Numerical and Experimental Investigations on Eruptive Fire Behaviors in Confined Forest Topographies

Emphasis on VOC Accumulations

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29émes Journées du **GDR Feux**

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Content

Introduction and Findings

- Wildfires and common forms of their eruptive behaviors.
- Numerical validation of experimental results of accumulations of steady state ethane mass flow rate, in a porous forest model with V-shaped valley.

Modeling wildfire VOC emissions

- Surface wildfire spread by Rothermel & Anderson fuel model .
- Crown fire initiation by Van Wagner.
- VOC emission factors correated with the fire spread model.
- Numerical results of accumulations of wildfire emissions in forest valley.

Conclusions & Future Prospects

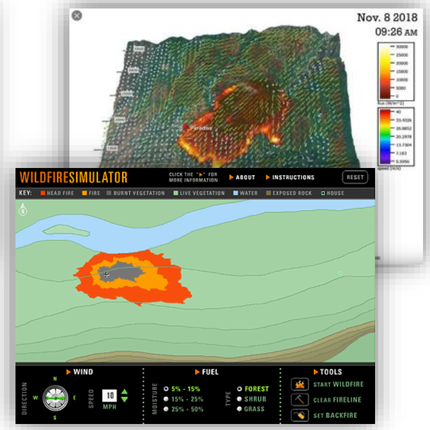
Wildfires & Common Eruptive Fire Behaviors

Wildfires:

- Surface fires, crown fires, spot fires, and ground fires.

Context :

- Uncontrolled fire in an area of combustible vegetation.
- 60 000 wildfires per year burning around 300 000 000 ha.
- Wildfire occurrences in the amazonian forest has increased by 30% in the last 10 years.
- 30 000 firefighters are mobilized every year.

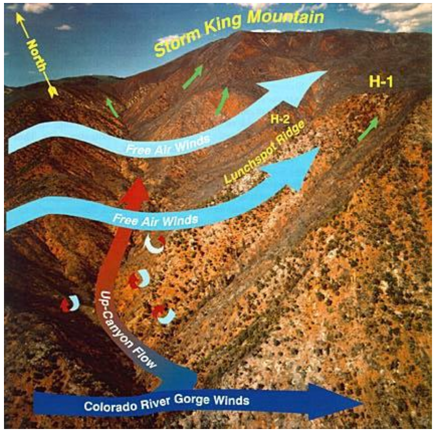


Support fire extinguishing operations: Understand, predict, and model wildfire behaviors.

Wildfires & Common Forms of Eruptive Fire Behaviors

Eruptive Fires:

- Also known as blow-up or flare up fires.
- Sudden and extreme increase in wildfire intensity and rate of spread.
- Normally occur in confined forest topographies with slope geometries.



South Canyon.USA

Wildfires & Common Forms of Eruptive Fire Behaviors

Cases of Fire Eruptions

Case	Year	Place	Country	Victims
1	1949	Mann Gulch	USA	13
2	1953	Rattlesnake	USA	15
3	1966	Sintra	Portugal	25
4	1984	La Gomera	Spain	20
5	1985	Armamar	Portugal	14
6	1986	A gueda	Portugal	16
7	1990	Dude	USA	6
8	1994	Storm King	USA	14
9	1996	Loop	USA	12
10	1999	Alajar	Spain	4
11	1999	Tabuaco	Portugal	2
12	2000	Palasca	France	2
13	2000	Mação	Portugal	2
14	2003	Cramer	USA	2
15	2003	Freixo	Portugal	2
16	2005	Guadalajara	Spain	11
17	2005	Mortagua	Portugal	4
18	2006	Famalicão	Portugal	6
19	2007	Kornati Island	Croatia	11
			Total:	181

Some accidents with multiple fatalities associated with eruptive fire behaviors in canyons in 58 years. Viegas et al. 2011

Wildfires & Common Forms of Eruptive Fire Behaviors

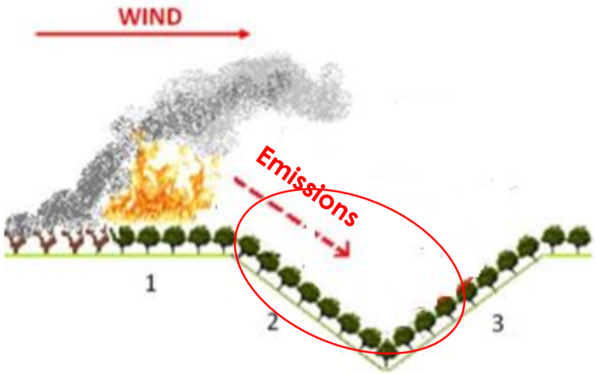
Fire Flashover :

- Premixed or partially premixed flame through potentially accumulated fuel vapor downslopes.

Palasca Wildfire, Corsica 2000: Eruption or Flashover.

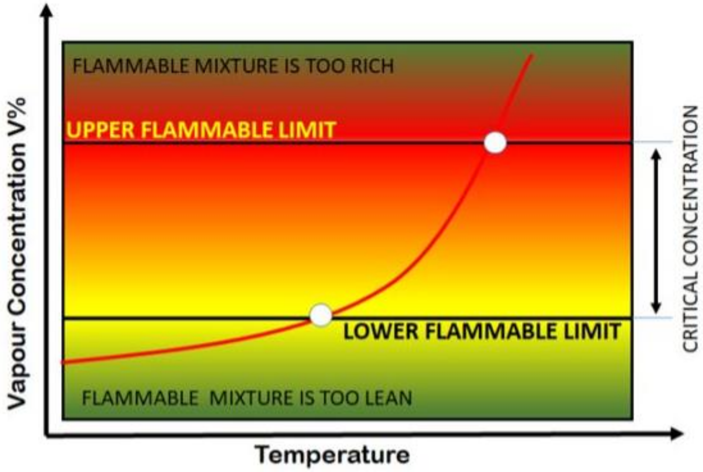
Caramelized plant after fire.

Wildfires & Common Forms of Eruptive Fire Behaviors



- Non-Methane BVOCs: Isoprene (C_5H_8)& Terpenoids.
- Other VOCs: Methane, Aliphatic and Aromatic hydrocarbons

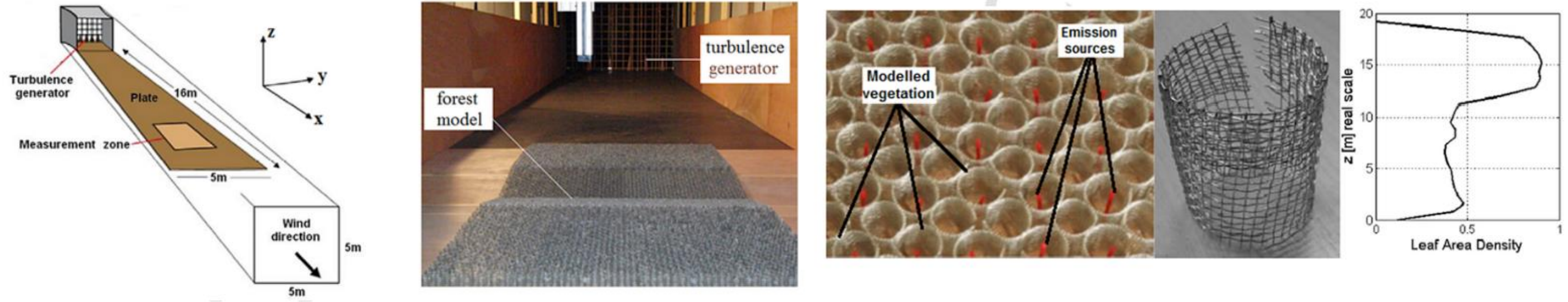
The blowup fire phenomenon can only occur if flammable VOC levels in the air are between two values:
Lower Flammable Limit (LFL)
and
Upper Flammable Limit (UFL).



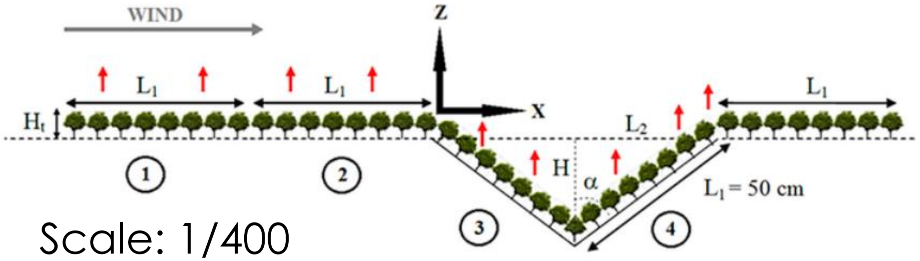
Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley

Inlet velocity = 6m/s

D=30mm
H=50mm



Modeled forest in a wind tunnel (PRISME Laboratories). Tree structure with meshed metallic cylinders and ethane injection tubes.



Scale: 1/400

Forest model: Deciduous Forest(1300-1500 tree/ha) with LAI=3.6 (dense forest), height=20m.

Achieve aerodynamic properties of the inside and above canopy flow as measured on site of forest. (Aubrun & Leitl, 2004)

Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley

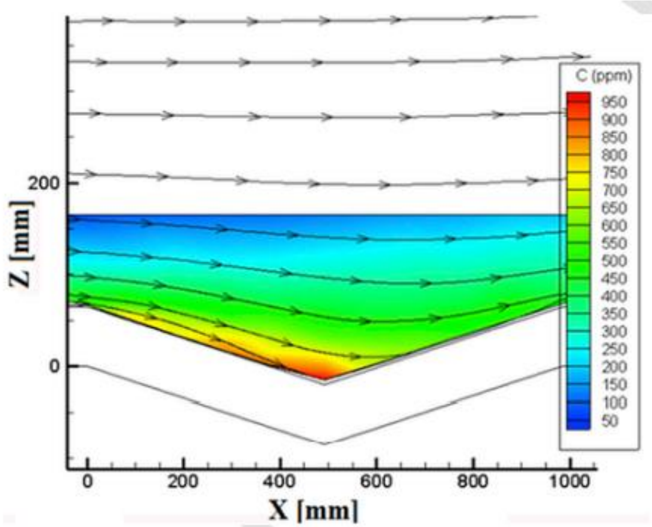


Fig. a.

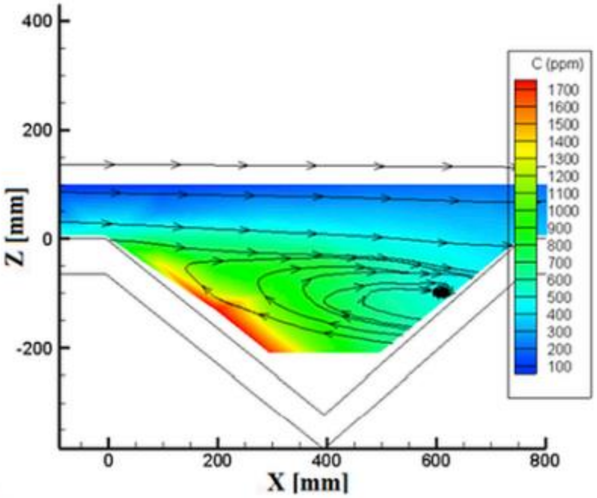


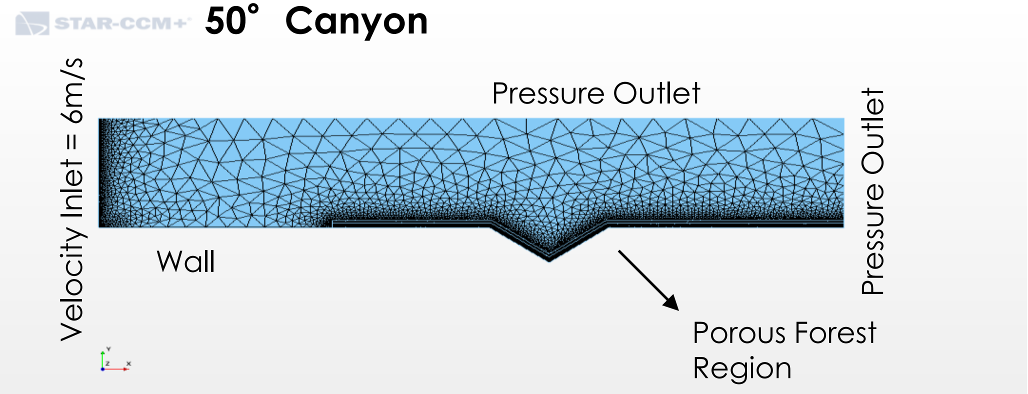
Fig. b.

Velocity streamlines (measured by LDV) and ethane concentrations (measured with FID) in the lee side of the 50° (Fig. a.) and 80° (Fig. b.) valley configurations.

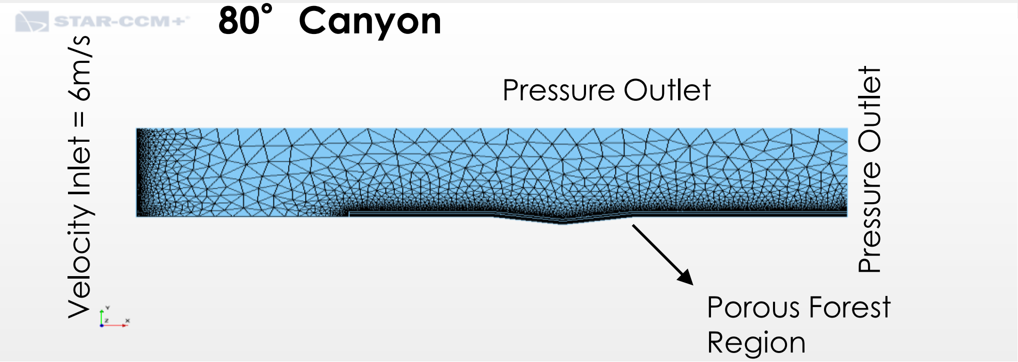
For 50° max @1790 ppm (3.5 x flat forest ppm)
For 80° max @ 980 ppm (2x flat forest ppm)
Recirculation in velocity of 50° due to detachment of boundary layer.

Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley

Numerical model with STARCCM+



50° Canyon



80° Canyon

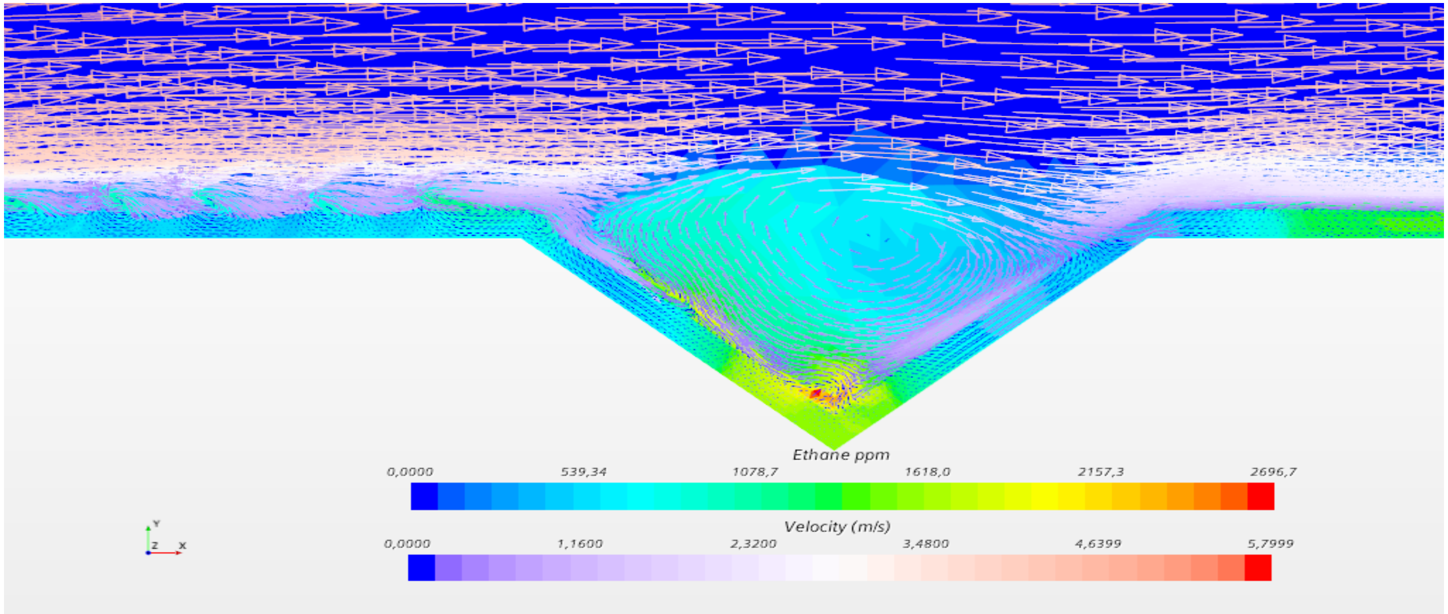
Porosity:
Particular case of Forchheimer equation:
Ergun equation for measure of pressure drop over a length of L of fluid passing through a packed bed. Viscous and intertial terms.

Mass flow rate of ethane = 0.001902 $kg/m^3.s$

Tetrahedral mesh with local refinements. Prism layer and wall treatment to resolve turbulent boundary layer.

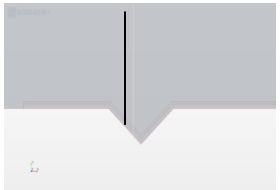
Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley

Numerical results of velocity vectors and ethane spatial concentration in 50° valley

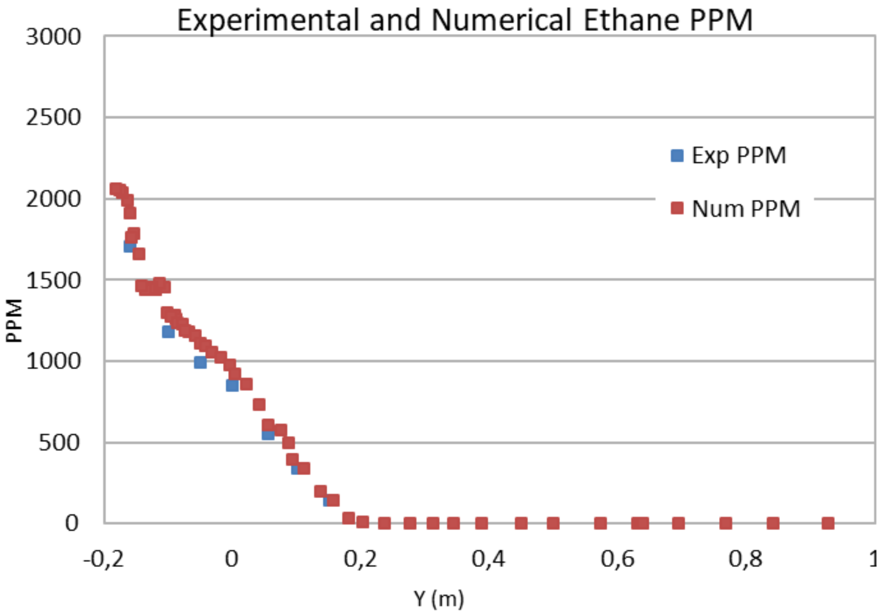


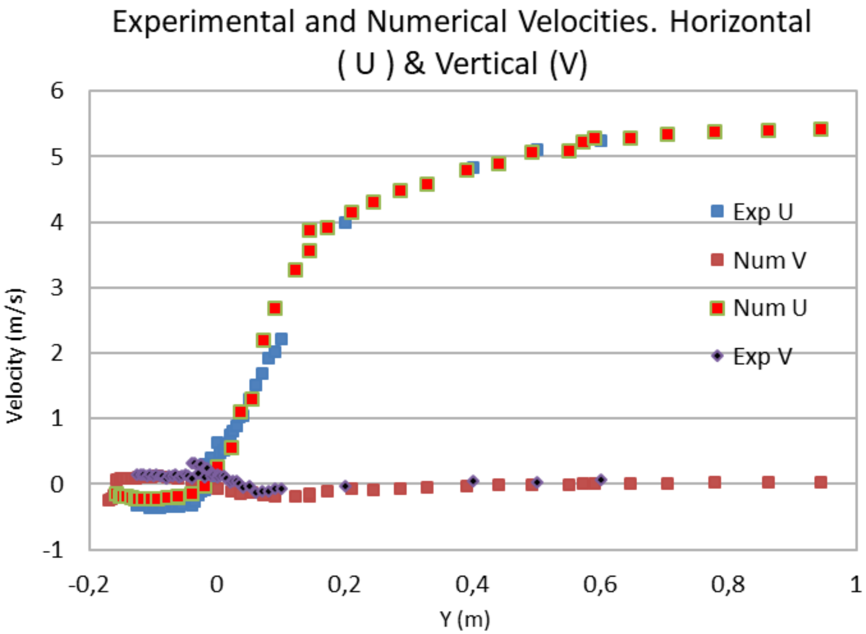
Circulation of velocity in the 50° angled canyon. Concentration of ethane noticed on the lee side and center of the valley.

Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley



Lee side position of 50° valley

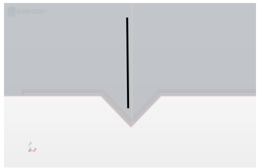




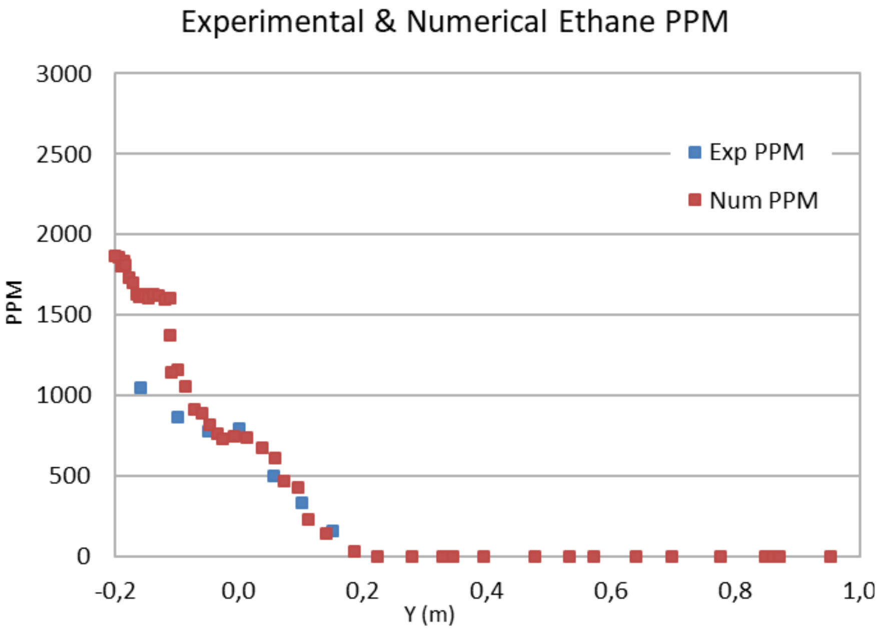
Velocity & ethane profiles on the Lee Side of the 50° valley

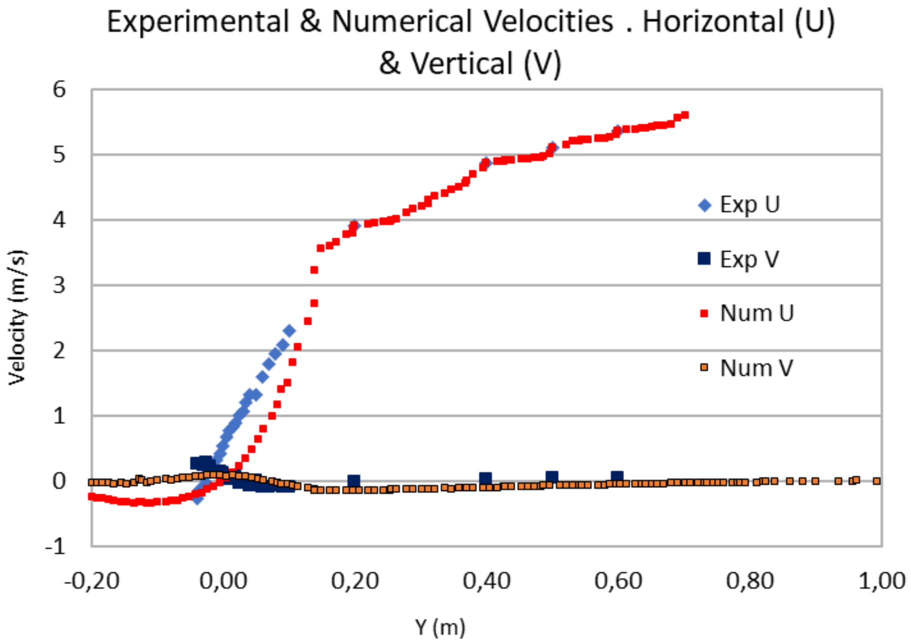
Negative U values indicating circulation favoring spatial concentration of ethane reaching 2057 ppm.

Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley



Center position of 50° valley

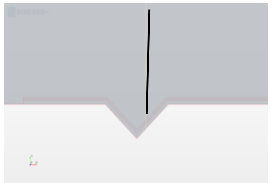

Experimental & Numerical Ethane PPM


Experimental & Numerical Velocities . Horizontal (U) & Vertical (V)

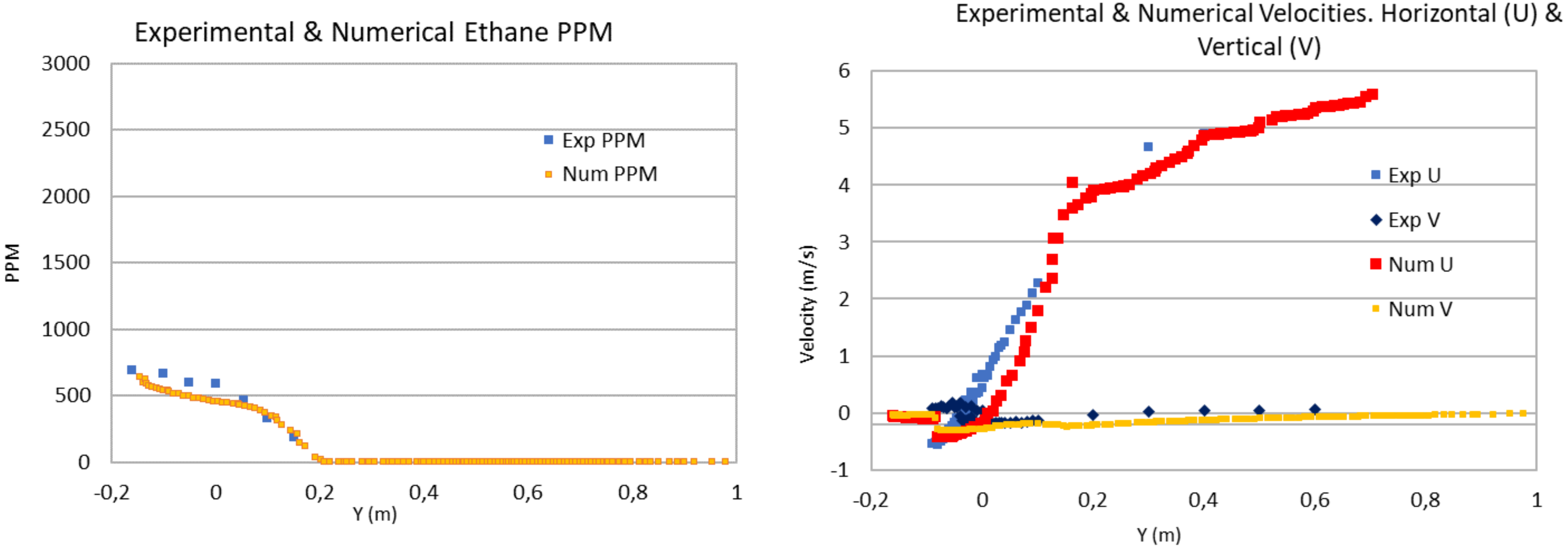
Velocity & Ethane Profiles on the Center of the 50° Valley

Negative U values indicating circulation favoring spatial concentration of ethane reaching 1805 ppm.

Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley



Wind side position of 50° valley

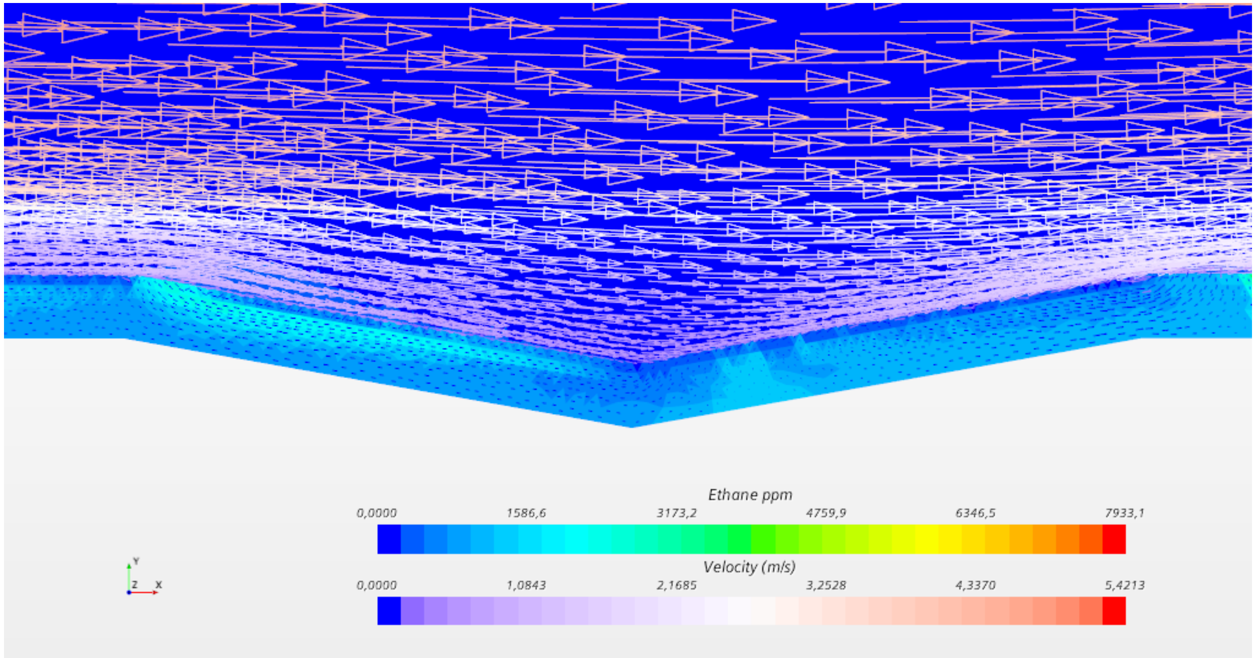


Velocity& Ethane Profiles on the Wind Side of the 50° Valley

Negative U values indicating circulation favoring spatial concentration of ethane reaching 638 ppm.

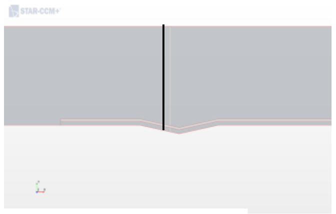
Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley

Numerical results of velocity vectors and ethane spatial concentration in 80° valley

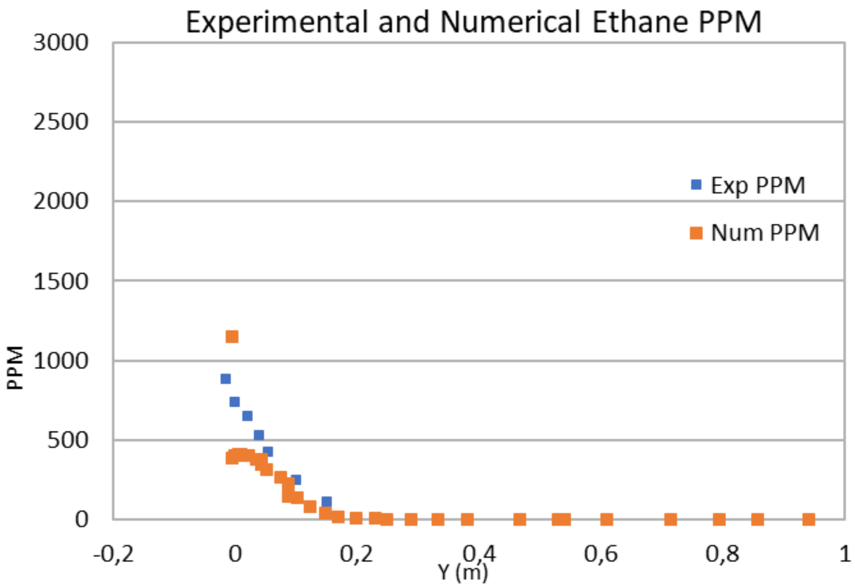


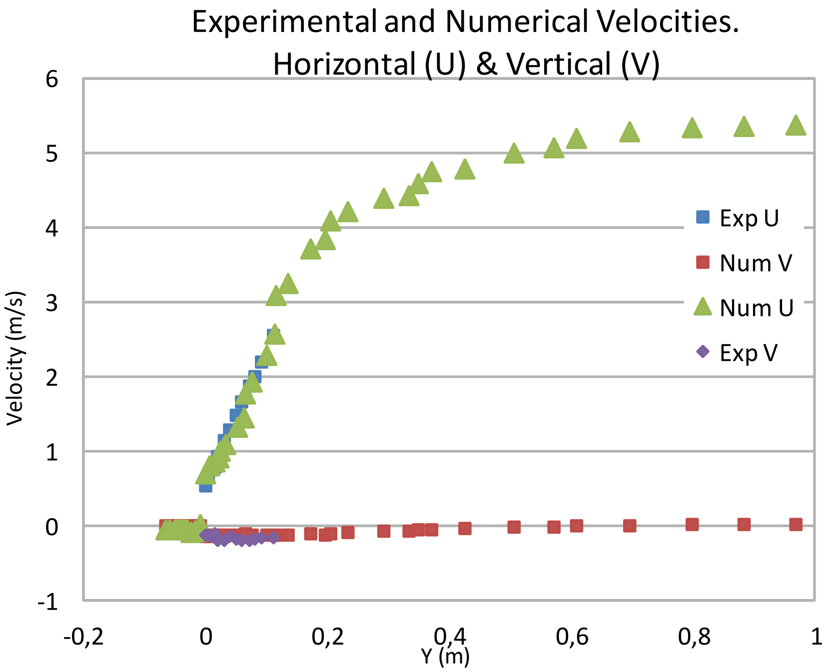
No circulation of velocity in the 80° angled canyon. Concentration of ethane noticed slightly on the lee side of the valley.

Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley



Lee side position of 80° valley

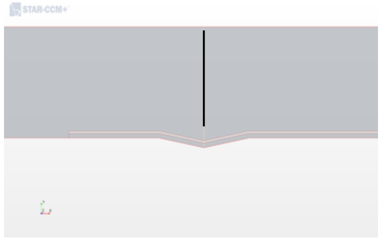




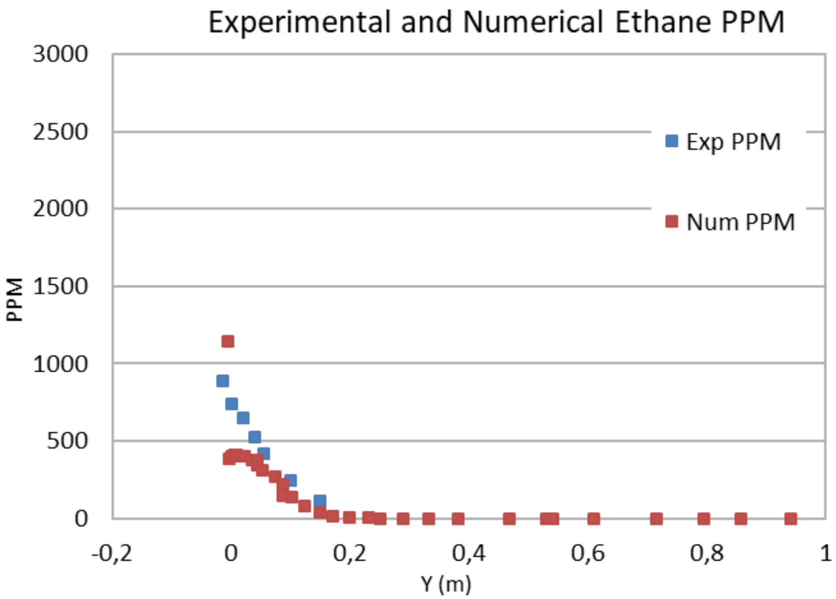
Velocity & Ethane Profiles on the Lee Side of the 80° Valley

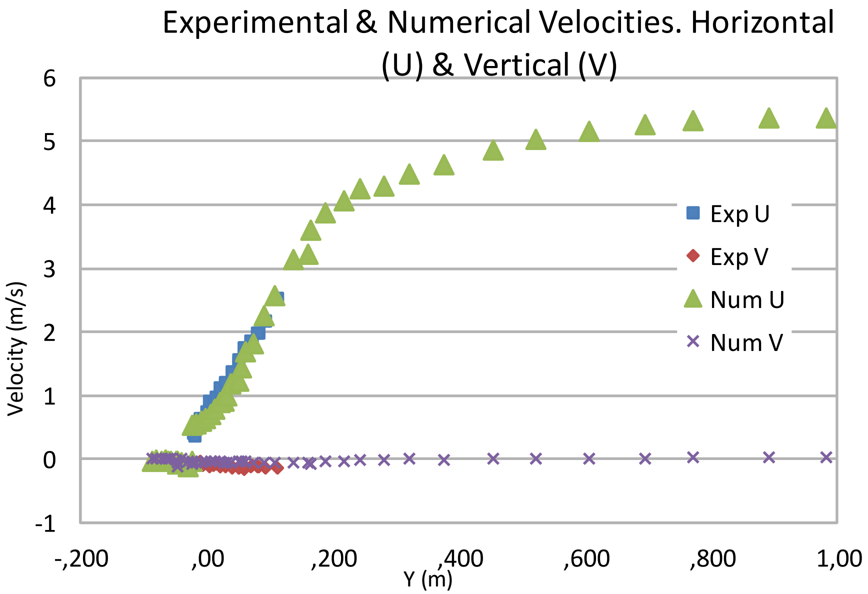
No negative U values. Limited concentrations of ethane in the valley 1114ppm.

Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley



Center position of 80° valley

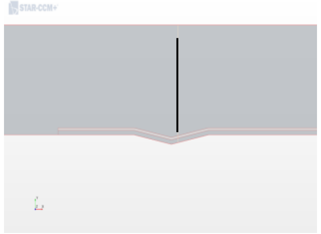




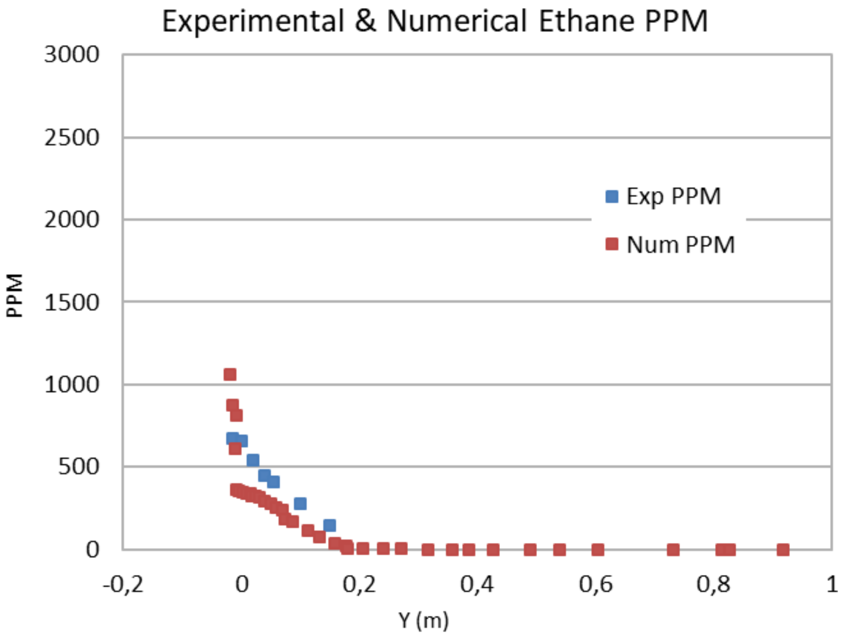
Velocity & Ethane Profiles on the Center of the 80° valley

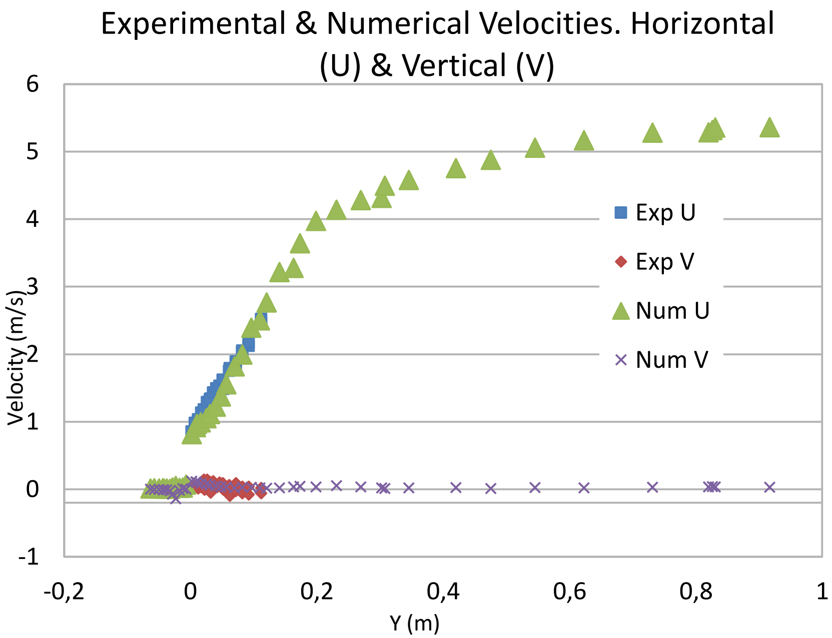
No negative U values. Limited concentrations of ethane in the valley 1041ppm.

Validation of Experimental Results of Ethane Accumulation in V-Shaped Valley



Wind side position of 80° valley





Velocity & Ethane Profiles on the Wind Side of the 80° Valley

No negative U values. Limited concentrations of ethane in the valley 1022 ppm.

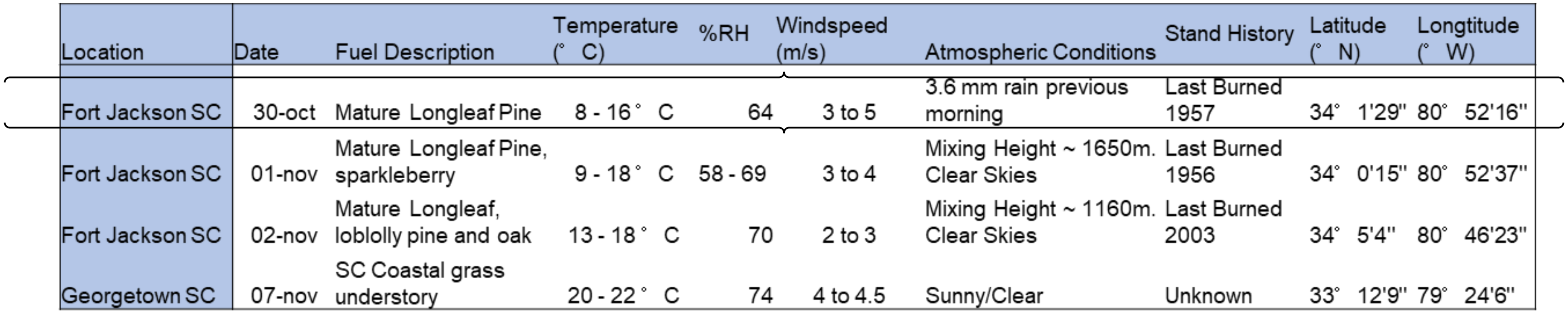
Fire Front Model

How to model VOC real wildfire emissions:

- VOC emissions are diverse. (Flaming, smoldering and pyrolysing)
- Quantification of VOC emissions from wildfires smoke plume (ground or airborne air samples).
- Choosing reliable source for wildfire emission factors (EF g/kg burned).
- Mechanisms of heat transfer are neglected in our model. Relatively high crosswind velocities (6m/s), we can neglect buoyancy effects on emission flow.
- Modeling fire intensity from biomass mass loss.
- Choosing the relevant forest model by Anderson (13 Fuel Models).
- Albini fuel model parameters to Rothermel mathematical equations of surface fire spread model.

Fire Front Model

Wildfire coordinates and atmospheric conditions:



Location	Date	Fuel Description	Temperature (° C)	%RH	Windspeed (m/s)	Atmospheric Conditions	Stand History	Latitude (° N)	Longtitude (° W)
Fort Jackson SC	30-oct	Mature Longleaf Pine	8 - 16 ° C	64	3 to 5	3.6 mm rain previous morning	Last Burned 1957	34° 1'29''	80° 52'16''
Fort Jackson SC	01-nov	Mature Longleaf Pine, sparkleberry	9 - 18 ° C	58 - 69	3 to 4	Mixing Height ~ 1650m. Clear Skies	Last Burned 1956	34° 0'15''	80° 52'37''
Fort Jackson SC	02-nov	Mature Longleaf, loblolly pine and oak	13 - 18 ° C	70	2 to 3	Mixing Height ~ 1160m. Clear Skies	Last Burned 2003	34° 5'4''	80° 46'23''
Georgetown SC	07-nov	SC Coastal grass understory	20 - 22 ° C	74	4 to 4.5	Sunny/Clear	Unknown	33° 12'9''	79° 24'6''

Fire location, date, fuel description, size, atmospheric conditions, and burn history of documented wildfires. (Akagi et al. 2013)

Fire Front Model

	Fuel Discription		
Selection of Compounds Emitted	Longleaf Pine	Pine + Sparkle Berry	Pine + Oak
	EF g/kg	EF g/kg	EF g/kg
Methane	5.20	11.50	10.34
Acetylene	0.25	0.22	0.14
Ethylene	0.89	1.53	1.25
Propylene	0.40	1.02	1.00
Methanol	2.35	6.42	3.60
1,3-Butadiene	0.10	0.15	0.09
Ethane	0.503	2.033	5.632
Propane	0.171	0.544	1.692
Benzene	0.268	0.429	1.712
Toluene	0.515	0.283	0.938
Terpenes	5.12	0.14	13.35

Emission factors (EF) in grams of selected compounds emitted per kg of biomass burned. (Akagi et al. 2013)

$$EF_x = FC \times 1000 \times (MM_X/ MM_C) \times (C_X/ C_T)$$

Where : EF is the emission factor of compound X ($g.kg^{-1}$).

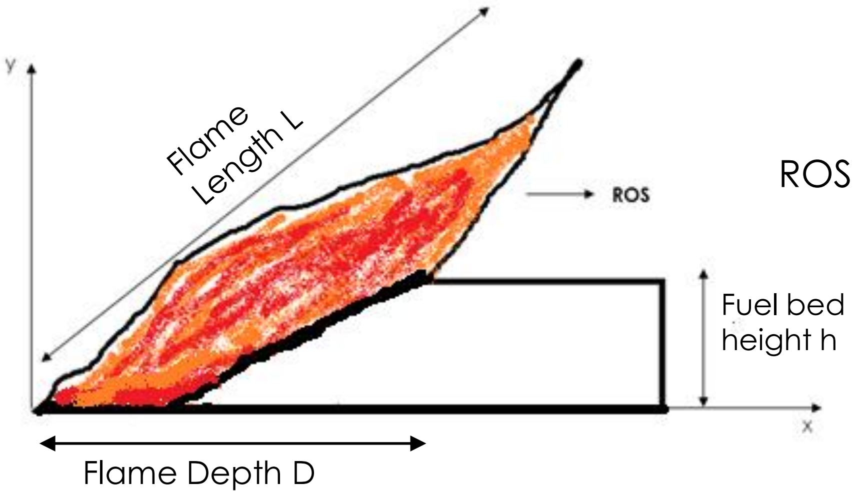
MM_x is the molecular mass of compound X ($g.mol^{-1}$)

MM_c is the molecular mass of carbon (12.011 g mol^{-1}).

C_x/C_T is the number of emitted moles of compound X divided by the total number of moles of carbon emitted.

Fire Front Model

Rothermel mathematical model for predicting fire spread



Mechanisms of heat transfer are not identified

$$\text{ROS ft/min} = \frac{\text{Heat source}}{\text{Heat sink}} = \frac{IR}{Q_{ig}}$$

Heat Source

Reaction Intensity IR (Btu/ft^2 .min) depends on:

- Speed of Wind
- Degree of slope

τR (Residence time): Conversion time of solid fuels to gases.

Flame depth (D) = ROS x τ_R

Heat Sink

Q_{ig} (Btu/ft^3) depends on:

- Temperature of ignition
- Moisture content,
- Amount of fuel involved in the ignition process (effective bulk density).

Fire Front Model

Fuel Models

Fire Front Model

13 Fuel models by Anderson.

Described by Anderson: Mature Pine stands create large load of dead materials on the forest floors. Fire intensities are predicted to be larger than other timber litter models, which may lead to fire control difficulties. i.e. Extreme Fire Behaviors.

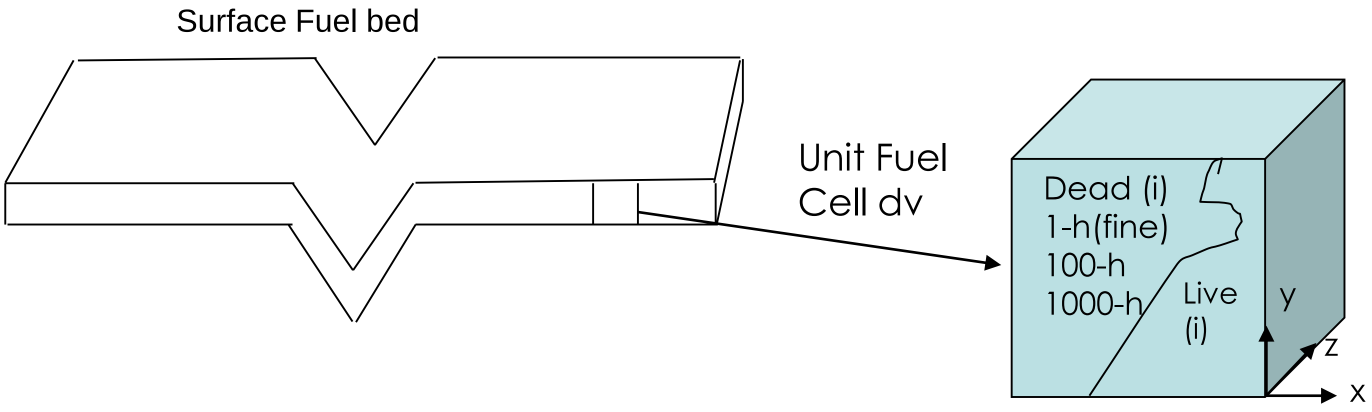
		Dead Fuel						Live Fuel			
		Fine 1-h		Medium 10-h		Large 1000-h					
		σ	w_0	σ	w_0	σ	w_0	σ	w_0		
Model	**Typical Fuel Complexes**	ft^{-1}	lb/ft^2	ft^{-1}	lb/ft^2	ft^{-1}	lb/ft^2	ft^{-1}	lb/ft^2	Fuel Depth ft	Moisture of Extinction $(M_x)_{dead}$
	Grass and Grass Dominated										
1	**Short Grass (1 ft)**	3500	0,034							1	0,12
2	**Timber (grass and Understory)**	3000	0,092	109	0,05	30	0,23	1500	0,02	1	0,15
3	**Tall Grass (2.5 ft)**	1500	0,138							2,5	0,25
	Chaparral and Shrubfields										
4	**Chaparral (6 ft)**	2000	0,23	109	0,18	30	0,092	1500	0,23	6	0,2
5	**Brush (2 ft)**	2000	0,046	1091	0,02			1500	0,09	2	0,2
6	**Dormant brush, hardwood slash**	1750	0,069	109	0,12	30	0,092			2,5	0,25
7	**Southern Rough**	1750	0,052	109	0,09	30	0,069	1550	0,02	2,5	0,4
	Timber Litter										
8	**Closed timber litter**	2000	0,069	109	0,05	30	0,115			0,2	0,3
9	**Hardwood litter**	2500	0,134	109	0,02	301	0,007			0,2	0,25
10	**Timber (litter and understory)**	2000	0,138	109	0,09	30	0,023	1500	0,092	1	0,25
	Logging Slash										
11	**Light logging slash**	1500	0,069	109	0,21	30	0,253			1	0,15
12	**Medium Logging slash**	1500	0,184	109	0,64	30	0,759			2,3	0,2
13	**Heavy logging slash**	1500	0,322	109	1,06	30	1,288			3	0,25

W_0: Ovendry loading. σ: surface-area to volume ratio.
Fuel models parameters used in Rothermel model equations. Albini 1976.

Fire Front Model

Weighting Rothermel Equations by Fuel Particle Surface Area

- Fine fuels of highest σ will respond the fastest and lead the fire front.



Two Categories (i): Dead and Live.
Each category has size class (j).

Two weighting parameters:

- Ratio of surface area of jth size class of total surface area of ith category per unit fuel cell.
- Ratio of surface area of ith category to total surface area per unit fuel cell.

Fire Front Model

Location	Date	Fuel Description	Temperature (° C)	%RH	Windspeed (m/s)	Atmospheric Conditions	Stand History	Latitude (° N)	Longtitude (° W)
Fort Jackson SC	30-oct	Mature Longleaf Pine	8 - 16 ° C	64	3 to 5	3.6 mm rain previous morning	Last Burned 1957	34° 1'29"	80° 52'16"

Used for moisture content of each size class in each category with correction factors

<u>Surface Fire Parameters of Model 10:</u>

Byram Surface Fire intensity I = 15209 Btu/ft.min

Surface Fire Reaction Intensity IR = 3642.9 Btu/ft^2.min

Rate of Spread (ROS) = 1.6 ft/min

Flaming zone depth (D) = 4.1 ft

Weight of fuel consumed in the flaming front

$$W_f = \frac{\text{HPA Btu/ft}^2}{\text{H Btu/lb}} = 4.88\ \text{kg/m}^2$$

<u>Van Wagner Criteria for Crown Fire Initiation:</u>

I'initiation = 14505.8 Btu/ft.min < I (surface fire)

Ractive = 14.24 ft/min

R'active = 3/CBD(kg/m^3)= 3.6 ft/min < Ractive

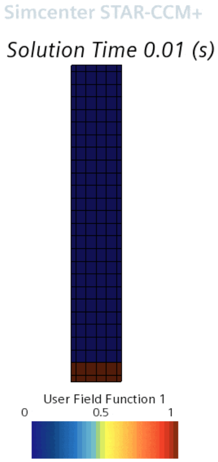
Active Crown Fire with final Fireline Intensity = 128814,94 Btu/ft.min

ROS final = 12.79 ft/min

D= 10.27m for a residence time = 2.6 min

Numerical Investigations on Accumulations of Wildfire Emissions in Forest Valley

Field function of mass flow inside forest depended on the residence time (2.6 mins) of flaming zone in fixed flaming depth D.

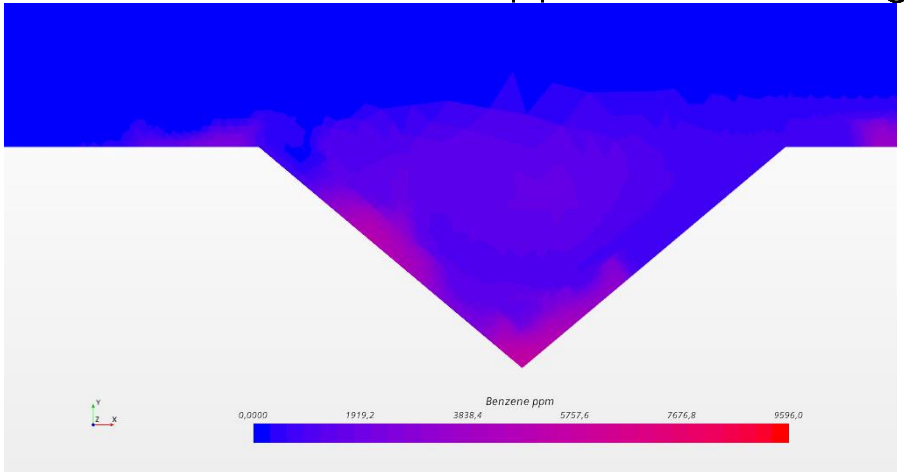


In SI units: ROS= 3.955 m/min
D=10.27m
Wf= 4.88 kg/m^2

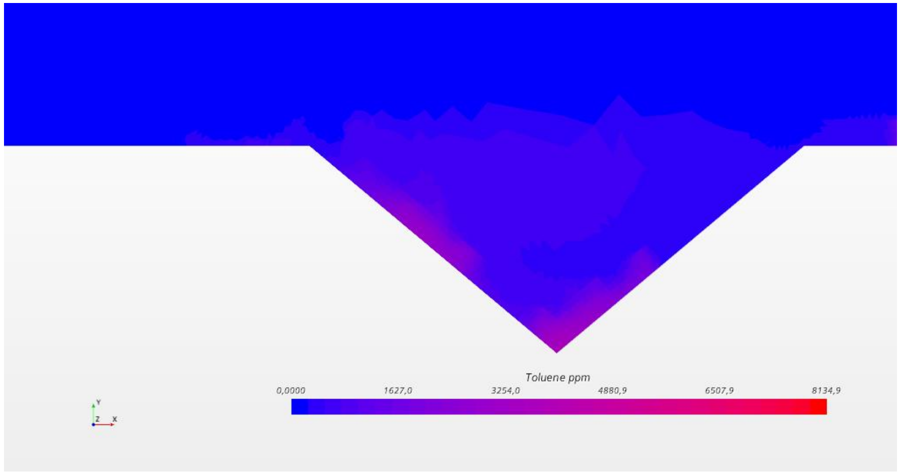
Selected Compounds Emitted	Emissions in Model Scale
	kg/sec
Methane	0,005005
Acetylene	0,00024063
Ethylene	0,00085663
Propylene	0,000385
Methanol	0,00226188
1,3-Butadiene	0,00009625
Ethane	0,00048414
Propane	0,00016459
Benzene	0,00025795
Toluene	0,00049569
Terpenes	0,004928

Numerical Investigations on Accumulations of Wildfire Emissions in Forest Valley

Spatial concentrations of benzene and toluene in 50° angled valley at the moment the fire front approaches the edge of the lee side after 101 mins.



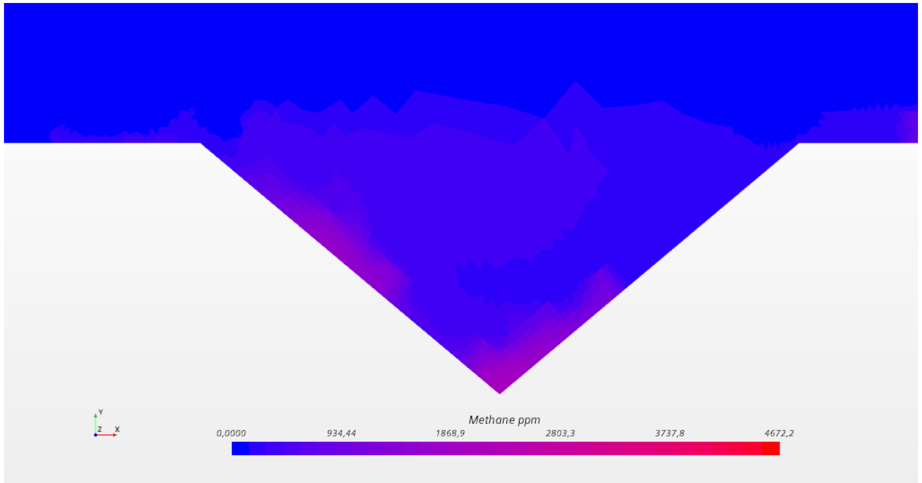
Benzene accumulations inside the valley. Maximum concentration 1098 ppm on lee side of valley.



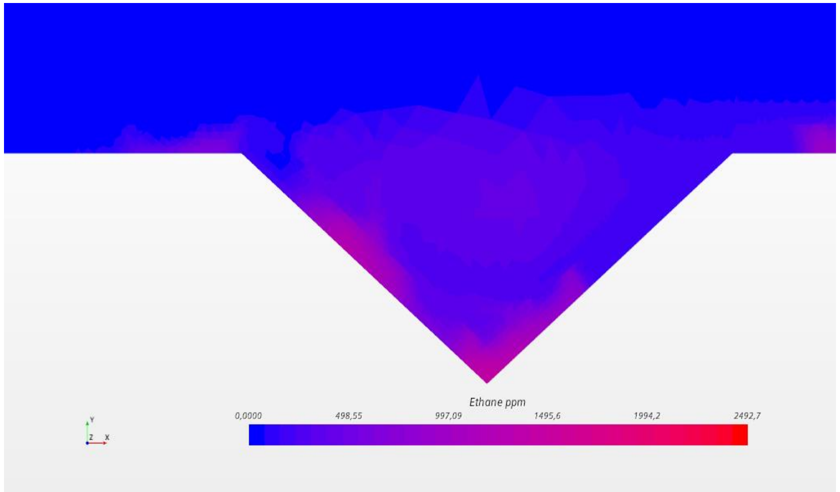
Toluene Accumulations inside the valley. Maximum Concentration 931 ppm on Lee side of valley.

Numerical Investigations on Accumulations of Wildfire Emissions in Forest Valley

Spatial concentrations of methane and ethane in 50° angled valley at the moment the fire front approaches the edge of the lee side after 101 mins.



Methane accumulations inside the valley. Maximum concentration 514 ppm on lee side of valley.



Ethane accumulations inside the valley. Maximum concentration 838 ppm on lee side of valley.

Conclusions and Future Prospects

Conclusions:

- VOC accumulations on the lee side and center of V-shaped valleys.
- Rothermal mathematical and biomass fuel mass loss.
- Heavy aromatic hydrocrabons > lighter hydrocarbons.

Future Prospects:

- Emissions from heated vegetation ahead of fire front.
- Emissions from smoledring vegetation .
- LFL < Concentrations < UFL .
- Fuel Model and Porosity.
- Thermal model and cross flow velocity.

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