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Updated jet flame radiation modeling with buoyancy corrections

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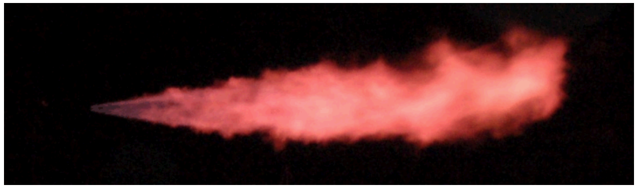
In 2008, Air Products commissioned radiative heat flux measurements from 2 large-scale H_2 jet flames.

Flame	d_j [mm]	$\dot{m}$ [kg/s]	L_f [m]	p_0 [barg]	T_0 [K]	RH [%]	T_{amb} [K]	p_{amb} [mbar]	U_{wind} [m/s]	Wind dir [°]
1	20.9	1.0	**17.4**	59.8	308.7	94.3	280	1022	2.84	68.5
2	52.5	7.4	**48.5**	62.1	287.8	94.5	280	1011	0.83	34.0

Flame 1



Horizontal jet flame tests were performed by GL Noble Denton (then Advantica) at the Spadeadam test site in North Cumbria, UK

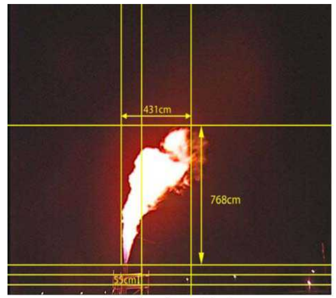
Flame 2

Analytic models did a poor job of predicting radiative heat fluxes from these flames... Why?

Simplified methods exist to model radiative heat flux boundaries from jet flames & flares

All methods require models of the following parameters:

1) Flame envelope ►

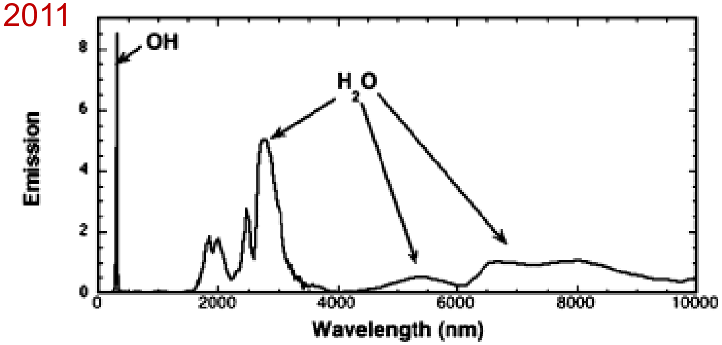


400 g/s release 2" pipe

40 g/s release 2" pipe

Willoughby et al., ICHS4, 2011

2) Energy fraction converted to radiation ►



Schefer et al., IJHE, 2009

◄ 3) Radiant energy transferred to observer

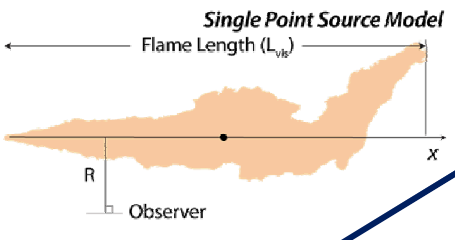
Models are often interdependent and only applicable for the given method

It is convenient to define jet flame/flare radiative heat flux models into 3 categories:

Single Point Source (SPS) models

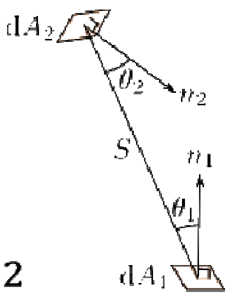
Flame shape:
- Non-dimensional radiant power to estimate radiant load distribution

Radiant fraction models:
- Empirical function: **temperature, composition, release rate, soot, residence time, heat release**



Single Surface models

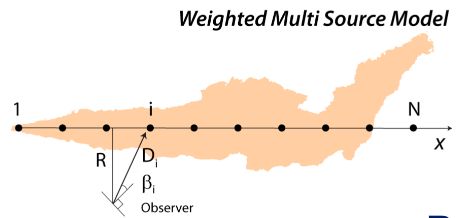
Flame shape:
- Assumed flame shape (e.g., cone) w/ empirically tuned radiating surface
- Geometric View Factors to calculate radiation transfer
- Empirical wind/buoyancy corrections



$$VF_{1\rightarrow 2} = \frac{\cos\theta_1 \cos\theta_2}{\pi S^2}$$

Radiant fraction models:
- Empirical function of exit velocity

Multi Source Models (MSM)



Flame shape:
- Weighted source emitters on flame centerline

Radiant fraction models:
- Same as SPS models

Note that all models incorporate empirical flame length and atmospheric transmissivity corrections

It is convenient to define jet flame/flare radiative heat flux models into 3 categories:

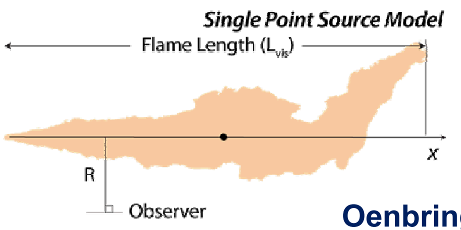
Single Point Source (SPS) models

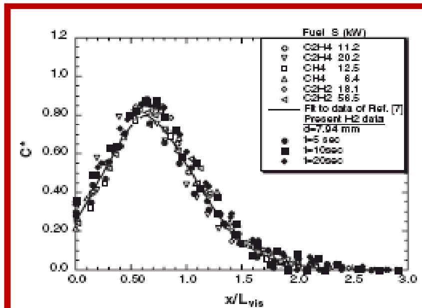
Advantages:
- Simplicity
- Good far-field accuracy (D > Lvis)
- Large number of fuel types & flame sizes

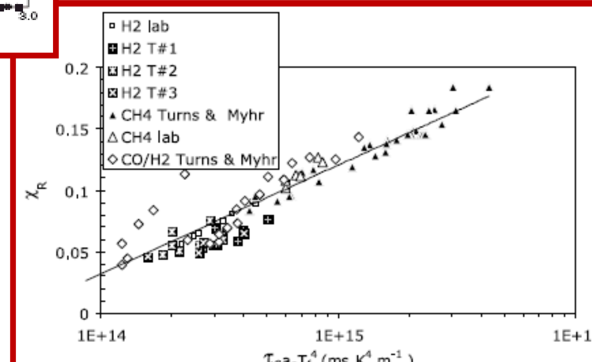
Drawbacks:
- Poor near-field performance (D < Lvis)
- No wind/buoyancy corrections
- Neglects flame headed towards observer
- Not suitable for transient jets or "fireballs"

$$q = \frac{\chi Q}{4\pi D^2}$$

χ: Radiant fraction
Q: Heat release
D: Distance to observer
q: Heat flux [W/m^2]







API Section 521, 1969

Oenbring & Sifferman, API Proc., 1980
Corrections for emission angle

Sivathanu & Gore, Combust. Flame, 1993
Corrections for axial dependence

1970 | 1980 | 1990 | 2000 | 2010

Brzustowski & Sommer, API Proc., 1973
Corrections for observer angle

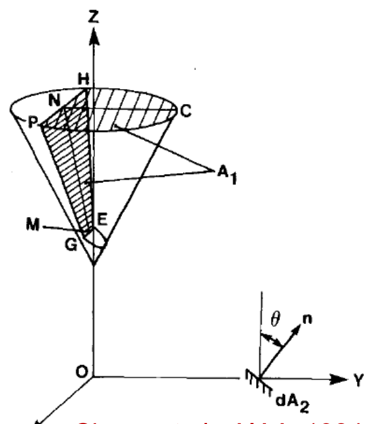
Turns & Myhr, Combust. Flame, 1991
Corrections for flame residence time

Molina et al., Proc. Combust. Inst., 2007
Corrections for product species emissivity

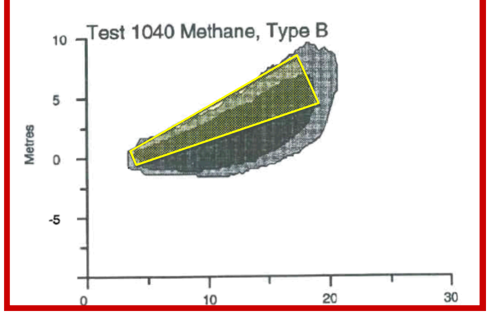
It is convenient to define jet flame/flare radiative heat flux models into 3 categories:

$$E = \frac{\chi \dot{m} \Delta H}{A}$$

E: Emissive Power
A: Surface Area
ΔH: Heat of combustion
m: mass



Chung et al., AIAA, 1984



Single Surface models

Advantages:
- Good far-field accuracy & reasonable performance in near-field
- Simple to use w/ validated view factors
- Amenable to wind/buoyancy corrections

Drawbacks:
- Models depend on assumed shape (i.e., not always representative of flame envelope)
- Extensive calibrations required
- Gas type specific

API Section 521, 1969

Leahey et al.,
Alberta Environment, 1979
Emissivity corrections
(cone frustum)

Cook et al.,
Chem. Eng. Res. Des., 1987
Radiant fraction correlation w/ velocity

Chamberlain,
Chem. Eng. Res. Des., 1987
Empirical vertical flame surface model
w/ wind/buoyancy corrections

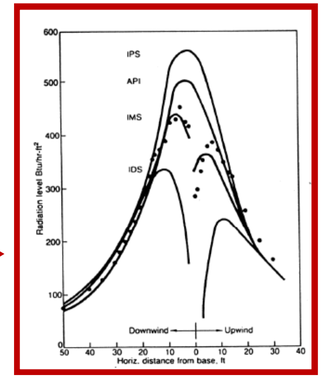
Johnson et al.,
Process Safety Environ. Prot., 1994
Empirical horizontal flame surface model
w/ wind/buoyancy corrections

1970 | 1980 | 1990 | 2000 | 2010

It is convenient to define jet flame/flare radiative heat flux models into 3 categories:

$$q = \int_0^L \frac{w\chi\dot{m}\Delta H}{4\pi D} cos\beta$$

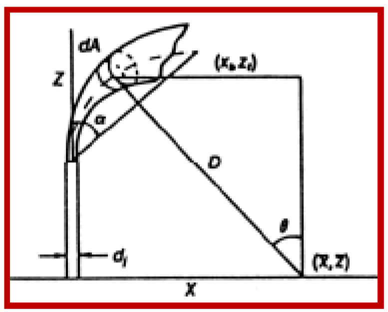
McMurray, Hydrocarbon Processing, 1982
Integrated mixed source model
(combined surface & point sources)



API Section 521, 1969

Hankinson & Lowesmith
Combust. Flame, 2012
Weighted multi-source

1970 | 1980 | 1990 | 2000 | 2010

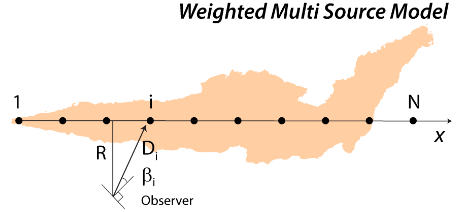


De-Faveri et al., Hydrocarbon Processing, 1985
Multi surface model w/ crosswind corrections

Ekoto et al.,
Proc. IPC, 2012
Ground reflection correction

Multi Source Models (MSM)

Weighted Multi Source Model



Advantages:
- Good near/far-field accuracy
- **Can account for flame trajectory**
- Surface reflection corrections
- Can be used for transient flames
- Better flame emissivity corrections

Drawbacks:
- Increased complexity

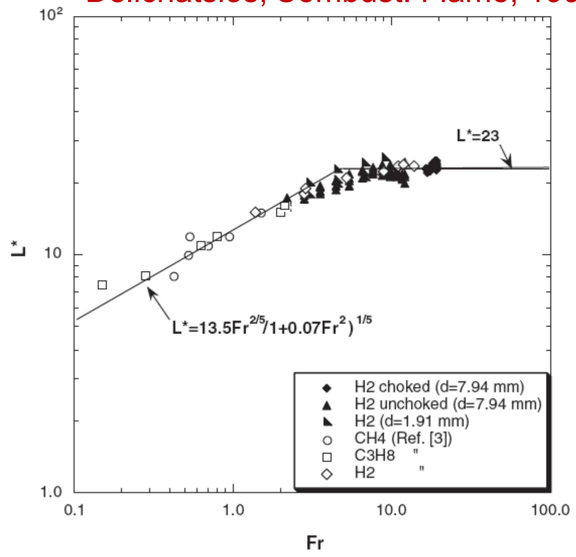
Validated empirical correlations are useful for establishing flame envelopes

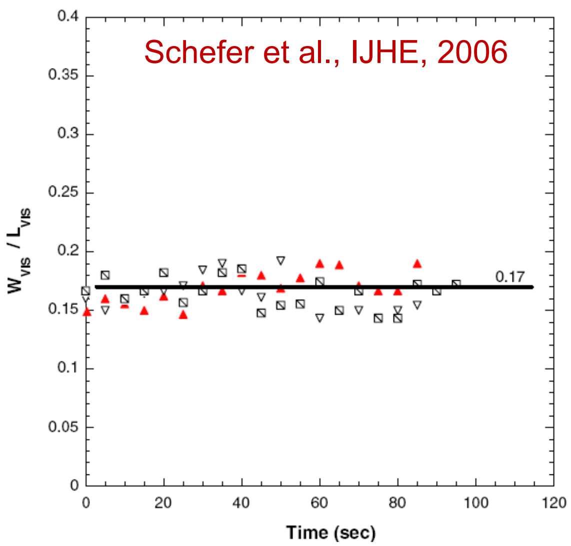
$$L^* = \frac{13.5 Fr_f^{0.4}}{\left(1 + 0.07 Fr_f^2\right)^{0.2}} \quad for\ Fr_f < 5$$

$$L^* = 23 \qquad for\ Fr_f \geq 5$$

where: $$Fr_f = \frac{u_{eff} y_s^{1.5}}{\left(\frac{\rho_{eff}}{\rho_{amb}}\right)^{0.25} \left(\frac{T_{ad-Tamb}}{T_{amb}} \cdot g \cdot d_{eff}\right)^{0.5}}$$

Delichatsios, Combust. Flame, 1993





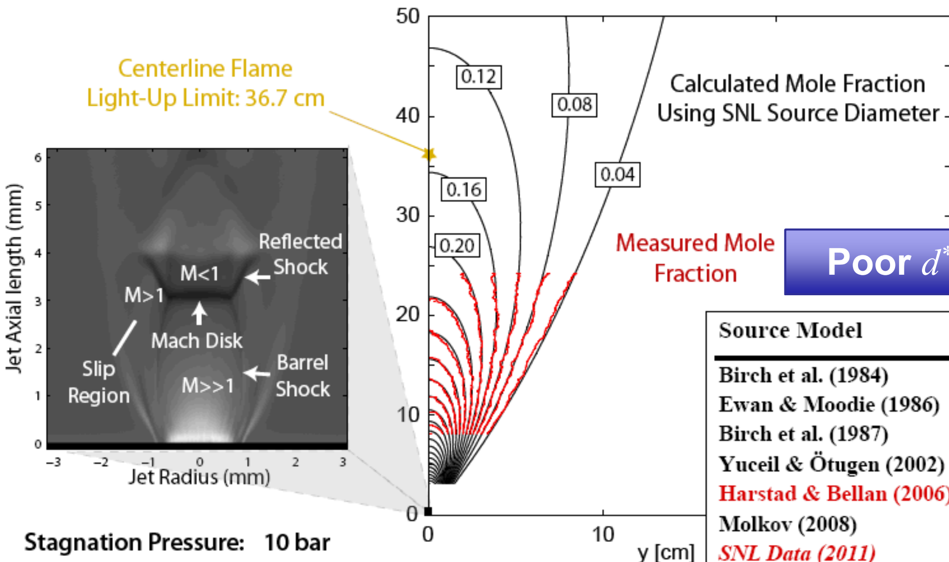
Flame width exhibits a strong dependence on length

$$L_f = \frac{L^*}{y_s} d^* \;\&\; W_f = 0.17 L_f$$

where: $$d^* = d_{eff} \sqrt{\frac{\rho_{eff}}{\rho_{amb}}}$$

Note that notional nozzle models needed to compute choked flow effective jet-exit conditions

Excellent agreement between computed & measured mole fraction statistics with measured d^*

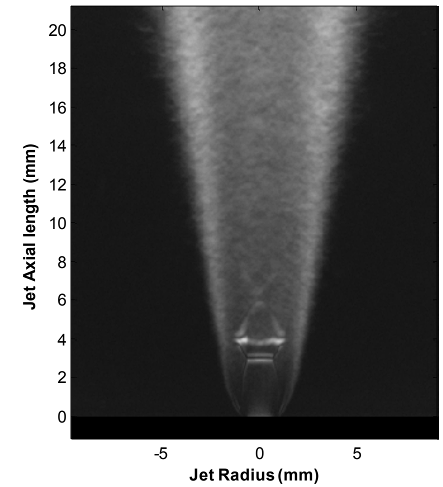


Stagnation Pressure: 10 bar
Nozzle Diameter: 1.5 mm

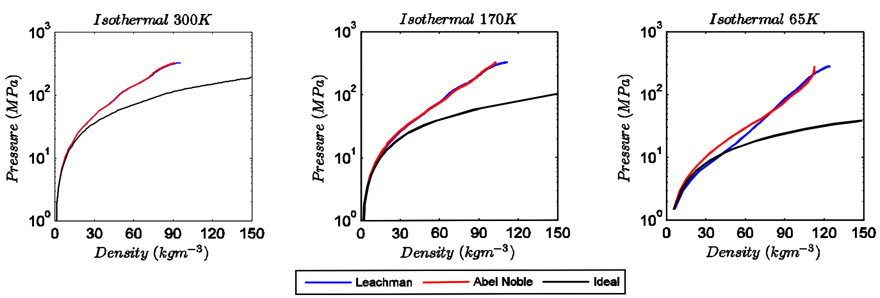
Poor d^* prediction

Source Model	d^* [mm]
Birch et al. (1984)	0.947
Ewan & Moodie (1986)	0.993
Birch et al. (1987)	0.790
Yuceil & Ötugen (2002)	0.790
Harstad & Bellan (2006)	1.440
Molkov (2008)	0.993
SNL Data (2011)	***0.867***

***All models updated w/ Able-Noble EOS**



Most fluid appears to be in the slip region

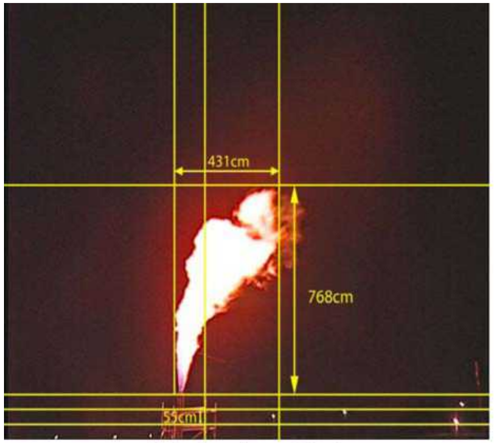


Abel-Noble EOS

$$p = Z\rho R H_2 T;\ Z = (1 - b\rho)^{-1}$$

- Works well at ambient T
- Cryogenic states poorly predicted (present in barrel shock; T < 70 K)

What about flame trajectory changes due to wind/buoyancy?



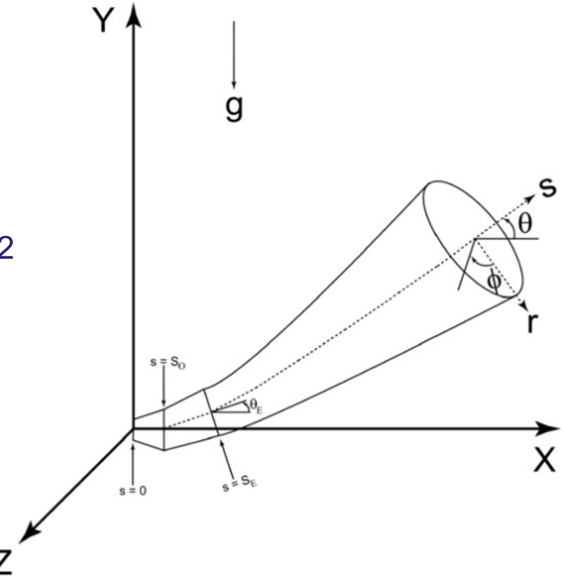
400 g/s release 2" pipe

40 g/s release 2" pipe

Willoughby et al., ICHS4, 2011

1-D integral models based on jet self-similarity have been used to model Established Flow Zone

Reichardt, *VDI-Forschungsheft*, 1942



Mass $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V r dr d\phi = \rho_{amb} E$$

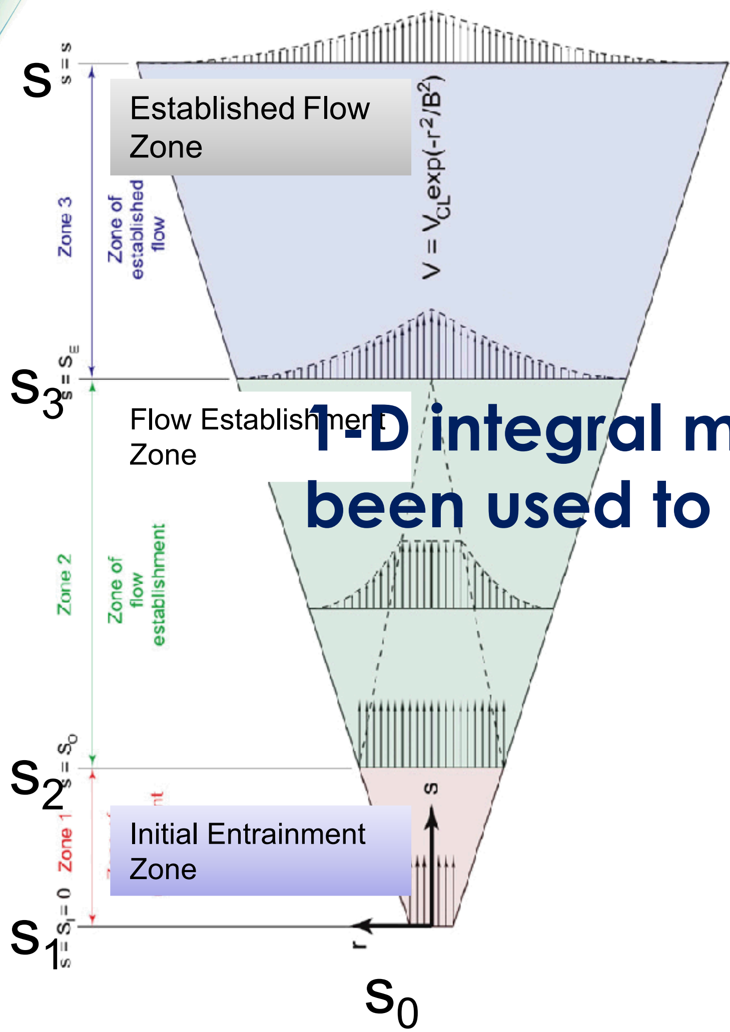
x-Mom $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V^2 \cos\theta \, r dr d\phi = 0$$

y-Mom $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V^2 \sin\theta \, r dr d\phi = \int_0^{2\pi}\int_0^{\infty}(\rho_{amb} - \rho) g r dr d\phi$$

Species $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V Y r dr d\phi = 0$$

Energy $$\frac{\partial}{\partial S}\int_0^{2\pi}\int_0^{\infty}\rho V (h - h_{amb}) r dr d\phi = 0$$

1-D integral models based on jet self-similarity hav been used to model Established Flow Zone



Velocity & Concentration profiles are Gaussian

B: Velocity jet width

λ: Concentration-to-Velocity jet width ratio

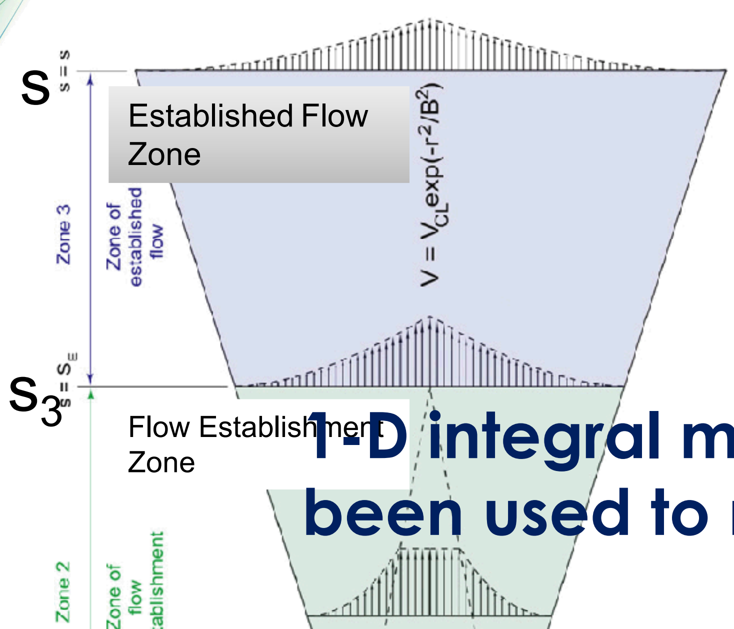
$$\frac{V}{V_{CL}} = \exp\left(-\frac{r^2}{B^2}\right)$$

$$\frac{\rho - \rho_{amb}}{\rho_{CL} - \rho_{amb}} = \exp\left(- \ldots\right.$$

$$\frac{\rho Y}{\rho_{CL} Y_{CL}} = \exp\left(-\frac{r^2}{\lambda^2 B^2}\right)$$

Unknowns

Mass $\frac{d}{dS}\left\{V_{CL}B^2\left[\rho_{amb} - \frac{\lambda^2}{\lambda^2+1}(\rho_{amb} - \rho_{CL})\right]\right\} = \frac{\rho_{air}E}{\pi}$



1-D integral models based on jet self-similarity been used to model Established Flow Zone

Integral flame model w/ buoyancy corrections used to adjust source emitter placement.

Negligible change for side heat flux prediction
downstream predictions improved dramatical

Summary

1. Three simplified methods exist to model jet flame radiat