FLARE MODELLING

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Atmospheric Study Group

- Upset flaring
- Combustion products include SO_2
- The black smoke is unburned petroleum products including H_2S

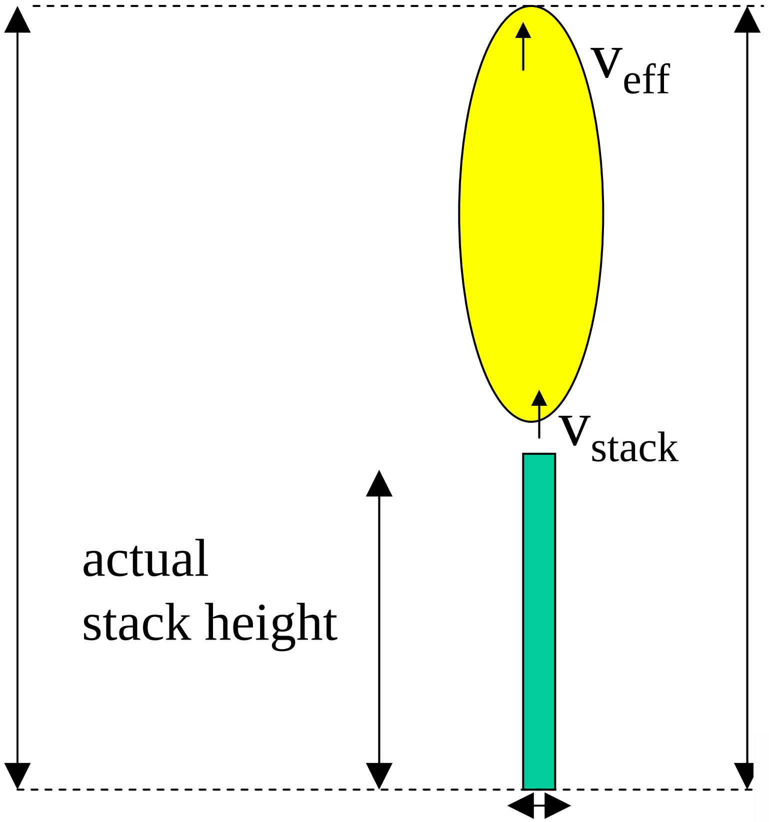
Flare Modeling

- Ignited source
  - ⇒ Hot => buoyant plume rise
  - ⇒ Ambient temperature stratification and vertical wind shear important along whole plume rise, not just at stack tip to determine entrainment and final plume rise
  - ⇒ Radiative losses
  - ⇒ Combustion efficiency, depending on flare type, flow rate and meteorology => % of H_2S

- Jet Flame
  - ⇒ High momentum before ignition => flame length
  - ⇒ effective stack height > actual stack height
  - ⇒ wind => flame tilt

Flare

- Point source with:
  - H_{eff}: Effective stack height
  - V_{eff}: Effective exit velociy
  - D_{eff}: Effective diameter
  - T_{eff}



effective stack diameter

V_{eff}

V_{stack}

Effective
stack height

actual
stack height

actual stack diamete

Flare modeling

- Effective properties (T,v,D, H)
- Effective stack height: (flare height + portion of flame length)
- Combustion efficiency (Affects net heat release and SO_2 and H_2S emission rates)
- Flare Temperature (radiation)

Dispersion modeling

- Typically: point source with Briggs buoyant plume rise
- But for a flare:
  - Non-Boussinesq
  - Radiative losses during plume rise
  - Shear effects non negligible
  - Temperature stratification affects plume rise
  - Momentum rise

Flare Modeling

Flare model – Effective properties

Effective stack parameters such that the buoyancy flux calculated by the model will be equivalent to the actual buoyancy flux of the flare's combustion gases

- Model buoyancy flux: traditionally Briggs plume rise,

  $$F_{b1} = (g\, V_{eff}\, D^2_{eff} /4)\, [T_{eff}-T_{amb})/T_{eff}\,] \qquad (1)$$

- Actual buoyancy flux : based on net heat released q_n during combustion (i.e. based on fuel composition, combustion efficiency, radiative losses)

  $$F_{b2} = Fb(q_n) \qquad (2)$$

- $F_{b1} = F_{b2}$; Set $T_{eff}\, V_{eff}$ and retrieve Deff

Flare model – Effective properties

TCEQ (Texas)-SCREEN3 Method 1

1. Set $V_{eff,}$, T_{eff}, and T_{amb}:
   - V_{eff}= 20 m/s (set to be high enough to avoid stack-tip downwash in Texas (v>=1.5 u)
   - T_{eff} = 1273 K (1000 C)
   - T_{amb} = 308 K (typical values in Texas: 0-40C; T=35C is fairly conservative)
2. Compute q_n according to Tan (1969)

   $Fb = (3.7\ 10^{-3}\ q_n\ ]$

   where $q_n=q(1-0.048\ (MW)^{1/2})$ (Tan formula,1969)

   q: gross heat release (in cal/s)

   MW: volume-weighted average molecular weight of the mixture being burnt

3. Retrieve D_{eff} : $D_{eff} = 10^{-3}\ q_n^{1/2}$
4. Set: $H_{eff} = H_{stk}$ (H_{stk} : height of the flare tip (no flame adjustment))

Flare model – Effective properties

TCEQ (Texas)-SCREEN3 Method 2 –EPD (Saudi Arabia)

1. Set $V_{eff,}$, T_{eff} , and T_{amb}:
   - V_{eff}= 20 m/s
   - T_{eff} = 1273 K (1000 C)
   - T_{amb} = 293 K (20C)
2. Compute q_n allowing for 55% radiative losses

   $Fb = (3.7\ 10^{-3}\ q_n\ ]$

   where q_n=0.45 q (Leahey, 1984))

   q: gross heat release (in cal/s)

3. Retrieve D_{eff} : $D_{eff} = 9.88\ ^{-4}\ q_n^{\ 1/2}$
4. Set: $H_{eff} = H_{\ stk} + [4.56\ 10^{-3}\ q^{0.478}\ ]$ (API, Beychok, 1969, assuming 45° flame tilt)

Note: TCEQ claims that the 2 methods lead to similar results. Method 2 uses a smaller net heat release (lower plume rise) (more conservative) but a higher effective hei lower Tamb(less conservative)

Flare model – Effective properties

EUB-ERCB (Alberta, Canada)

1. Set T_{eff}, and T_{amb}:
   - T_{eff} = stochiometric temperature (~2700K!),
   - T_{amb} = 288 K (15C)

2. Compute q_n (includes radiative losses and combustion efficiency) (function of composition, wind speed, and exit velocity before ignition)

   Wind speed: climatological values (min,max,average) for Alberta

3. Retrieve D_{eff} <u>and</u> Veff based on conservation of buoyancy <u>and</u> momentum

4. Set: $H_{eff} = H_{stk} + H_{flame}$ (Brzustowski) + stack tip downwash

ERCB-EUB Pseudo Stack Parameters

- Pseudo-stack gas exit velocity (v_{eff}):

  $V_{eff} = g\ (F_m/F_b)\ \ (T_{eff}-T_{amb})/T_{amb}$

  - **Fm**: exit momentum flux (before ignition)
  - **Fb**: buoyancy flux (based on net heat release)
  - **Tamb** : ambient air temperature (***kept constant at 288K in EUB***)
  - $\mathbf{T_{eff}}$: **pseudo-stack** exit temperature (T stochiometric >> Tflame)

- Pseudo-stack gas exit diameter (D_{eff}) such that:

  $Fm= (T_{amb}/T_{eff})(D_{eff}/2)^2\ V^2_{eff}$

  - Momentum and buoyancy conserved

EUB Pseudo-Stack Parameters

- Pseudo-stack exit temperature (T_{eff}):
  - T_{eff} is the stochiometric temperature (~2700K), not the flame tip temperature (~1000^{o}C) such that $T_{eff} >>> T_{ambient}$ and hourly variations of $T_{ambient}$ can be ignored by EUB spreadsheet (thus producing constant emission characteristics)Briggs plume rise,

$$F_{Briggs} = (g\ V_{eff}\ D^{2}_{eff} /4)\ [T_{eff}-T_{amb})/T_{eff}\ ]$$

- Pseudo-stack height (H_{eff}):
  - Actual stack height + portion of flame length
  - Takes stack-tip downwash into account

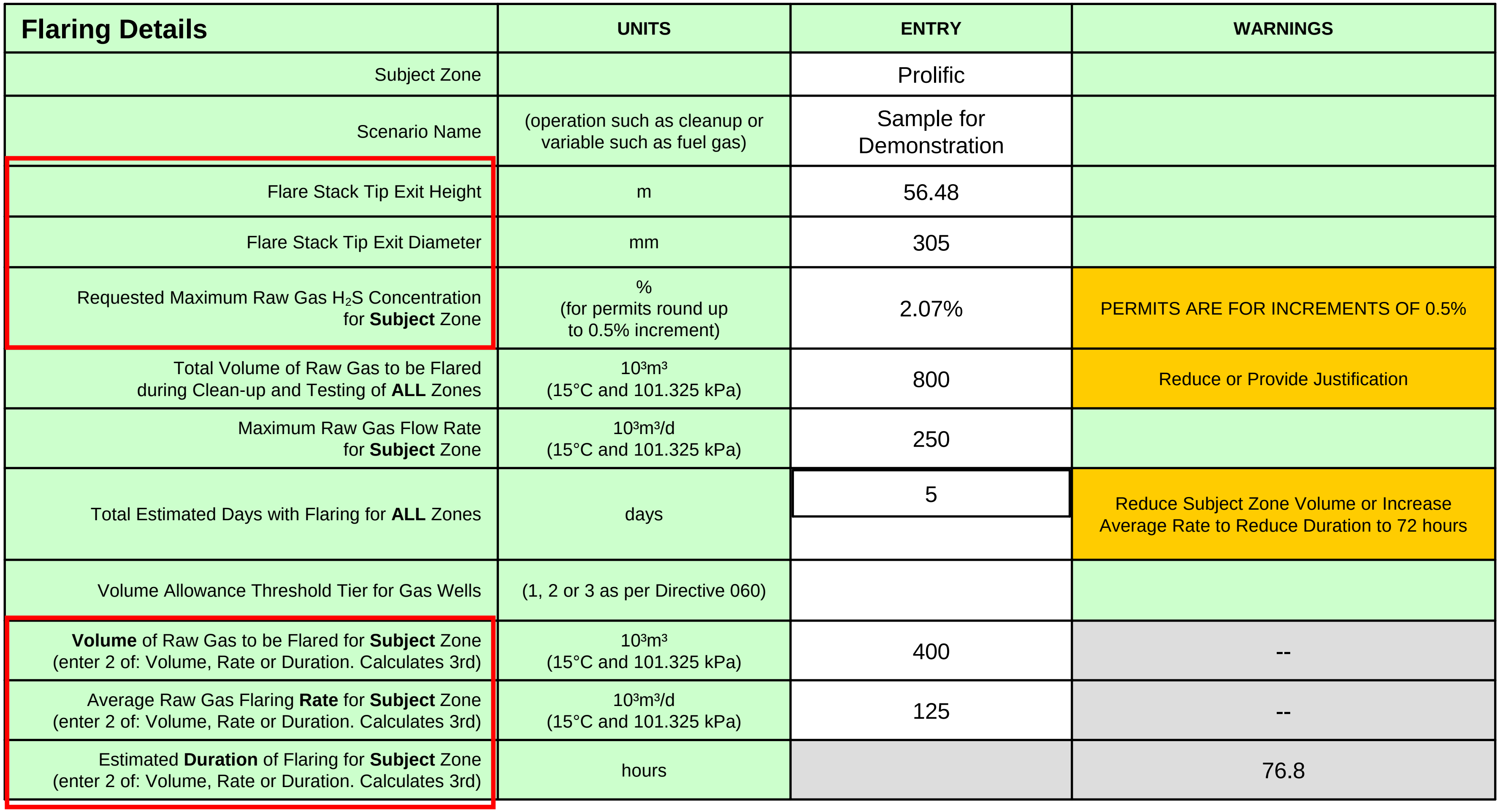
    (=> turn “stack-tip downwash) option off in dispersion model)

Issue with EUB Parameters

- EUB $T_{effective}$ (~ 2700K) >> $T_{exhaust}$ (~1200K):
  - Not an issue with Briggs plume rise as long as effective diameter and effective exit velocity are computed to conserve buoyancy (Fb) and momentum (Fm) fluxes (which they are)
  - **But** it is an issue in numerical plume rise algorithm because radiative losses during rise depend on T^4_{source} and would be overestimated if $T_{combustion}$ rather than T_{flame} were used.

=> CALPUFF flare module turns off the radiative losses during plume rise, as they should not be significant

1. Enter Physical Stack Parameters



Flaring Details	**UNITS**	**ENTRY**	**WARNINGS**
Subject Zone		Prolific	
Scenario Name	(operation such as cleanup or variable such as fuel gas)	Sample for Demonstration	
Flare Stack Tip Exit Height	m	56.48	
Flare Stack Tip Exit Diameter	mm	305	
Requested Maximum Raw Gas H_2S Concentration for **Subject** Zone	% (for permits round up to 0.5% increment)	2.07%	PERMITS ARE FOR INCREMENTS OF 0.5%
Total Volume of Raw Gas to be Flared during Clean-up and Testing of **ALL** Zones	10^3m^3 (15°C and 101.325 kPa)	800	Reduce or Provide Justification
Maximum Raw Gas Flow Rate for **Subject** Zone	$10^3m^3/d$ (15°C and 101.325 kPa)	250	
Total Estimated Days with Flaring for **ALL** Zones	days	5	Reduce Subject Zone Volume or Increase Average Rate to Reduce Duration to 72 hours
Volume Allowance Threshold Tier for Gas Wells	(1, 2 or 3 as per Directive 060)		
Volume of Raw Gas to be Flared for **Subject** Zone (enter 2 of: Volume, Rate or Duration. Calculates 3rd)	10^3m^3 (15°C and 101.325 kPa)	400	--
Average Raw Gas Flaring **Rate** for **Subject** Zone (enter 2 of: Volume, Rate or Duration. Calculates 3rd)	$10^3m^3/d$ (15°C and 101.325 kPa)	125	--
Estimated **Duration** of Flaring for **Subject** Zone (enter 2 of: Volume, Rate or Duration. Calculates 3rd)	hours		76.8

EUB spreadsheet – Flaring Input Worksheet

2. Enter Gas Composition

Gas Compositions (mol fraction)	**Raw Gas**	**Fuel Gas**
H_2O	0.0000	0.0000
H_2		
He		
N_2	0.0724	0.0724
CO_2	0.0847	0.0847
H_2S	0.0207	0.0207
CH_4	0.8037	0.8037
C_2H_6	0.0140	0.0140
C_3H_8	0.0022	0.0022
i-C_4H_{10}	0.0004	0.0004
n-C_4H_{10}	0.0007	0.0007
i-C_5H_{12}	0.0003	0.0003
n-C_5H_{12}	0.0002	0.0002
n-C_6H_{14}	0.0003	0.0003
C_7^+	0.0004	0.0004
Total	1.00000	1.00000
Location Reference Gas Analysis from	do not use sample raw gas of pure methane	

EUB spreadsheet – Flaring Input Worksheet

3. Check Assumptions

Assumptions, Guidelines and Criteria	UNITS	DEFAULTS
Minimum Conversion and Combustion Efficiency	%	98%
Flame Radiation Loss (**RAD** fraction)	%	25%
Release Temperature before Combustion	°C	15
Ambient Air Temperature	°C	15
Minimum Recommended Net Heating Value	MJ/m^3	20.0
Minimum Allowed Net Heating Value	MJ/m^3	12.0
Background Thermal Radiation	kW/m^2	1.04
Maximum Recommended Total Thermal Radiation	kW/m^2	4.73
Minimum Alberta wind speed at 10 m reference height	m/s	1.00
Average Alberta wind speed at 10 m reference height	m/s	3.42
99th percentile Alberta wind speed at 10 m reference height	m/s	10.28
Stability Class F Plume Rise Criterion Wind Speed	m/s	1.0
Stability Class F Vertical Potential Temperature Gradient	K/m	0.035
Maximum Slope Criterion	%	5%
UofA Flare Research Project constant A	(MJ/kg)^3	133.3
UofA Flare Research Project constant B		

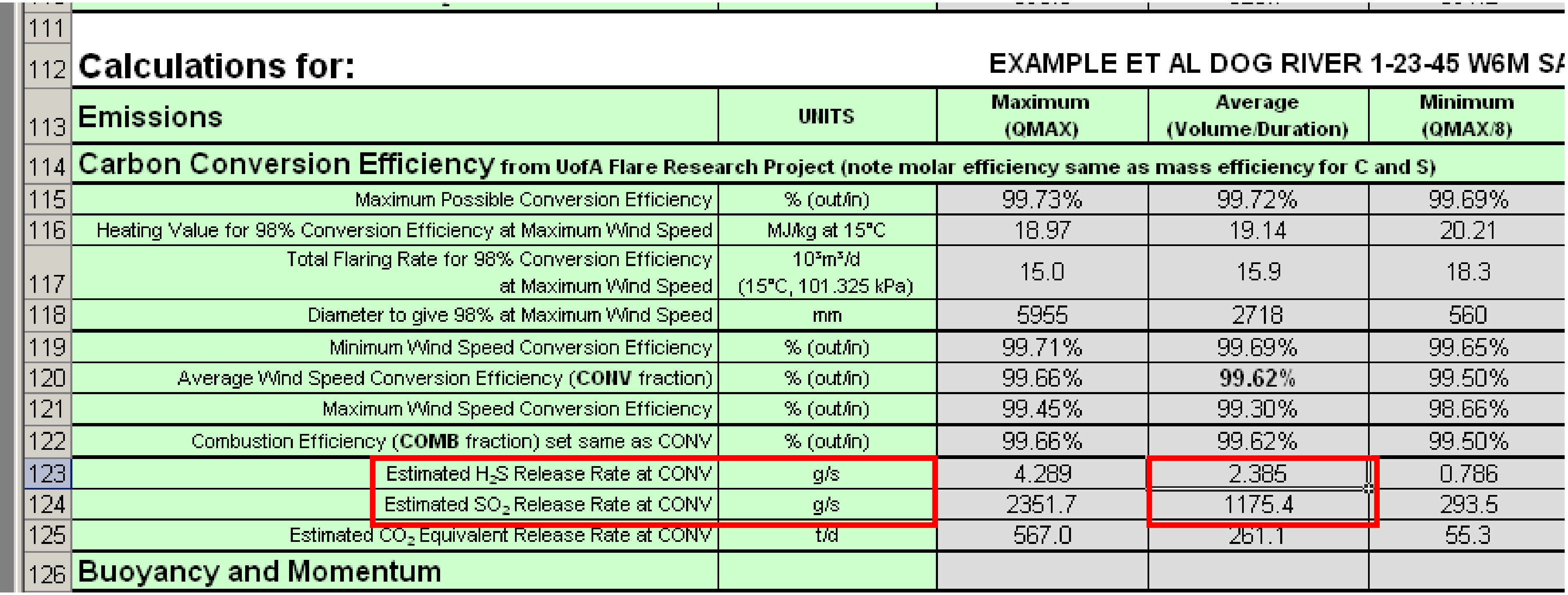
EUB spreadsheet – Calculations Worksheet

5. Read Pseudo-Stack Parameters

Pseudo-Stack Parameters USED **(with Fuel Gas)** ***Conserve Fb and Fm***	**UNITS**	**Maximum (QMAX)**	**Average (Volume/Duration)**	**Minimum (QMAX/8)**
Effective Pseudo-Stack Height (h_S) Adjusted for Flare tip downwash	m	63.954	61.323	58.206
Pseudo-Stack Inside Diameter (D_E)	m	8.202	8.198	8.187
Pseudo-Stack Gas Exit Velocity (V_E)	m/s	4.254	2.128	0.533
Pseudo-Stack Gas Exit Temperature (T_E)	K	2733.73	2733.73	2733.73
Assumed Ambient Air Temperature (T_A)	K	288.15	288.15	288.15

EUB spreadsheet – Calculations Worksheet

6. Read SO_2 and/or H_2S emission rates



111					
112	**Calculations for:**		**EXAMPLE ET AL DOG RIVER 1-23-45 W6M SA**		
113	**Emissions**	**UNITS**	**Maximum (QMAX)**	**Average (Volume/Duration)**	**Minimum (QMAX/8)**
114	**Carbon Conversion Efficiency from UofA Flare Research Project (note molar efficiency same as mass efficiency for C and S)**				
115	Maximum Possible Conversion Efficiency	% (out/in)	99.73%	99.72%	99.69%
116	Heating Value for 98% Conversion Efficiency at Maximum Wind Speed	MJ/kg at 15°C	18.97	19.14	20.21
117	Total Flaring Rate for 98% Conversion Efficiency at Maximum Wind Speed	$10^3 m^3/d$ (15°C, 101.325 kPa)	15.0	15.9	18.3
118	Diameter to give 98% at Maximum Wind Speed	mm	5955	2718	560
119	Minimum Wind Speed Conversion Efficiency	% (out/in)	99.71%	99.69%	99.65%
120	Average Wind Speed Conversion Efficiency (**CONV** fraction)	% (out/in)	99.66%	**99.62%**	99.50%
121	Maximum Wind Speed Conversion Efficiency	% (out/in)	99.45%	99.30%	98.66%
122	Combustion Efficiency (**COMB** fraction) set same as CONV	% (out/in)	99.66%	99.62%	99.50%
123	Estimated H_2S Release Rate at CONV	g/s	4.289	2.385	0.786
124	Estimated SO_2 Release Rate at CONV	g/s	2351.7	1175.4	293.5
125	Estimated CO_2 Equivalent Release Rate at CONV	t/d	567.0	261.1	55.3
126	**Buoyancy and Momentum**				

EUB spreadsheet – Calculations Worksheet

Dispersion Modeling

Briggs Plume Rise

- Boussinesq approximation

  ⇒ not ok when plume density is << ambient air density

- Linear ambient air stratification (dθ/dz=constant)

  => not ok for highly buoyant plumes from short stacks

- Vertical wind shear above stack top is not taken into account

  => not ok for highly buoyant plumes from short stacks

Numerical Plume Rise

- Compute plume rise using a numerical solution to the non-Boussinesq conservation laws:

  Additional $\Delta\rho$ effects act as if turbulent entrainment into the plume is enhanced

  => increased dilution

  ⇒ smaller plume rise

- In CALPUFF numerical plume rise algorithm allows for:

  (1) arbitrary ambient temperature stratifications

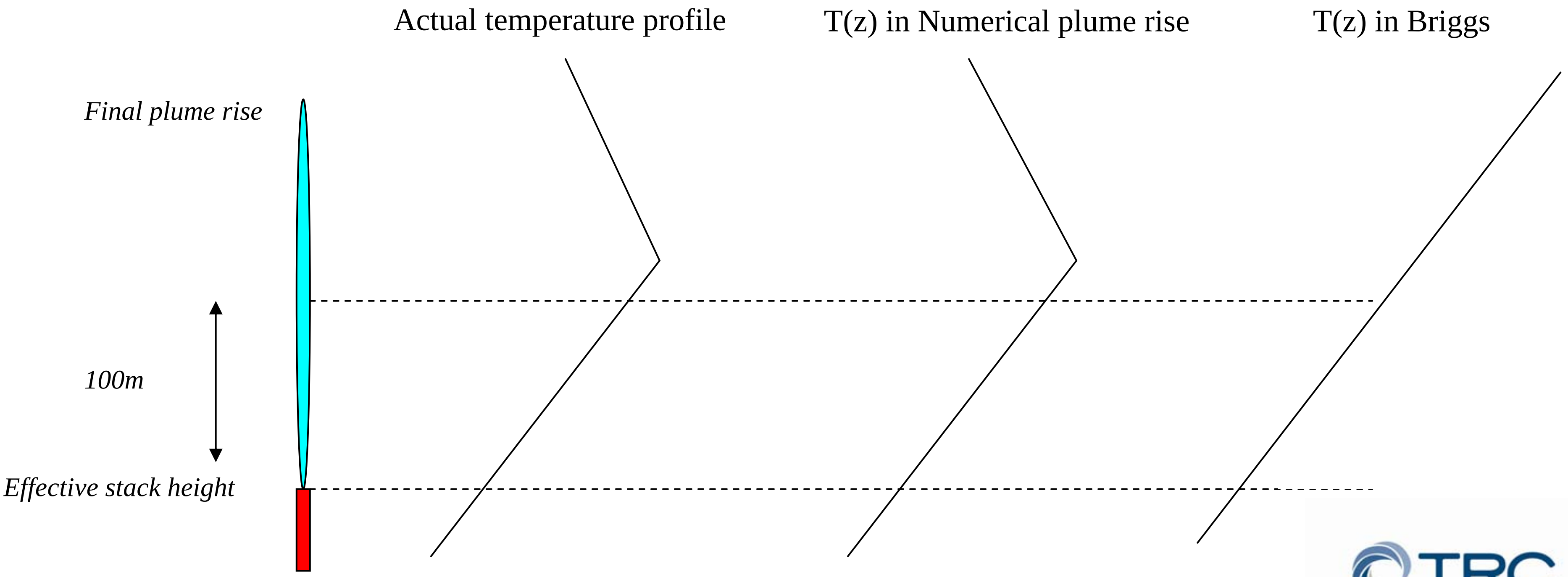
  (2) arbitrary wind stratification

  (3) any size of finite emission source

  (4) radiative heat loss

Stratification

- Briggs: Uses stratification between stack top and 100m above stack top => for short stacks and very buoyant plumes (e.g. flares) and $d\theta/dz$ (z) (e.g. morning inversion): stratification aloft might be very different and misrepresented in Briggs rise



Actual temperature profile

T(z) in Numerical plume rise

T(z) in Briggs

Final plume rise

100m

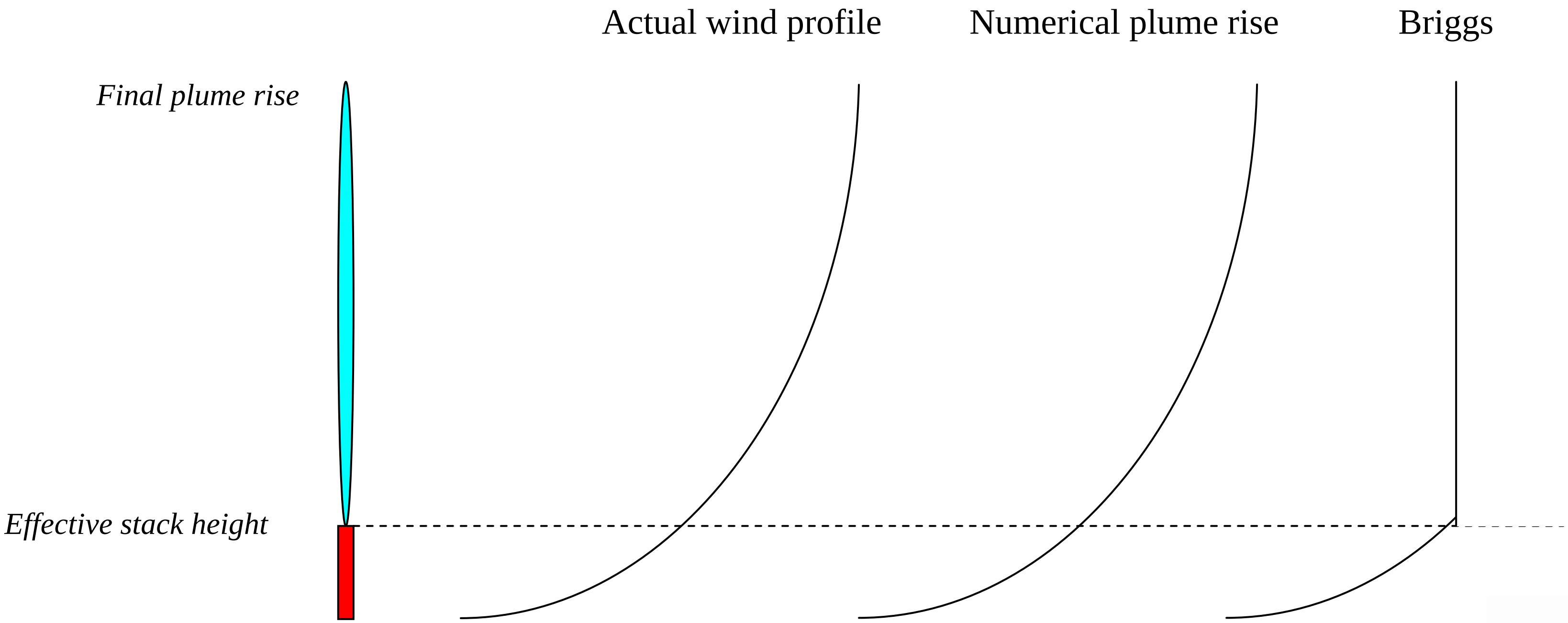
Effective stack height

Partial penetration of elevated inversion

- If unstable layer (PG stability < 4) and elevated inversion: simple correction applied to both Briggs plume rise and numerical plume rise for partial penetration of an elevated stable layer
- This is separate and in addition to either plume rise equation

Vertical wind shear

- Briggs: takes vertical wind shear up to stack height into account, to compute U at stack height but do not take dU/dz above stack height into account.



Testcase

- **Flare**: “Example et al, Dog River” (EUB spreadsheet example on download website EUBFlare_V0101.xls, with 100% CH_4, Flow rate: 125 10^3 m^3/d) – H_{stack}=30.5m)
- Average pseudo-stack parameters:

Teff = 2753.94K

Deff = 9.438m

Veff = 2.314m/s

Heff = 36.986m

Fb= 452.56 m^4/s^3

Fm= 12.48 m^4/s^2

- **Meteorology**: CALMET base testcase (1st hour)

Teff = 2753.94K

Deff = 9.438m

Veff = 2.314m/s

Heff = 36.986m

Fb= 452.6 m^4/s^3

Fm= 12.48 m^4/s^2

(From EUB spreadsheet)

Briggs Plume rise	Numerical plume rise effects	Numerical plume rise
314	Radiative losses, stratification, shear	76.7
	No radiative losses	129.4
	No radiative losses, no shear	131.9
	No radiative losses, no shear, no stratification	205.3

In this case, main differences with Briggs are non-Boussinesq effects, stratification and radiative losses BUT Teff is not realistic and the radiative losses are overestimated

Note: Teff= Tstochiometric (not actual Texhaust)

Texhaust = 1111.68K	Fb= 452.6 m4/s3
Deff = 17.954 m	Fm= 12.48 m4/s2
Veff = 0.773 m/s	
Heff = 36.986m	

Briggs plume rise	Numerical plume rise effects	Numerical plume rise
313	Radiative losses, stratification, shear	126.1
	No radiative losses	128.5
	No radiative losses, no shear	131.1
	No radiative losses, no shear, no stratification	205.0

In this case, main differences with Briggs are non-Boussinesq effects and stratification (early morning). Radiative losses are insignificant with realistic exhaust temperature

Note: Deff and Veff are recomputed s.t. Fb and Fm are conserved, but T=Texhaust

Flare Modeling in CALPUFF

Flare input parameters :

1. Horizontal coordinates (x,y)
2. Base Elevation
3. Effective stack height (m, above ground), H_{eff}
4. Effective Diameter
5. Effective exit velocity
6. Effective source temperature

Flare computational flags (internal)

- Numerical plume rise (no necessarily for other sources in same run)
- No stack tip downwash for flare (ok for other sources in same run)
- Radiative losses off (or bounded at T=1273K)

Combined EUB Flare-CALPUFF

1. Currently developing an interface between hourly meteorology data (u (stack tip), Tamb), hourly stack emissions (un-ignited) and EUB spreadsheet

   ⇒ hourly emission rates and effective stack parameters

2. Validation

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