MODEL FOR FUEL DROPLET EVAPORATION IN COMBUSTION CHAMBER OF LIQUID PROPELLANT ROCKET ENGINES

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ABSTRACT

Complete burning of liquid propellants droplets is very important to avoid combustion instability and to get higher specific impulse from liquid rocket engines. Combustion takes place in gaseous phase and reaction is fast. So, the time consumed by a droplet for complete burning is the time taken by a droplet to get evaporated. An analytical mono component fuel droplet evaporation model is developed and proposed for droplet evaporation in liquid rocket engine based on heat and mass transfer. Effect of the fuel droplet curvature on vapor pressure is incorporated in the model. The model is applied on a small-scale combustion chamber of bi-propellant liquid rocket engine where fuel concentration away from droplet is not zero. A code is generated and applied. The results of the model show that fuel droplet diameter, combustion chamber pressure, chamber diameter, mass flow rate and droplet relative velocity with hot gas has significant effects on the life of droplet and characteristic length. Effects of chamber pressure and diameter are more significant for larger droplet size.

KEYWORDS: *Fuel Droplet Evaporation, Combustion Chamber, Characteristic Length, Characteristic Velocity, Liquid Rocket Engine*

INTRODUCTION

Combustion in liquid rocket engine is non-premixed turbulent diffusion combustion. Such combustion is diffusion limited so; efficiency of the combustion in liquid rocket engines is dependent on good mixing and high diffusion rate. Atomization play important role, smaller the droplet diameter, less is the time required for fuel droplet evaporation and combustion. Reaction is very fast due to high temperature. Most of the time is consumed by evaporation and mixing.

The speed of evaporation depends on many factors which include, combustion chamber pressure, temperature, initial fuel droplet temperature before injection, size of the droplet, type of fuel, relative velocity between droplet and hot gas inside chamber, hot gas transport properties and turbulent intensity (Birouk and Gökalp, 2006).

The factors discussed above are link together and change in one will affect the others. If combustion chamber is regenerative cool then chamber inside temperature will affect initial fuel injection temperature, which will affect droplet evaporation time and combustion chamber temperature in return. Higher chamber temperature will produce more pressure at a given throat diameter.

I-Single droplet evaporation

Combustion reaction takes place in gaseous phase, therefore evaporation of fuel is very important process for the performance of liquid fueled combustion systems, such as gas turbines, automobiles and propulsion systems. A lot of work has been done on the evaporation of spray and droplet evaporation (Kim *et al.,* 2003; Sirignano, 1988; Faeth, 1977; Law. 1982; Kim and Sung, 2003).

In liquid rocket engine or other spray combustion systems, the spray is dense and there are a number of droplets close to one another. Modeling or experimental study of dense spray is very difficult; therefore, modeling of single droplet is performed, which gives a very good picture of the real problem (Wang, 2016). The study of the evaporation of the single droplet is simplification of the real complex spray evaporation. The study of evaporation of single fuel droplet is very important for scientist and engineers. The evaporation of the single fuel droplet is studied in past and will be studied in future in quiescent state, gas moving around the droplet and turbulent condition around the droplet.

Different models are available in literature for fuel

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droplet evaporation and they can be grouped on the basis of different criteria. The most important groups can be mono-component and multi-component.

A-Stagnant condition or no relative movement

At stagnant condition there is no movement of the drop relative to ambient gas. Most of the work for spray or droplet evaporation is done at stagnant condition. The work of Godsave (1951), led to the quasi steady state model, which is also called d^2 law.

At stagnant condition heat transfer from the surrounding to the droplet surface takes place only through conduction and radiation.

B-Convective Conditions

At stagnant conditions heat transfer take place only due to conduction and radiation but when there is relative motion between droplet and ambient gases then convection come into play its role and then heat transfer take place through conduction radiation and convection. With more heat transfer there is more mass transfer from droplet surface to ambient atmosphere. Convection effects on droplet evaporation were studied by Froessling, (1968); Kinzer and Gunn, (1951); Acrivos and Taylor, (1962); Ranz & Marshall, (1952); Yang & Wong, (2002); Umr *et al.,* (2008); and Kristyadi *et al.,* (2010).

Applying Froessling correlation

$$\frac{K_L}{K_q} = 1 + 0.27 R_e^{0.5} S_c^{1/3} \qquad (1)$$

In equation (1) and K_q are evaporation constant at laminar flow and quiescent conditions.

C-Turbulent Environment

Combustion of spray takes place in turbulent conditions. The flow of hot gas around droplet affects the spray/droplets in different ways. Faeth and Gökalp (1983) reports three different types of effects of turbulence on spray combustion. He reports droplet distribution over wide area, change of turbulence properties and change of transport properties due to motion of droplet (Birouk *et al.*, 2008).

Theoretical and experimental work on droplet evaporation under turbulent environment is very limited. Work dealing with turbulent droplet evaporation at high temperature and pressure is almost unavailable and most of the work done is at standard temperature and pressure (Birouk *et al.*, 2008). In 1950 Maisel and Sherwood (Maisel and Sherwood, 1950) were the first who started work on effects of ambient turbulence condition on mass transfer. Maisel and Sherwood were followed by many researchers (Hsu and Sage, (1957); Brown *et al.,* (1958); Venezian *et al.,* (1962); Galloway and Sage, (1964); Galloway and Sage, (1967); Gostkowski and Costello, (1970); Sandoval-Robles *et al.,* (1981); Masoudi and Sirignano, (2000). The entire researcher reported increase in mass transfer rate except reference (Hsu and Sage, 1957). Later on, Gökalp *et al.,* (1992), introduced vaporization damkhuler number. Gökalp *et al.,* (1992), reported that mass transfer is more for vaporization Damkuhler number from 0.0001 to 0.1. Mass transfer decreases with increase in vaporization Damkuhler number and it will not affect mass transfer if vaporization Damkuhler number is one or more than one. The findings of Gökalp *et al.,* (1992), were verified by Wu *et al.,* (2001); Wu *et al.,* (2003).

According to Wu *et al.,* (2001), for Damkuhler (Da_v) number in the range from 0.0001 to 0.1, ratio of evaporation constant at turbulent condition, K_T and laminar flow condition K_L

$$\frac{K_T}{K_L} = 0.77 D_{a_v}^{-0.111} \qquad (2)$$

Hiromitsu et al., (1995); tested damkuhler vaporization correlation of Gokalp *et al.,* (1992) for ambient temperature from 323 K to 423 K and they found that correlation of Gokalp *et al.,* (1992) does not work for temperature above atmospheric.

A correlation was proposed by Birouk and Gökalp, (2002) for turbulent effects on evaporation of droplet with zero convection mean velocity. The correlation is given below.

$$\frac{K_T}{K_q} = 1 + 0.02 Re_{td}^{2/3} S_c^2 \qquad (3)$$

Where, $Re_{td} = q^{0.5} \frac{d_o}{\upsilon_a}$ and $q = \frac{3}{2} u^{'2}$ for isotropic Turbulence.

II-Analytical droplet evaporation model for liquid

propellant rocket engine

- A-Assumption of the model
- Spherical droplet
- Radiation is neglected
- Droplet temperature is uniform
- Fuel is pure liquid of single component(mono-component) having a well-defined boiling point
- Unity Lewis number
- Evaporation take place in heating and steady state phase

The total time required for complete evaporation of the droplet is divided in two phases. One is heating phase and the other is steady state droplet evaporation phase.

During the heating phase, heat supplied from environment is partially used to raise temperature of the droplet and partially used to evaporate fuel at the surface of the droplet. While heating the droplet a temperature reaches where all of the heat is used to evaporate the droplet and no further temperature increase takes place. This is called steady state evaporation phase. The droplet surface temperature reaches wet bulb temperature and all of the heat supplied is used to provide latent heat of vaporization.

Heat transferred from environment = Heat used to raise temperature of droplet + Heat used for evaporation of the droplet

Neglecting heat transfer through radiation,

$$\dot{Q} = m_d C_{pl} \frac{dT_s}{dt} + \dot{m}L \qquad (4)$$

Where is heat transfer from ambient to droplet, is mass evaporation rate from droplet, m_d is mass of droplet Cpl specific heat capacity at constant pressure and L is latent heat of vaporization. Heat transfer is also given by following equation.

$$\dot{Q} = \pi D_d k_1 \left(T_\infty - T_s\right) Nu_d \qquad (5)$$

D_d is droplet diameter, N_{ud} is Nusselt number of droplet and k_1 is thermal conductivity at reference point.

The classical droplet evaporation rate is given by, where BM is Spalding mass transfer number, $\overline{D}$ is diffusion coefficient , ρ_1 density of gas reference point and Sh_d is Sherwood number.

$$\dot{m} = \pi D_d \rho_1 \overline{D} B_M Sh_d \qquad (6)$$

$$m_d = \rho_{lf} \frac{\pi D_d^3}{6} \qquad (7)$$

Where is density of liquid fuel

Putting in equation (4),

$$\frac{dT_s}{dt} = \frac{k_1\left[\left(T_\infty - T_s\right) Nu_d - \frac{B_M Sh_d L(Ts)}{C_{p1}}\right]}{\frac{1}{6}\rho_{fl} D_d^2 C_{pl}} \qquad (8)$$

$\frac{dT_s}{dt}$ is the rate of change of temperature during complete life of the droplet.

Lewis number = $\frac{\alpha}{\overline{D}}$, Assuming unity Lewis number, so $\overline{D} = \alpha$,

Where, $B_M = \frac{Y_{fs} - Y_{f\infty}}{1 - Y_{fs}}$ (9)

Y_{fs} is fuel mass fraction at the surface of droplet and is fuel mass fraction in ambient away from the droplet.

Assuming fuel and oxidizer is uniformly distributed in evaporation zone of the combustion chamber and fuel mass fraction away from the droplet is equal to the ratio of total fuel to total propellant. So $Y_{f\infty} = F_{fr} = \frac{Total\ Fuel}{Total\ Propellant}$,

Then equation 9 becomes,

$$B_M = \frac{Y_{fs} - F_{fr}}{1 - Y_{fs}} \qquad (10)$$

$$Y_{fs} = \left[1 + \left(\frac{P}{P_{fs}} - 1\right)\frac{M_{amb}}{M_f}\right]^{-1} \qquad (11)$$

P is combustion chamber pressure, M_{amb} is molecular weight of ambient and M_f is molecular weight of Fuel.

Vapor pressure, P_{fs} at T_s is calculated by using Antoine correlation (Reid *et al.,* 1987), which is given below.

$$lnP_{fs} = A - \frac{B}{C + Ts} \qquad (12)$$

Where, A, B and C are constant depending on type of fuel.

Curvature of liquid droplets affects vapor pressure. Vapor pressure of liquid with convex curved surface is greater than liquid with flat surface. Using Kelvin equation Skinner (1972),

$$P_{vapf} = P_{fs} Exp\left(\frac{2\sigma V_m}{R_d R T_s}\right) \quad (13)$$

Replacing P_{fs} with P_{vapf} in equation 11

$$Y_{fs} = \left[1+\left(\frac{P}{P_{fs}}-1\right)\frac{M_{amb}}{M_f}\right]^{-1} \quad (14)$$

Spalding heat transfer number is given by $B_T = \frac{C_{p1}(T_\infty - T_s)}{L(Ts)}$ (15)

$$L(Ts) = L(Tbp)\frac{Tcr-Ts}{Tcr-Tbp}^{0.38} \quad (16)$$

So temperature T_s at the surface of the droplet can be found from the following equation

$$T_S = T_\infty - \frac{Y_{fs} L(Ts)}{(1-Y_{fs})C_{P1}} \quad (17)$$

Y_{fs} In the above equation, is dependent on vapor pressure (P_{fs}) on the surface of the drop and Vapor pressure (P_{fs}) is dependent on temperature T_s. It changes with drop surface temperature T_s. So value of Ts is calculated iteratively. Moreover, the value of Ts should be such that both B_M and B_T converge at this temperature. C_{p1} Is calculated at reference temperature and reference composition, which are calculated according to one third rule of sparrow and Gregg (Kleinstreuer et al., 2007) as follow.

$$T_r = T_s + \frac{1}{3}(T_\infty - T_s) \quad (18)$$

$$Y_{fr} = Y_{fs} + \frac{1}{3}(Y_{f\infty} - Y_{fs}) \quad (19)$$

$$Y_{or} = 1 - Y_{fr} \quad (20)$$

T_r is reference point temperature, Ts is droplet surface temperature, Y_{fr} is fuel mass fraction at reference point and Y_{or} oxidizer mass fraction at reference point in equation 18,19 and 20 respectively.

The rate of change of mass of the droplet or evaporation rate is

$$\frac{dm_d}{dt} = m \quad (21)$$

Putting equation 21 in equation 6

$$\frac{dm_d}{dt} = \pi D_d \rho_1 \overline{D} B_M Sh_d \quad (22)$$

$$m_d = \rho_{lf}\frac{\pi D_d^3}{6} \quad (23)$$

From equation 22 and 23

$$\frac{dD_d^2}{dt} = \frac{2\rho_1 \overline{D}_1 B_{MSh_d}}{\rho_{lf}} \quad (24)$$

When Lewis number is unity then,

$$\overline{D}_1 = \frac{k_1}{\rho_1 c_{p1}} \quad (25)$$

Putting values, equation 24 becomes as,

$$\frac{dD_d^2}{dt} = \frac{2k_1 B_M Sh_d}{C_{p1}\rho_l} \quad (26)$$

$\frac{dD_d^2}{dt}$ is change in square of the droplet diameter with respect to time.

$$\frac{dD_d^2}{dt} = \frac{2k_1 B_M Sh_d}{C_{p1}\rho_l} \quad (27)$$

Equation 27 gives rate of change of droplet diameter during complete life of the droplet.

Value of Sherwood number (Sh_d) and Nusselt number (Nu_d) is different at different condition and different assumptions. Many relations have been introduced by different authors to find Nusselt and Sherwood number at different conditions. (Sazhin *et al.,* 2006) compared different equation to calculated Sherwood and Nusselt number at different conditions.

In practical application, conditions around droplets are turbulent and yearling Yearling, (1995) proposed correlation for Sherwood and Nusselt number for turbulent flow around the droplet, which are as follow,

$$Nu_d(1+B_T)^{0.7} = 2 + 0.58 Re_d^{1/2} Pr_1^{1/3}(1+0.07I^{0.843}) \quad (28)$$

$$Sh_d(1+B_T)^{0.7} = 2 + 0.58 Re_d^{1/2} Pr_1^{1/3}(1+0.07I^{0.843}) \quad (29)$$

Putting,

$$2+0.58Re_d^{1/2}Pr_1^{1/3}=Nu_0 \quad (30)$$

$$2+0.58Re_d^{1/2}Pr_1^{1/3}=Sh_0 \quad (31)$$

Equation 28 and 29 becomes,

$$Nu_d\left(1+B_T\right)^{0.7}=Nu_0\left(1+0.07I^{0.843}\right) \quad (32)$$

$$Sh_d\left(1+B_T\right)^{0.7}=Sh_0\left(1+0.07I^{0.843}\right) \quad (33)$$

For stagnant droplet with no evaporation N_{u0} is equal to 2 and Sh_o with no relative movement of the droplet with ambient is also 2.

B-Application on Combustion chamber of liquid rocket engine

Velocity and Reynolds number of hot gas inside combustion chamber is given by

$$V_\infty=\frac{\dot{m}}{\rho_\infty A_{cc}} \quad (34)$$

$$Re_\infty=\rho_\infty V_\infty D_c/\mu_\infty \quad (35)$$

Turbulent intensity (I) inside combustion chamber and velocity fluctuation Fluent, 2017.

$$I=0.16Re_\infty^{-\left(\frac{1}{8}\right)} \quad (36)$$

$$u=IV_\infty \quad (37)$$

$$L^*=\frac{M_{dot}}{\rho_g A_T}t_{res} \quad (38)$$

Where M_{dot} is total propellant mass flow rate, ρ_g density of hot gas in combustion chamber and is t_{res} fuel droplet residence or life time which is calculates as follow.

t_{res}= time step x Number of iterations

Numbers of iterations are those numbers of iteration which the code takes to make fuel droplet diameter equal to zero. Volume of chamber (Vc) is the production of throat area, A_T and characteristic length L^*.

$$V_c=A_T L^* \quad (39)$$

Solution procedure

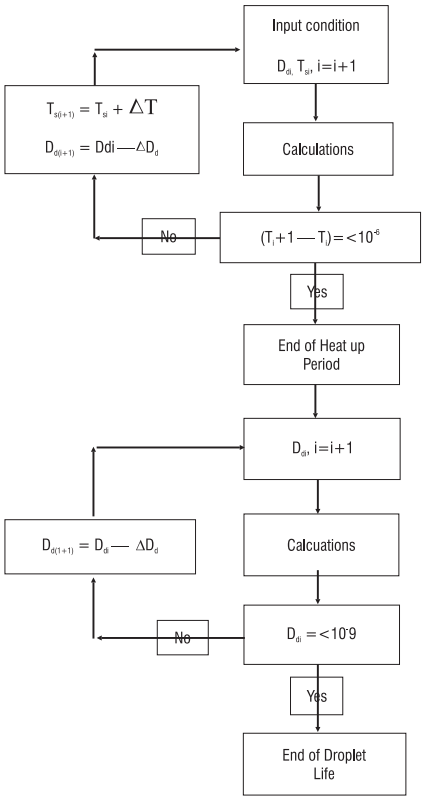

Figure 1: Solution Process.

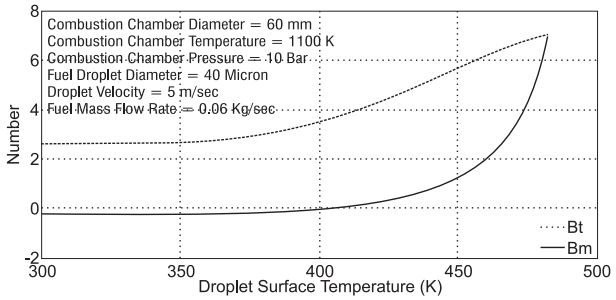

Figure 2: End of the heating phase.

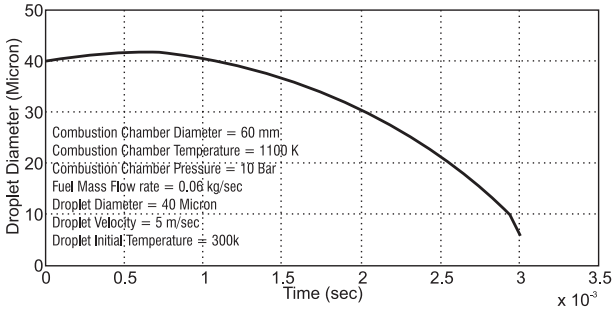

Figure 3: Fuel droplet diameter in heating phase.

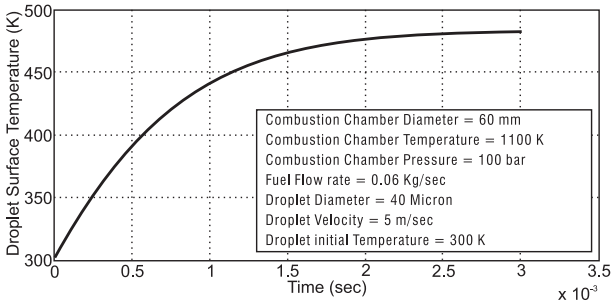

Figure 4: Fuel droplet surface temperature in heating phase.

The model is applied on lower temperature small scale combustion chamber of bi-propellants with oxidizer to fuel mixing ratio of 0.3. The propellants are liquid oxygen and Kerosene. The model developed is mono-component droplet evaporation model. Kerosene droplet is assumed as single component of Dodecane. Droplet of liquid oxygen takes very less time as compared to kerosene, therefore time taken by kerosene droplet is the time required for complete evaporation of both propellants.

Solution procedure is elaborated in figure1. It shows that heating phase ends when increase in droplet temperature is less or equal to 10^{-6}K and evaporation time is completed when droplet radius is equal or less than 10^{-9} m.

The solution of the model takes place in two stages. In first stage heating phase is solved and required values are calculated. In heating phase some of the heat is used to raise the temperature of the droplet and some is used to evaporate droplet. In the second stage, steady state phase of the life of the droplet is solved.

Computer Code starts with initial, given surface temperature of the droplet. Reference temperature is calculated using this initial temperature. Corresponding required values of density, viscosity, thermal conductivity, enthalpy, entropy, specific heat capacity at constant pressure and volume, pressure and etc. at that reference temperature is taken from the data files. There are two data file one for fuel and another for oxidizer. Vapor pressure at the droplet surface is calculated. Fuel concentration on droplet surface along with fuel and oxidizer concentration at reference point is calculated. Spalding mass and heat transfer numbers are calculated at this temperature. Rate of change of temperature and diameter of the droplet is calculated from equation (8) and (Masoudi and Sirignano, 2000). If rate of change of temperature is not equal to zero then surface temperature increases with increment, equal to product of rate of change of temperature and a small-time step. Heating period is terminated when rate of change of temperature is zero or B_M is equal to B_T as shown in figure2. Calculation for steady state starts after heat up period. Droplet surface temperature and diameter of the droplet after heat up phase is used in steady state as initial value of droplet diameter and droplet surface temperature. Figure3 and figure4 shows fuel droplet diameter and surface temperature in heating phase. Total time consumed by a droplet for its complete life is the sum of the time taken in heating phase and steady state evaporation. Figure5 and figure6 shows droplet diameter and surface temperature during its life. Droplet diameter, Reynolds number, Sherwood number and Nusselt number changes at each iteration. Droplet diameter remains same during a time step but changes from one step to another. Total evaporation time required for complete droplet evaporation is used to calculated characteristic length of the combustion chamber.

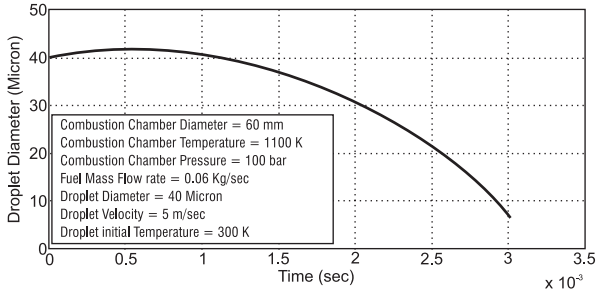

Figure 5: Fuel droplet diameter with time.

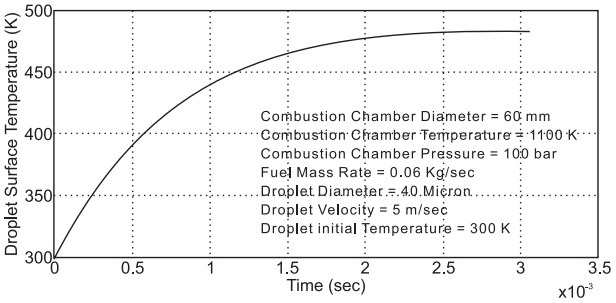

Figure 6: Fuel droplet surface temperature for its complete life time.

RESULTS AND DISCUSSION

The developed model is applied on low temperature combustion chamber with different input conditions. The results are showing effects of input condition on characteristic length of combustion chamber, volume of combustion chamber and time required for complete evaporation.

Figure 7 shows increase in droplet evaporation time with increase in droplet velocity up to a point and then start decreasing. As droplet velocity increases, it reduces relative velocity between droplet and hot gas. Relative velocity is zero at peak point in the figure 7. Reduction in relative velocity reduces convection coefficient, so required time increases.

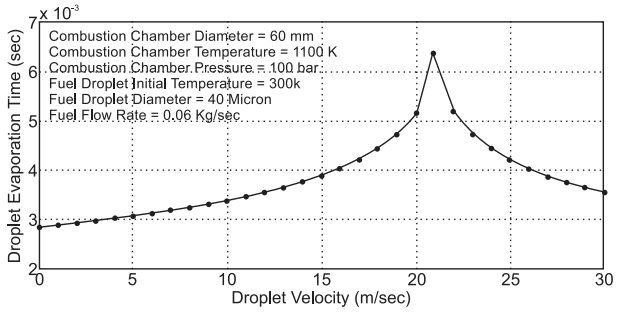

Figure 7: Effects of droplet velocity on required evaporation time.

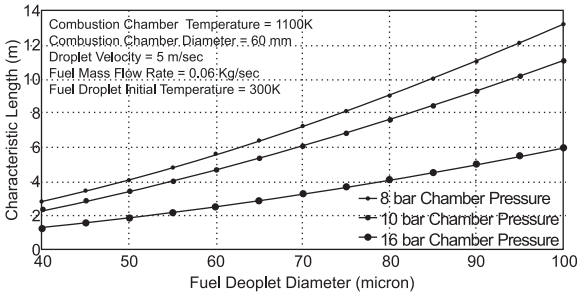

Figure 8: chamber pressure effects on characteristic length.

Figure 8 shows that effect of combustion chamber pressure is more when droplet diameter is greater. Size of characteristic length is increasing with decrease in chamber pressure.

Figure 9 shows that effects of the combustion chamber diameter are more at larger fuel droplet size. When diameter of combustion chamber reduces for a given input condition then less area is available for hot gas to flow due to which velocity of hot gas increases. Increase of velocity causes increase in Reynolds number, turbulent intensity and convection coefficient. Increase in turbulent intensity helps in heat and mass transfer, which consequently increases rate of fuel droplet evaporation.

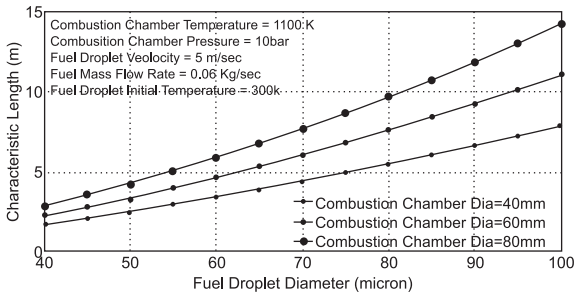

Figure 9: characteristic length with variation in combustion chamber diameter.

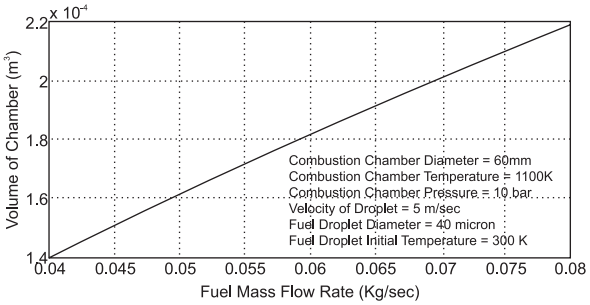

Figure 10: Mass flow rate effects on volume of chamber.

If mass flow rate of a chamber is increased at a fixed throat area then pressure and temperature of combustion chamber both will increase and characteristic length size requirement will change but if throat area is changed to keep pressure and temperature fixed then mass flow rate will affect volume of combustion chamber as shown in Figure 10.

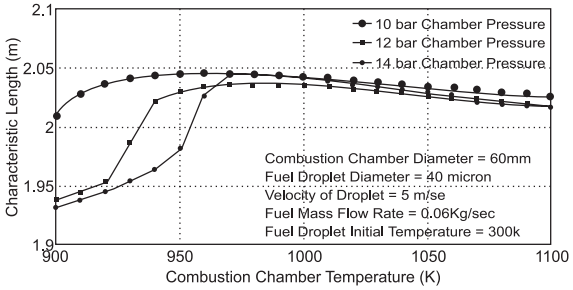

Figure 11: Unusual behavior of characteristic length against chamber pressure and temperature.

Figure 11 shows that initially characteristic length is increasing with increase in combustion chamber temperature but after getting a peak then it goes down with further increase in temperature. This peak in characteristic length shifts towards the right with increase in combustion chamber pressure. The reason of this shift is increase in boiling point of fuel droplet with pressure. When combustion chamber pressure is high then fuel droplet vaporizes at higher temperature. Fuel droplet surface Temperature and reference temperature is also high at higher pressure. Properties of fuel are calculated at reference temperature and reference temperature is low at low combustion chamber temperature and pressure. As long as the reference temperature is below boiling point of fuel droplet at that pressure then characteristic length will increase with increase in temperature. The characteristic length is decreasing with increase in combustion chamber temperature after peak of characteristic length because reference temperature is above boiling point of fuel droplet. This phenomenon is not supposed to happen at higher temperature (more than 1030K for Dodecanese) even with increase in combustion chamber pressure because of the critical point of fuel. Higher the combustion chamber temperature higher will be reference temperature will above the critical temperature of the fuel.

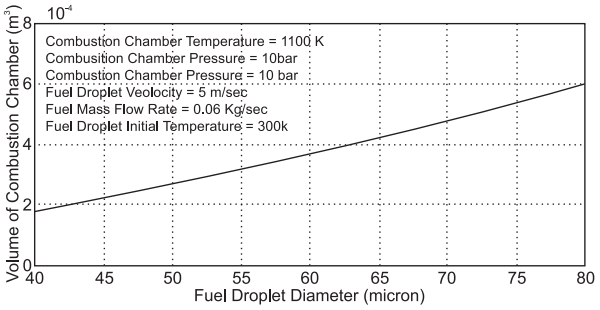

Figure 12: droplet size and volume.

Figure12 shows effects of droplet size on volume of combustion chamber. If volume of combustion chamber is more, weight of the chamber will be more and it will be comparatively difficult to cool it through regenerative cooling. Increase of weight of one Kg in last stage of rocket will reduce one Kg of pay load if that engine is fitted in last stage. If chamber is not properly cool then it is prone to failure.

Figure13 shows that effects of rise of fuel droplet initial temperature are more significant well. If we raise

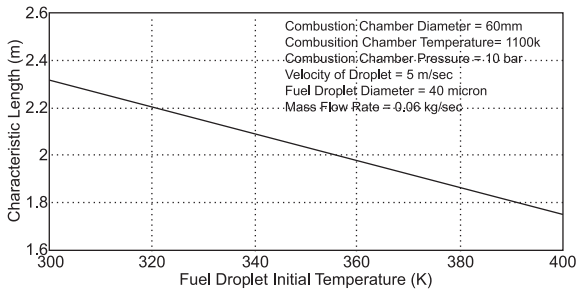

Figure 13: characteristic length with fuel droplet initial temperature.

temperature of combustion chamber then pressure of chamber will increase automatically but if we want the same pressure then volume of combustion chamber will increase with increase in chamber temperature because with increase in temperature density reduces and propellant requires more volume as shown in figure14.

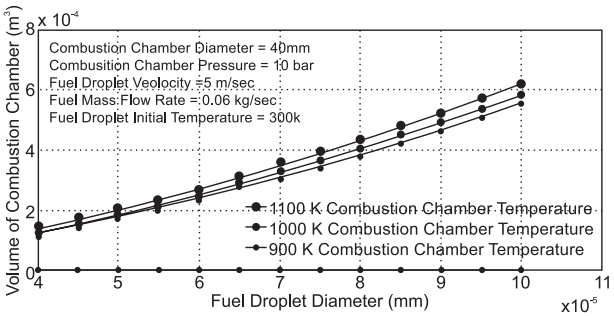

Figure 14: effects of fuel droplet diameter and chamber temperature on volume of combustion chamber.

CONCLUSION

Results of the model show that life of a droplet in combustion chamber of liquid rocket engine is dependent on many factors. Diameter of the droplet is one of the most important factors, which dictates volume and characteristic length of the combustion chamber. The effects of combustion chamber pressure and combustion chamber diameter are higher at higher fuel droplet diameter. Fuel droplet initial temperature has a good effect on characteristic length. Designer should take care of the boiling point of fuel droplet at that pressure while designing combustion chambers for lower temperature. Temperature of the combustion chamber should be high enough to make Reference point temperature higher than the critical temperature of fuel droplet at that pressure because properties of the fuel are taken at reference temperature.

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