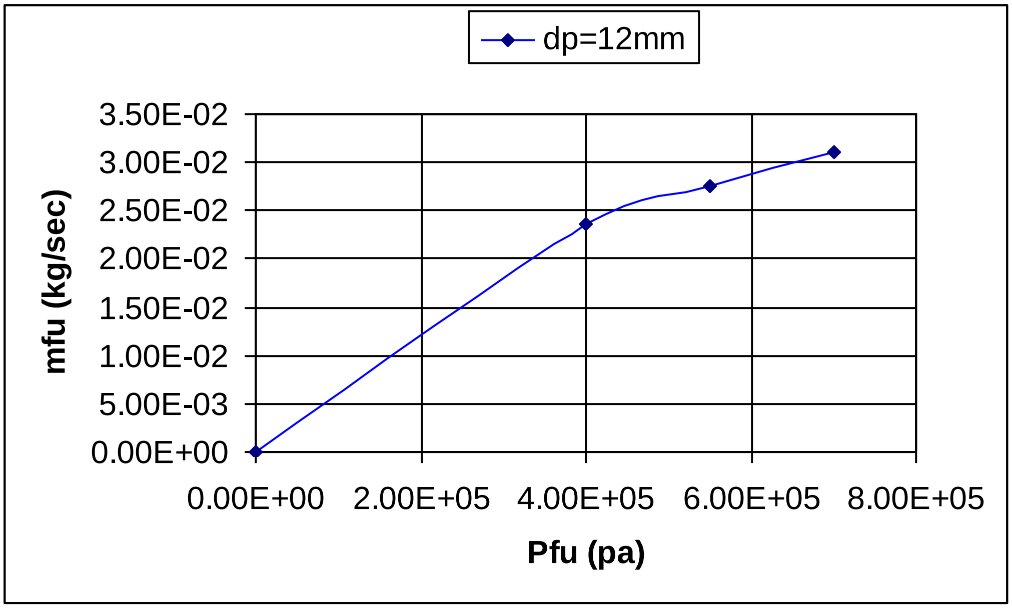

Figure (4.8b) Relation between pressure and mass flow rate at dp=12mm & δ=0.4 when flow is radial (fu).

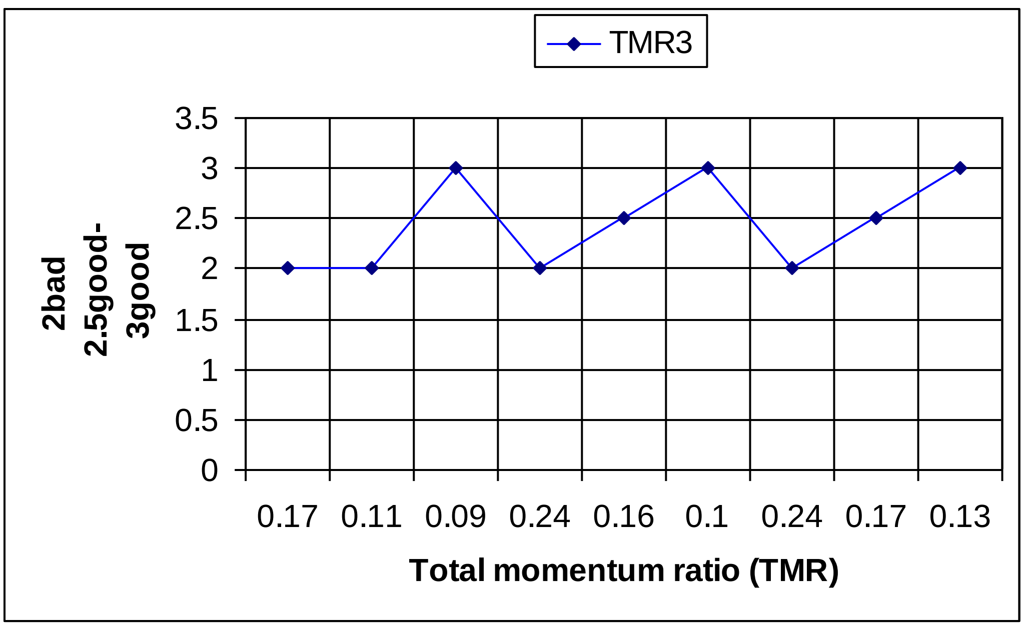

Figure (4.9) TMR with visible test.

The last calculation to calculate blockage factor (BF), with three different pintle injector head.

$$BF = \frac{n.dfu}{\pi.dp}$$

Where:

n. № of holes around pintle diameter.

dfu. Diameter of hole around pintle diameter.

n	dfu	dp	BF=
8	0.6	12	0.127324
8	0.6	8	0.190986
8	0.6	6	0.254648

To see the different BF in three pintle injector at constant TMR as shown in three figures 4.10, 4.11, and 4.12.

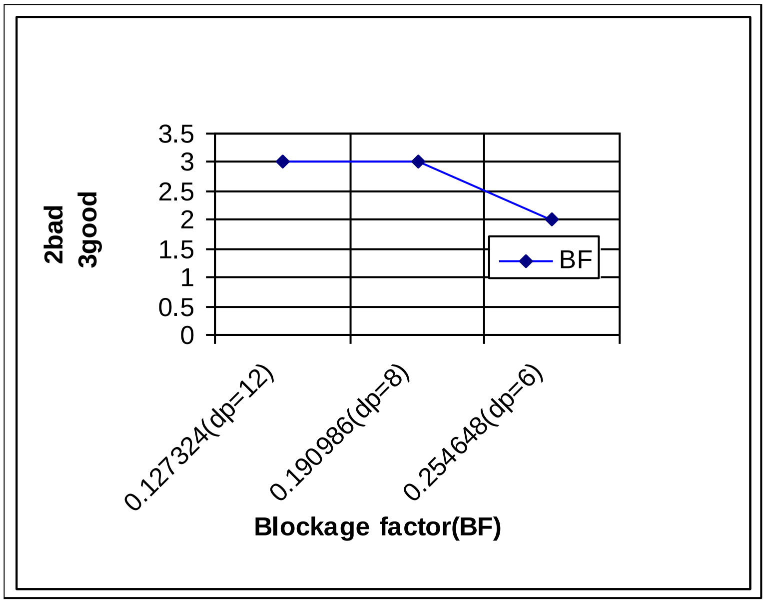

Figure 4.10 (BF) Diagram for different (dp) at TMR=0.07

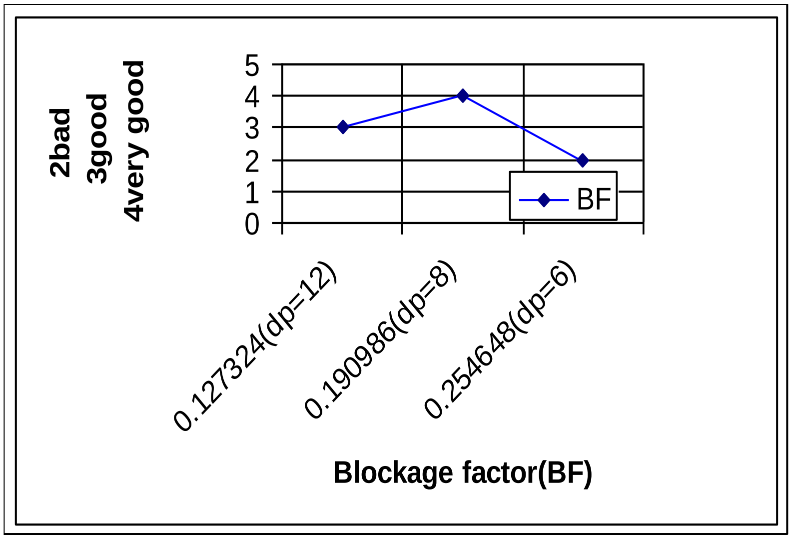

Figure 4.11(BF) Diagram for different (dp) at TMR=0.1

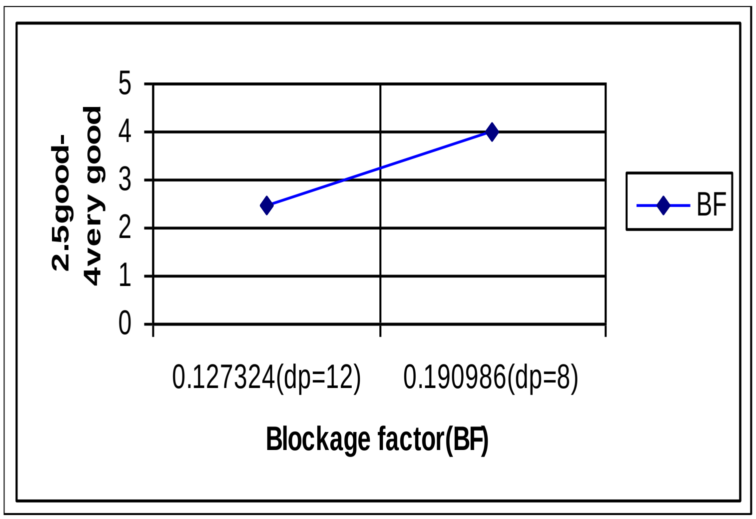

Figure 4.12 (BF) Diagram for different (dp) at TMR=0.15

CHAPTER 5

Conclusions

Finally from this project we can conclude the following points:

1. Mixture formation represents a group of processes, which are performed from the moment of the components injection to combustion chamber to the moment of the formation of the homogenous mixture.
2. The work is carried out on the assumption that the mixing of the components happen between drops. In fact, due to continues drop vaporization will cause gas stream that leads to turbulence mixing of the gas stream with the main stream, also we have mixing of the gases during the vaporization at the greater distances from the engine head.
3. Pintle injectors also offer simple high-thrust-per-element designs. Very little fundamental work on pintle injectors is available in the open literature, and the design process is highly empirical. More than the other injectors.
4. The design of the pintle injector must be combined with the design of the combustion chamber to yield good results. Better understanding of the interactions between the pintle injector flow and the combustor could help reduce the combustor size.

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