

**Fundamentals of Combustion**  
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**Lecture – 48**  
**Laminar Diffusion Flames - Part 8**  
**Diffusion flame stability and Worked examples**

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Instability in Diffusion Flames

In diffusion/non-premixed flames, the primary instability is flame **lift-off or its extinction** as the fuel flow rate (or oxidizer flow rate or both) is increased.

Figure in the right shows **LPG jet flames** from an orifice of 0.4 mm. Flame is attached to the orifice at a fuel velocity of 13.9 m/s and it **lifts-off at 15.4 m/s**. At increased fuel momentum, more air entrains from ambient and mixes with the fuel. However, the **residence time is not sufficient** for the reaction to complete near the orifice exit. Thus, the flame lifts-off. The lifted flame is like a **partially premixed flame** and displays bluish colour at its base.



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Now instability in diffusion flames. The possible instabilities we have in the diffusion flames is only one; that is liftoff and subsequent extinction. Again, I am given the example of the LPG jet flame. You can see that, this LPG jet flame is coming out from a very small orifice what we see in a Bunsen burner, it is about 0.4 mm orifice.

And the flow rate is such that, the velocity of the fuel jet is 13.9 m/s; you see a flame which is intact. The flow rate is very low, because of the diameter of the orifice is very low but you see a good flame where there is no soot production etcetera here.

But when I increase the velocity of the fuel jet to 15.4 m/s, you see the flame lifts off to a particular height  $h$ . So, I will say  $h_1$  that is the lift off height. So, when you increase the flow rate in the same burner, when you increase the flow rate to 13.9 to 15.4; you see the flame lifts off and sustains at a particular height called  $h_1$  which is called the lift off height.

When you increase the fuel momentum in a cold jet what we have seen is; when you increase the fuel momentum, the air entrainment also increases. So, Reynolds number of the jet is increased. So, as a result of it the air entrainment will be increased. So, jet speeding rate will be higher and so on. So, when you increase the fuel momentum, from 13.9 to 15.4, the velocities increase, momentum increases; obviously more air should have entrained.

Rate at which air has entrained also is higher. So, due to the increased rate of fuel momentum as well as the air supply, you will see that the mixing also will be enhanced.

So, proper mixing should have taken place, but why the flame has not formed here; that is because the residence time for the mixture to sustain the combustion there is very low. The flow time has become close to the reaction time or even slightly lesser than that, causing an insufficient residence time for the reactant which are found here. So, it is not burning there.

So, you know that the jet velocity decays. So, after a particular distance, you can see that velocities have decayed to a lower value, jet has spread, enough mass of air has come in. In that case you will see that the velocities are low; the residence time is higher, so that the flame sustains at a particular height.

But if you try to increase it more and more, then what happens; to some extent the  $h_f$  will increase and after that it just puts off. So, the only one instability what we will see is liftoff which initiates due to the low residence time for the reactants to burn very near to the burner rim. Subsequently, increasing the flow rate beyond this, at one particular point you will see the flame to be blown off.

And this lifted flame, it is not a diffusion flame, it is a partially premixed flame as indicated by the colour; when I premix the fuel jet with the partial amount of primary air, you will see that the bluish regime was seen, similar bluish regime is seen here in a LPG flame. So, that indicates that there is a partially premixing which has happened; obviously now there is a mixing due to the air entrainment in this regime and the mixture is partially premixed in this.


You can see this, these reaction zones here which indicate that, the bright blue colour indicating a premixed flame at the base. So, lifted flames cannot be analyzed using the simple chemical reaction systems; we need reaction rates, kinetics are going to be important in this. No kinetics is required in the pure diffusion flame.

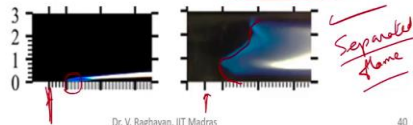

Slightly higher flow rate, so 14 m/s to say around 15 m/s you get this, where you need kinetics to analyze the flame.

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### Instability in Diffusion Flames

Like a lifted premixed flame, lifted diffusion flames are oscillatory and noisy. The flame length decreases as a result of partial premixing. Combustion efficiency may decrease in these cases. If the fuel velocity is increased further, the flame may blow-off. In cross-flow flames, when air velocity is increased, the flame separates from its anchoring point, as indicated by the top view of the flame in the figure. If the air velocity is increased further, the flame blows-off. In opposed flow flames, if the flow rates of fuel and oxidizer streams are increased, the strain rate of the flame increases and it extinguishes at a given strain rate, called extinction strain rate.







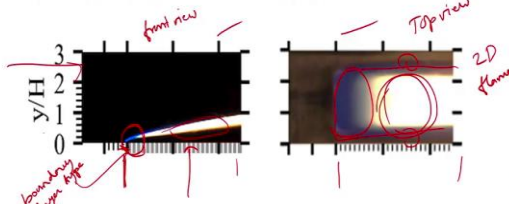

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### Cross-flow Diffusion Flames

Figure shows front and top views of LPG-air cross flow flame. LPG is sent from a horizontal injector vertically upwards and air is fed perpendicular to the LPG stream. A boundary layer type flame is formed. Proper mixing happens at the leading edge of the fuel injector, where the flame is bluish and relatively non-luminous. Flame becomes luminous downstream of the leading edge, contributed by factors such as soot radiation.



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So, as I told you in this stable crossflow flame here, you can see a boundary layer formed, this is the leading edge of the fuel injector; a flame is formed very close to the leading edge of the fuel injector and it goes like this.

And phenomenally you can see this, a 2D flame anchoring, that is appearing over the entire width of the fuel injector; but when you increase the air flow rate, you can see that from the initial point the flame has moved. So, this is the initial point of the injector, flame has moved away and it is not anchoring properly, you can see this. So, it is no

more 2 dimensional; it is called separated flame. It is not 2 dimensional in nature and you can see it has moved away.

So, if we increase the air velocity, still the flame will blow off. So, before coming to that, like a lifted premixed flame we have seen that; lifted diffusion flame are oscillatory, it will oscillate, the base will oscillate, tip will oscillate and so on and it will also be noisy. The flame length decreases as a result of partial premixing; that is what is illustrated here.

Combustion efficiency may decrease, as I told you more CO, unburned hydrocarbons may result from a lifted flame; because there is no control, when the flame is very close to the rim, then the control will be there. As we saw in the premixed flame; when the lifted flame occurs, control is lost. At higher fuel velocity, the flame will blow off.

Now, in the crossflow flames, when the air velocity is increased; the flame separates from the anchoring points, this is the anchoring point. So, it separates, moves away and it is not attached to the width also properly and it is a separated flame which is not anchored properly anywhere. Again, you see that an incomplete combustion may occur and whatever disorders we see in the lifted flames same will be applicable here also.

At a higher air velocity, the flame will blow off. Now, coming to the opposed flow flames. In opposed flow flames when I increase the momentum of the fuel and air jets you can see that the strain rate of the flame will increase. At a particular strain rate, the flame will put off or extinguish that is called extinction strain rate.

This is the only instability, there is no lift off possible there; but the flame becomes stretched and stretched and strain rate is increased, so that at a particular point, the flame will tear up and it will extinguish. So, this is about the instability in the diffusion flames.

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**Worked Example 1**

(1) Using non-reacting jet theory, estimate the length of an ethane-air diffusion flame for an initial velocity of 5 cm/s. The velocity profile issuing from the 10-mm-diameter port is uniform. Both the air and ethane are at 300 K and 1 atm. The viscosity of ethane is approximately  $9.5 \times 10^{-6}$  N-s/m<sup>2</sup>. Compare your estimate using an average viscosity  $(\mu_{air} + \mu_{ethane})/2$ , with the predicted value from Roper's experimental correlations.

**Solution:** Reactant mixture is:  $C_2H_6 + 3.5(O_2 + 3.76 N_2)$ .  
 $(A/F) = 3.5 \times 4.76 \times 28.84 / 30.069 = 15.98 \rightarrow Y_{F,stoich} = 1/(1+15.98) = 0.059$ .  
 From non-reacting jet theory, the flame length is got by setting  $r = 0$  (or  $\xi = 0$ ) in  $Y_F$  profile and using  $Y_{F,stoich}$  value for  $Y_F$ :

$$Y_F = \frac{3 \pi R^2 v_e}{8 \pi D x} \left(1 + \frac{x^2}{4}\right)^{-2} \Rightarrow L_f = \frac{3 \pi R^2 v_e}{8 \pi D Y_{F,stoich}}$$

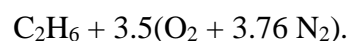
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So, let us see couple of worked examples The first one is using non reacting jet theory; we have already seen the non reacting jet theory. Let us estimate the length of ethane air diffusion flame, initial velocity of 5 cm/s. Please understand that I do not need reactions at all for a diffusion flame, pure diffusion flame I do not need. Just by analyzing the non-reacting jet theory, I can find the flame length.

Initial jet velocity is given as 5 cm/s and the velocity profile issuing from 10 mm port diameter. So,  $2R = 10$  mm, and uniform velocity is coming out, that is given in the problem and the average velocity is 5 cm/s. Now, both the air and ethane are at 300 K and 1 atmospheric pressure. So, reactants are at the same temperature, and viscosity of ethane is given as  $9.5 \times 10^{-6}$  Ns/m<sup>2</sup>.

Then you calculate the flame length with this data and compare the result; anyway, you have to calculate the flame length using a mixture viscosity like this. So, viscosity of the ethane is given; try to take viscosity of air from a table at same temperature 300 K. Then you get the average viscosity calculated as  $\mu_{air} + \mu_{ethane}$  by 2; then you have to compare the result what we get from this theory, non-reactive theory with the Ropers experimental correlation.

The main problem with this is you will get an estimate, same order of flame length can be got; but accurate value cannot be got from the theory, that is what we are trying to illustrate here. So, the reaction mixture is stoichiometry; because wherever the flame zone is formed, we can say that stoichiometric mixture is prevailing there.



$$(A/F) = 3.5 \times 4.76 \times 28.84 / 30.069 = 15.98$$

$$Y_{F,stoich} = 1/(1+15.98) = 0.059.$$

So, the air to fuel ratio is calculated as 15.98.  $Y_F$  stoichiometric, that is calculated. That is the value which will bound the flame area, that is  $\Phi = 1$  contour.

So, that will be 0.059,  $1/(1 + \nu)$ , that is this. Now, from non-reacting jet theory, the flame length is got by setting  $r = 0$ , that is  $\xi = 0$ , in the  $Y$  profile. So, this is the  $Y$  profile what we have got. Now, try to put  $\xi = 0$ , I get the flame length; not only  $\xi = 0$ , please understand I have to also set  $Y = Y_{F,stoich}$ .


$$Y_F = \frac{3}{8\pi} \frac{\pi R^2 v_e}{Dx} \left(1 + \frac{\xi^2}{4}\right)^{-2} \implies L_f = \frac{3}{8\pi} \frac{\pi R^2 v_e}{DY_{F,stoich}}$$

So,  $x$  you take in this side and  $Y_F$  you bring it here, then put this as 0. Then you get this relationship. So,  $Y_F$  is taken here and substituted as  $Y_F$  stoichiometric;  $x$  is taken to the left-hand side and that is put as  $x = L_f$  where the flame length is  $L_f$ . So, this is the equation we need to solve. So, from the theory we got this, now I put  $r = 0$ ,  $x$  I am taking to the left hand side,  $Y_F$  I am bring to the right hand side to the denominator and substituting  $Y_{F,stoich}$  for the  $Y_F$  to get the flame length.

Now,  $R$  is known,  $v_e$  is known,  $Y_{F,s}$  is known,  $D$  is not known. How will you calculate  $D$ ?

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**Worked Example 1**



As per the assumption of  $Sc = 1$ ,  $D = \nu = (\mu/\rho)$ . For air, density is  $\rho/RT = 101325/(8314/28.84 \times 300) = 1.17 \text{ kg/m}^3$ .  $\mu_{ethane} = 9.5 \times 10^{-6} \text{ N-s/m}^2$ .  
 For air,  $\mu_{air} = 18.46 \times 10^{-6} \text{ N-s/m}^2$  (from air tables).  
 This  $\mu_{avg} = 1.4 \times 10^{-5} \text{ N-s/m}^2$ . Thus  $D = 1.4 \times 10^{-5} / 1.17 = 1.195 \times 10^{-5} \text{ m}^2/\text{s}$ .

$$L_f = \frac{3}{8\pi} \frac{\pi (0.01)^2 \times 0.05}{1.195 \times 10^{-5} \times 0.059} = 0.66 \text{ m}$$

By Roper's correlation:

$$L_f = 1330 \frac{Q_F (T_\infty / T_F)}{\ln(1 + 1/S)}$$

Here,  $T_\infty = T_F = 300 \text{ K}$ ,  $S = 4.76 \times 3.5 = 16.66 \text{ kmol/kmol-fuel}$  and  $Q_F = \pi R^2 v_e = 3.927 \times 10^{-7} \text{ m}^3/\text{s}$ .

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Now, again go for the assumption which we already made in the theory. So,  $\nu = D$ . So,  $\mu/\rho = \nu$ , so that we will do. So,  $\nu$ ,  $\mu$  is nothing but the average which is given here. So, for air, first we will calculate the density by  $\rho/RT$ ;  $p$  is atmospheric pressure, 1 atm. It is divided by molecular weight of the air is 28.84. So, the specific gas constant is 8314 by molecular weight into temperature, so the density is  $1.17 \text{ kg/m}^3$ .

$$L_f = \frac{3}{8\pi} \frac{\pi(0.01)^2}{1.195 \times 10^{-5} \times 0.059} = 0.66 \text{ m}$$

$\mu_{\text{methane}}$  is given, but  $\mu_{\text{air}}$  is taken from tables; you can see the Stephen turns tables itself. It gives air properties; So,  $18.46 \times 10^{-6} \text{ Ns/m}^2$ . Now, the average viscosity got by taking average of these two and now  $D = v$ ; that is nothing but  $\mu/\rho$ , this is  $\mu_{\text{avg}}/\rho$ .

$$L_f = 1330 \frac{Q_F(T_\infty/T_F)}{\ln(1 + 1/S)}$$

$$L_f = 1330 \frac{3.927 \times 10^{-7} (300/300)}{\ln(1 + 1/16.66)} = 0.09 \text{ m}$$

So, now this is the value. Now, you substitute and get the flame length as 0.66 m that is all we can get from the theory. However, when you do the Ropers correlation; I do not need everything, I need only S value. S value is calculated as  $x + y/4$  divided by  $x \text{ O}_2$  or we can also calculate by  $4.76 \times 3.5/1$ . So, 16.66 is x value in kmol basis, kmol/kmole-fuel  $T_F, T_\infty$  are 300 K, that is given. So, everything is known.  $Q_F$  you have to calculate,  $Q_F = \pi R^2 v_e$ .

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**Worked Example 1**


Thus, estimation of flame height by Roper's correlation is:

$$L_f = 1330 \frac{3.927 \times 10^{-7} (300/300)}{\ln(1 + 1/16.66)} = 0.09 \text{ m}$$

The estimation by Roper's experimental based correlation is approximately 7 times lesser than that got by non-reactive jet theory. It can be noted that both values are of same order but quite different.

Reasons are:  
 Assumption of  $Sc = 1$  may be not correct for this scenario  
 Variable density may be required.





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So, substituting, you get  $L_f = 0.09$ . So, maybe take it as 0.1 m, from the theory it is 0.7 m, 0.66 m. So, you are getting 7 times lesser from the correlation. So, what is the possible reason? So, this is correct, the ropers correlations should be correct; because this is experimental data, several correlations are visible in flame, several experiments have been done and data is got here.




So, what is the discrepancy? This discrepancy is due to what? Reasons are, this may not be always correct; the  $Sc = 1$ . Main culprit should be the variable density, that may be required. Because when you do a non-reacting jet, the density is taken as a constant.

But with temperature if you try to calculate. So, go back and try to calculate here, instead of taking density at say 300 K and getting the density as 1.17; if you try to take an average temperature and calculate density, that may give a closer value. So, these are the possible reasons. The theory has several assumptions. But one thing what you should understand is the same order of magnitude we are getting. So, this is not 0.1 and that is not say 1 or maybe 2 or something like that.


So, the same order of magnitude you are getting. So, that is the advantage in the theoretical calculations.

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### Worked Example 2


(2) Design a methane fuelled burner for a cooking stove that has a number of circular ports arranged in a circle. The burner must deliver 2.2 kW at full load and operate with 40 percent primary aeration. For stable operation, the loading of an individual port should not exceed 10 W per mm<sup>2</sup> of port area. Also, the full-load flame height should not exceed 20 mm. Determine the number and the diameter of the ports.



**Solution:** If  $N$  is the number of holes and  $d$  is the diameter of each hole, total area of the feed of fuel and primary air is  $A = N\pi d^2/4$ . Power per mm<sup>2</sup> is restricted to 10 W/mm<sup>2</sup>. Thus,  $10 = 2200/A$  (mm<sup>2</sup>). This means,  $Nd^2 = 2200 \times 4/(10\pi) = 280$  mm<sup>2</sup>. Here,  $d$  or  $N$  should be chosen. If  $N$  is chosen as 36 as first trial, then  $d = 2.79$  mm.

Fuel flow rate:  $\dot{m}_F \times \Delta h_C = 2200$ . Or  $\dot{m}_F = 2200/(50016 \times 10^3) = 4.4 \times 10^{-5}$  kg/s.

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Next, the final worked example, here we need to design a methane or natural gas fuelled burner cooking stove that has number of circular ports arranged in a circle. So, for example, you have a circular burner like this and there will be lot of circular ports through which methane comes out, methane comes out and burns.

So, this is the top view what I am showing, some holes through which the methane is coming out. Some restrictions are given here. So, what is the desired condition? The burner must deliver 2.2 kW, the power of the burner is given; then on a full load. So, when I say full load, it is a turned down ratio; full load to lower load or like a lowest load. That ratio is fixed. So, let us first calculate for the full load.

Now, I want 40% primary aeration; because this 40% primary aeration will not allow the mixture to be flammable and in a domestic cook stove, we do not need any flashback.



So, now, first condition is this. We have to satisfy these two; second condition is, for stable operation, the loading of an individual port should not exceed  $10 \text{ W/mm}^2$ . So, the total power is 2.2 kW; when you take all the holes into consideration, the total power generated is 2.2 kW.

Now, divided by total area of cross section, that will be the power per area. So, you take one particular port, the maximum power flux, will be  $10 \text{ W/mm}^2$ . So, this is the constraint what we have. Second constraint is, at the full load also the height of the flame should not be 20 mm. The height of flame means, from individual port the height of the flame should not exceed 20 mm.

So, these are two constraints. So, how will you go designing this? Let us take if  $N$  is the number of holes and  $d$  is the diameter of the each small hole here; then total area will be number of holes times the area of each hole that is the total area which is available.

So, this is  $\text{mm}^2$ . So, power per mm square is now restricted to  $10 \text{ W/mm}^2$ ; that means it should be equal to 2200 which is total power in W, not kW, divided by area in  $\text{mm}^2$ . So, from this we can calculate  $Nd^2 = 280 \text{ mm}^2$ . Now, there are two unknowns here  $N$  and  $d$ . So, we have to guess one and fix another and see whether the constraints are met. That is the procedure of designing.

So, let us fix one of this. It is normally easy to fix the number of holes. So, 36 holes I am keeping; some PCD, Pitch Circle Diameter and keeping 36 holes. So, some minimum spacing will be there between these two holes, any two holes. So,  $N$  is chosen as 36 at the first trial. Let us see whether this is last trial or not; because if I choose  $N$ , I get  $d = 2.79 \text{ mm}$  and with these two constraints,  $10 \text{ W/mm}^2$  which is already been met.

Another constraint is the flame length should not be 20 mm. One constraint is already met; if the second constraint is also met, then that is done. Now, let us calculate the mass flow rate of the fuel. So, that is done by total mass flow rate of the fuel  $m_F \times \Delta h_c$  which is the heat of combustion or the calorific value of the fuel, this should be equal to 2200 W. So, that means  $m_F$  should be equal to this. The power divided by the calorific value of the methane 50 MJ; when substitute it, you get  $4.4 \times 10^{-5} \text{ kg/s}$ , mass flow rate of the fuel.

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### Worked Example 2

$\dot{m}_F = 4.4 \times 10^{-5}$  kg/s.

Mass of primary air,  $\dot{m}_A = 0.4 \times 17.1 \times 0.4 = 3.01 \times 10^{-4}$  kg/s.

Total volumetric flow rate =  $(\dot{m}_F + \dot{m}_A) / \rho_{\text{mix}}$ . Here,  $\rho_{\text{mix}}$  is the density of the reactant mixture:  $\text{CH}_4 + 0.4 \times 2(\text{O}_2 + 3.76 \text{N}_2)$ . Mole fraction of air is  $X_A = (0.4 \times 2 \times 4.76) / (0.4 \times 2 \times 4.76 + 1) = 0.792$  and  $X_F = 1 - X_A = 0.208$ .

$M_{\text{mix}} = 0.792 \times 28.84 + 0.208 \times 16 = 26.17$  kg/kmol.  $\sum X_i M_i$

$\rho_{\text{mix}} = 101325 / [(8314 / 26.17) \times 300] = 1.063$  kg/m<sup>3</sup>.

Volumetric flow rate of reactant =  $3.45 \times 10^{-4} / 1.063 = 3.24 \times 10^{-4}$  m<sup>3</sup>/s.

Volume flow rate per port =  $Q_p = 3.24 \times 10^{-4} / 36 = 9 \times 10^{-6}$  m<sup>3</sup>/s.

To calculate the flame length:

$$S = \frac{1 - X_{\text{pri}}}{X_{\text{pri}} + (1/S_{\text{fuel}})}$$

Here,  $S_{\text{fuel}} = 2 \times 4.76 / 1 = 9.52$  and  $X_{\text{pri}} = 0.4$ . Thus,  $S = 1.19$

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Then mass flow rate of oxidizer, I want 40% primary air. So, I know this 17.1 is the stoichiometric air flow rate. See for 1 kg of methane, I need 17.1 kg of air.

So, for  $4.4 \times 10^{-5}$  kg/s of methane and the primary air is only 40%, so  $4.4 \times 10^{-5} \times 17.1 \times 0.4 \times 28.84$ . So, that will be equal to  $3.01 \times 10^{-4}$  and that is the mass flow rate of the air. So, what will be the total mass flow rate? Mass rate of fuel + mass flow rate of air and volumetric flow rate is what we want; so, this divided by the density of the mixture, which is calculated again using the reactant mixture which is shown here.

So, you know the mass flow rate of say, this  $\text{CH}_4 + 0.4 \times 2$ , this is the mixture what we have. So, mole fraction of air is calculated as  $0.4 \times 2 \times 4.76 / [(0.4 \times 2 \times 4.76) + 1]$ , that is the mole, number of kmol of the methane also is added. So, mole fraction of air is 0.792 and that of the fuel is 0.208; now calculate the molecular weight of the mixture as  $\sum X_i M_i$ . So, that will be the case then it will get the 26.17 kg/kmol.

Now, density is  $p/RT$ ,  $101325 / (8314 / 26.17) \times 300$ . So, this will be the density. Now, once you know density of the mixture; volumetric flow rate of the reactant will be  $3.45 \times 10^{-4}$  that is this plus this,  $3.45 \times 10^{-4}$  is  $(3.01 \times 10^{-4} + 4.4 \times 10^{-5}) / 1.063$  which is  $3.24 \times 10^{-4}$  m<sup>3</sup>/s.


Now, volumetric flow rate per port. So, there are 36 ports and the total volumetric flow rate is this. What is volumetric flow rate? If you divide it equally among the 36 ports, you get  $9 \times 10^{-6}$  m<sup>3</sup>/s, per port. Now, go for the correlation, empirical correlation by Roper as I told you; these empirical correlations are very useful for designing. So, let us take this primary aeration is there.

So, S value has to be calculated by using the formula what we have already projected 1 minus the fraction of primary air this is 0.4 divided by  $X_{\text{pri}}$  plus 1 by S fuel; S fuel is

nothing, but 9.52. When you have no primary air, the methane plus 2 times oxygen plus 3.76 nitrogen. So, in this case, you will get S as  $2 \times 4.76 / 1 = 9.52$  and  $X_{pri}$  is 0.4; then you substitute to get the value of S as 1.19.

$$S = \frac{1 - X_{pri}}{X_{pri} + (1/S_{fuel})}$$

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### Worked Example 2

Flame length in each port is estimated by Roper's correlation:

$$L_f = 1330 \frac{9 \times 10^{-6} (300/300)}{\ln(1 + 1.19)} = 0.0196 \text{ m}$$

$L_f = 19.6 \text{ mm}$ , which is less than the constraint of 20 mm. This ensures that the trial value for N as 36 is fine enough to meet the constraint of port power loading of  $10 \text{ W/mm}^2$  as well as maximum flame length per port to be less than 20 mm.



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Now, substitute this in the correlation, Roper correlation; you know the  $Q_F$  for individual port that is  $9 \times 10^{-6} \text{ m}^3/\text{s}$ .  $T_F$ ,  $T_\infty$  are 300 K. Then  $\ln(1 + 1/S)$ ,  $1/S_{fuel}$ . So, 19.6 mm. You get flame length as 19.6 mm, which is less than the constraint given, 20 mm, that is fine.

$$L_f = 1330 \frac{9 \times 10^{-6} (300/300)}{\ln(1 + 1.19)} = 0.0196 \text{ m}$$

So, that means the guess what we have done,  $N = 36$  is fine enough and we meet both the constraints; one is the power loading flux, which is  $10 \text{ W/mm}^2$  that is met, because  $d$  is calculated with that equation. And by calculating the volumetric flow rate and the flame length, we find the flame length to be less than 20 mm.. So, this finishes the topic.