



National Technical University of Athens
School of Mechanical Engineering
Heterogeneous Mixtures & Combustion Systems



Flow Dynamics and Thermal Characteristics of Surface Wildland Fires: An Experimental Investigation

Dionysis Kolaitis

Assistant Professor

School of Mechanical Engineering

National Technical University of Athens

ERCOFTAC Autumn Festival 2026 and 21st Da Vinci Competition Final - 15/10/2026 - NTUA - Athens, Greece

◇ Introduction

- » Main Phenomena in Wildland Fires
- » Parameters Affecting Wildland Fire Spreading Rate
- » Aim and Objectives

◇ Experimental Apparatus

- » Sensor Network

◇ 1st Stage: Point Ignition

- » Parametric Study
- » Results and Discussion

◇ 2nd Stage: Linear Ignition

- » Results and Discussion



◇ **Heterogeneous Mixtures and Combustion Systems (HMCS) laboratory**

» School of Mechanical Engineering, NTUA

◇ **Staff**

» Prof. Emer. Maria Founti

» Assist. Prof. Dionysis Kolaitis

» 3 Special Research and Teaching staff

» 4 Post-doc researchers

» 7 Ph.D. candidates

◇ **Main Research Units**

» Fire Engineering Unit (FEU-HMCS)

» Combustion Systems Unit

» Building Energy Assessment Unit



◇ Fluid Dynamics

- » Turbulent Flow
- » Thermal Buoyancy
- » Multicomponent Flow
- » Multiphase Flow (fire brands)
- » Air entrainment

◇ Chemical Reactions

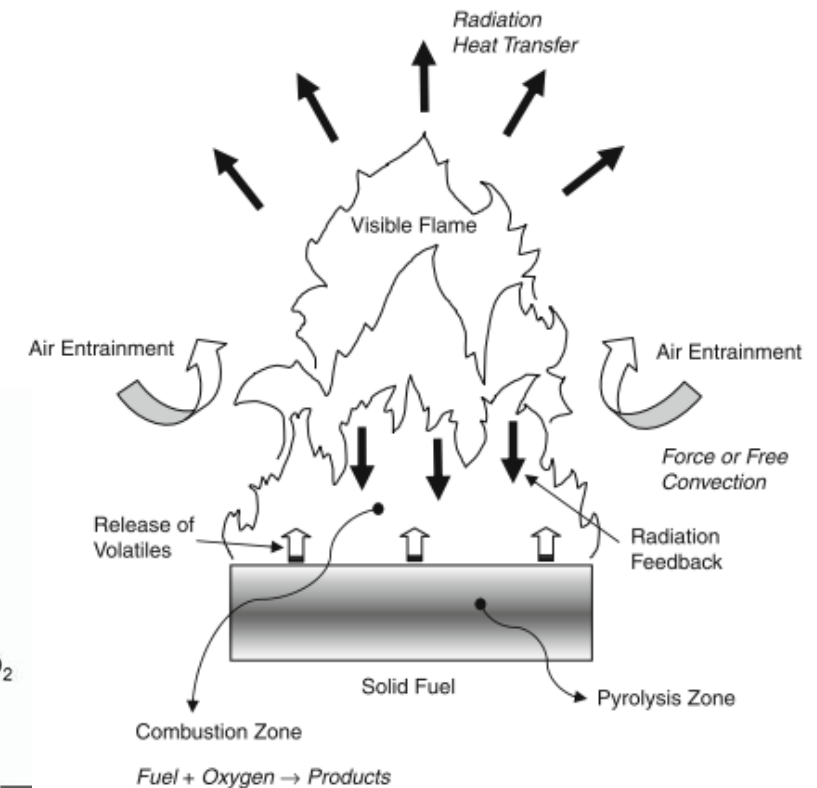
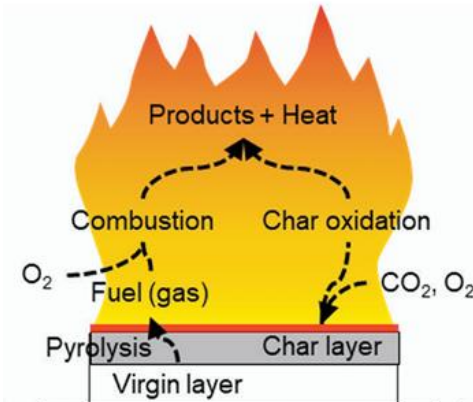
- » Gas phase combustion
- » Solid phase pyrolysis
- » Charring
- » Smoldering

◇ Heat Transfer

- » Conduction
- » Convection
- » Radiation

◇ Mass Transfer

- » Diffusion
- » Convection



Wildland Fires: Key Parameters Affecting Spreading Rate

◇ Fuel Characteristics

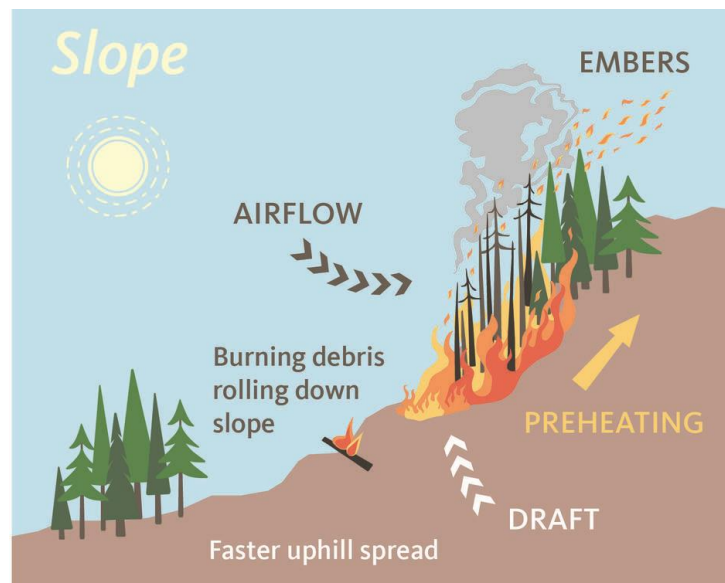
- » Fuel particle properties (e.g. moisture content)
- » Fuel bed bulk properties (e.g. fuel load)

◇ Terrain Topography

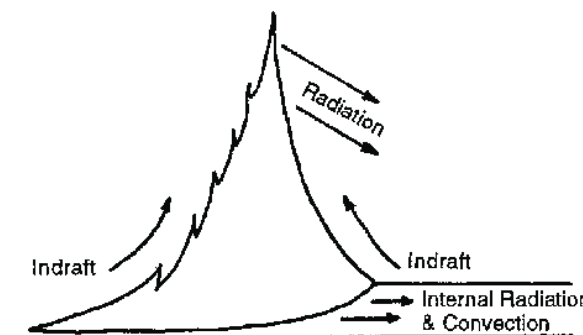
- » Slope

◇ Weather Conditions

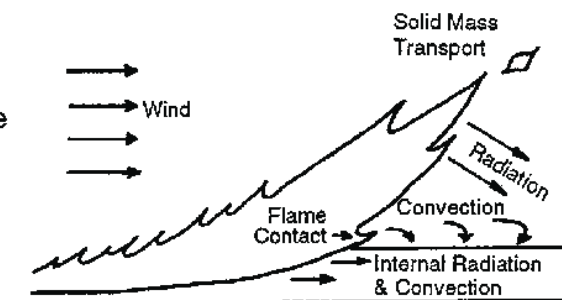
- » Wind velocity
- » Ambient temperature
- » Relative humidity



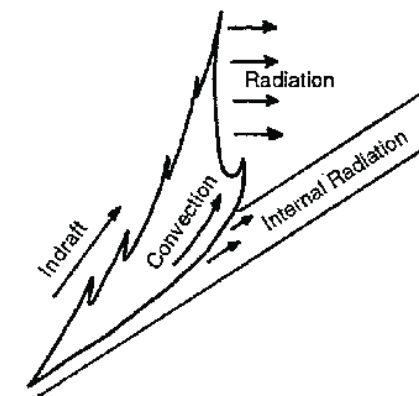
No-wind Fire



Wind-driven Fire



Upslope Fire

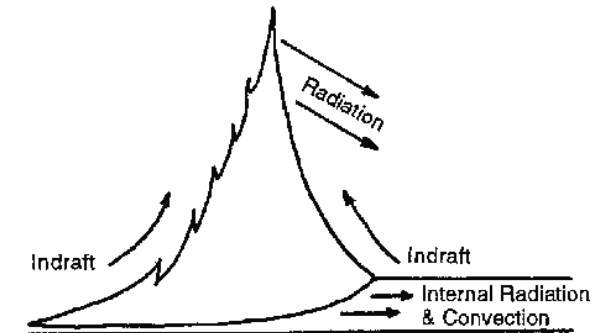


◇ Importance

- » Horizontal air entrainment flows in a spreading fire front directly affect
 - Flame front rate of spread
 - Oxygen supply
 - Flame inclination
 - Convective cooling
 - Plume dynamics

◇ Physical Mechanisms

- » Thermal buoyant flow produces converging horizontal entrainment from both sides
- » Increasing terrain slope breaks the symmetry of entrainment
 - Possible transition from opposed flow to forward-directed flow (U_{down})
- » Open questions...



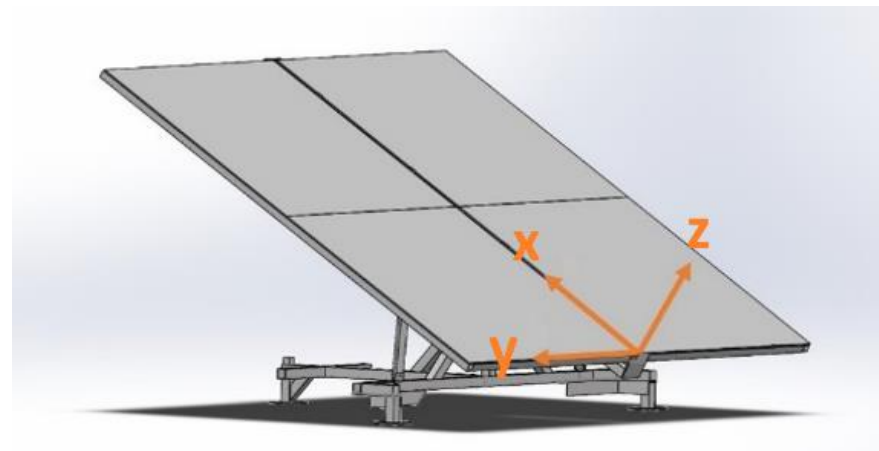
◇ Inclined Combustion Table

- » Area: 2 m x 2 m
- » Adjustable slope angle
- » **1st Stage:** Point ignition
- » **2nd Stage:** Linear ignition

◇ Pine needles (Pinus Halepensis)

◇ Measurement Equipment

- » Side-view and Back-view Cameras
 - In-house developed flame identification algorithm
- » Gas analyzer
 - O₂, CO₂, CO concentration measurements
 - Oxygen calorimetry to estimate instantaneous HRR



Model representation of the inclined combustion table

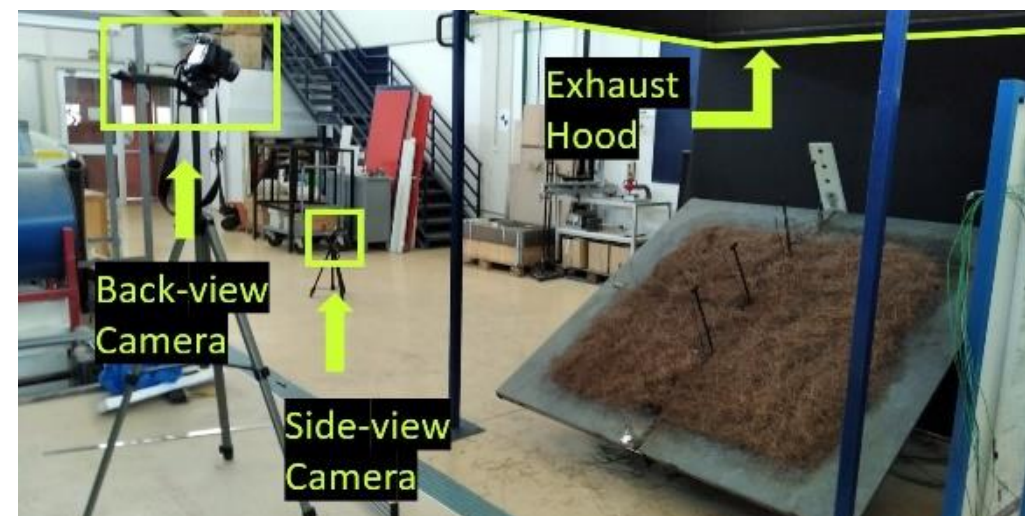
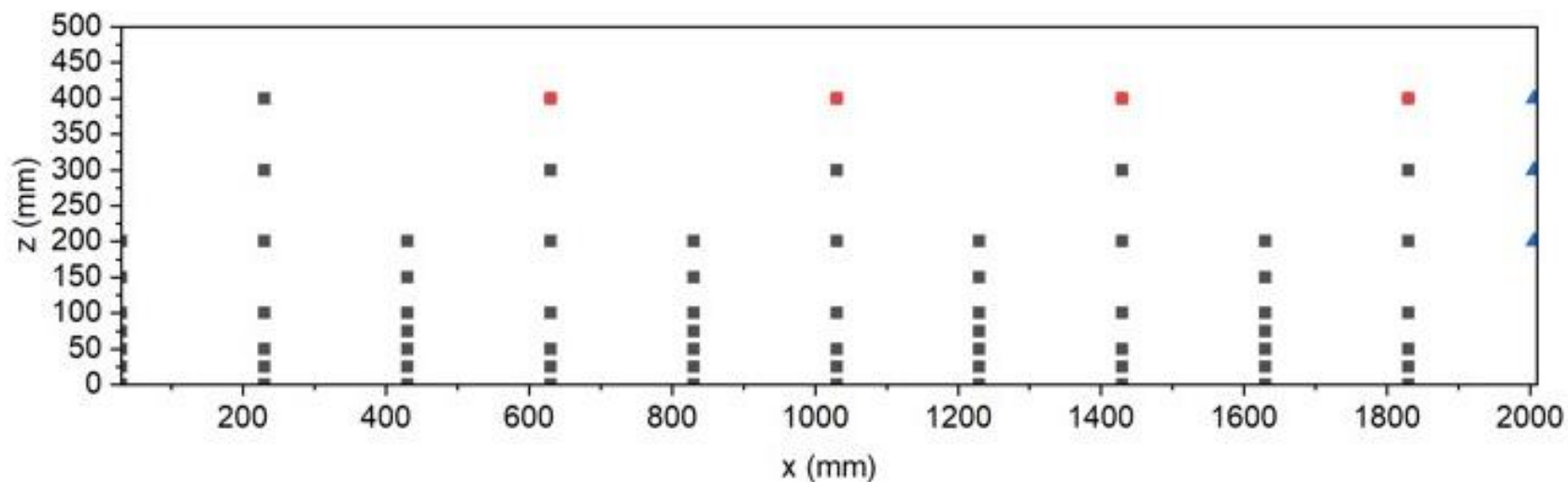


Image of the experimental apparatus

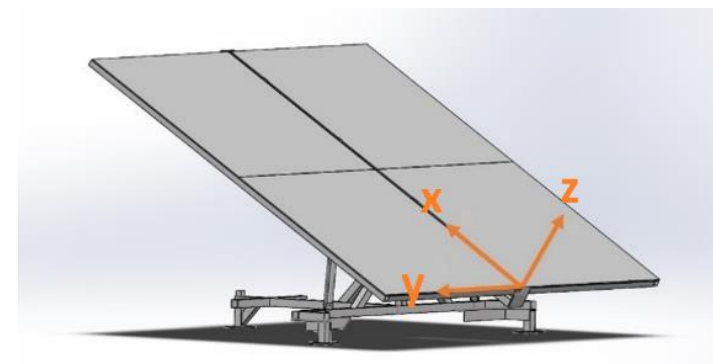
◇ Sensor Network

- » 70 thermocouples ($y = 70$ mm)
- » 16 thermocouples ($x = 1000$ mm)
- » 4 bi-directional velocity probes ($y = 0$ mm)
- » 3 heat flux sensors ($y = 0$ mm)



Plane ($y=70$ mm) and ($y=0$)

- Thermocouple ($y=70$ mm)
- Bi-directional Pitot tube ($y=0$)
- ▲ Heat flux sensor ($y=0$)



◇ Recorded and Calculated Properties

» Flame Geometry

- Flame Height: H (mm)
- Flame angle: α (°)
- Flame Length: L (mm)

» Thermal Field

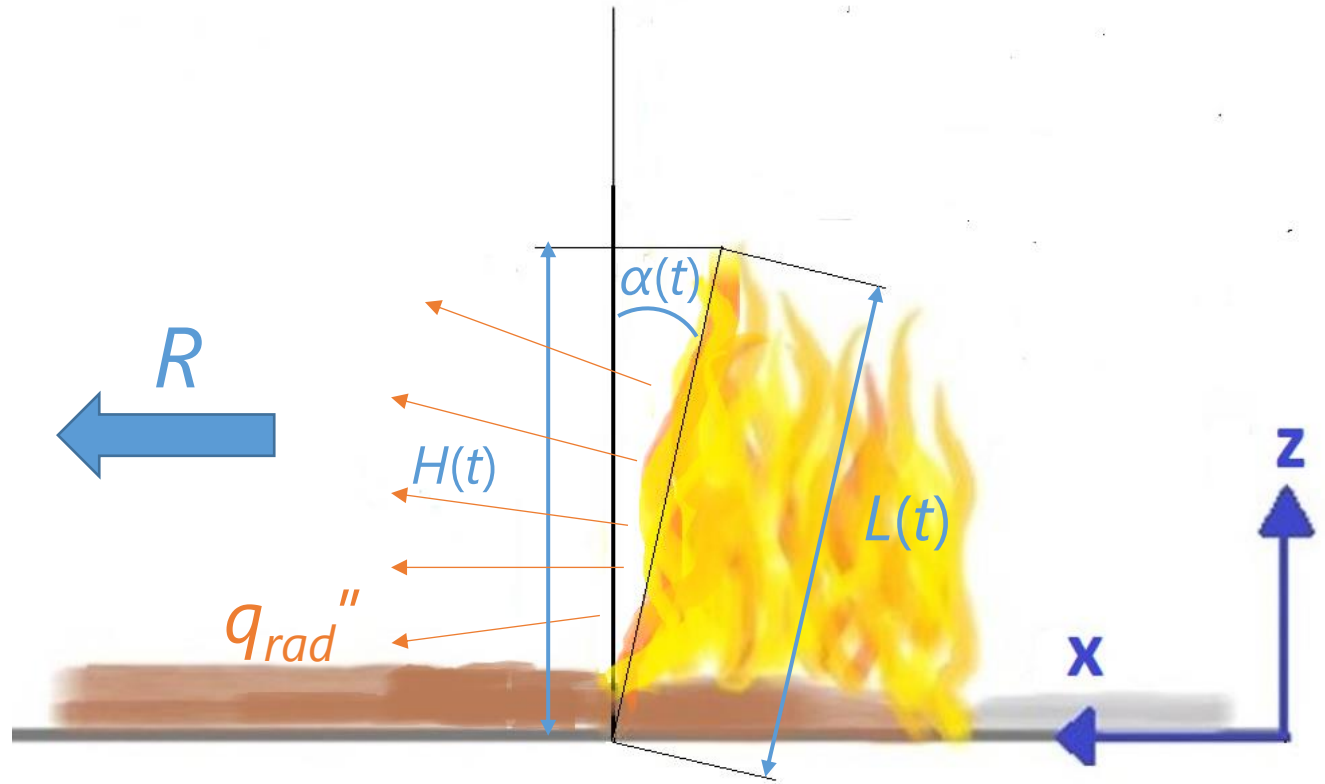
- Radiant Heat Flux: q_{rad}'' (kW/m²)
- Temperature profiles: T (°C)

» Flow Field

- Horizontal velocity profiles: U (m/s)

» Flame Front

- Rate of Spread: R (mm/s)
- Heat Release Rate: Q (kW)



◇ 1st Stage: Point Ignition

- » Focus on **thermal field** and **flame geometry**
- » Investigation of the impact of 3 key parameters
 - **Slope angle**: 0°, 10°, 20°, 30°
 - **Fuel Load** (wet basis): 0.5 and 1.0 kg/m²
 - **Fuel Moisture Content** (wet basis): 1% (oven treated) and 8% (untreated)
- » 6 test cases
- » 10 different fire tests (repeatability tests)

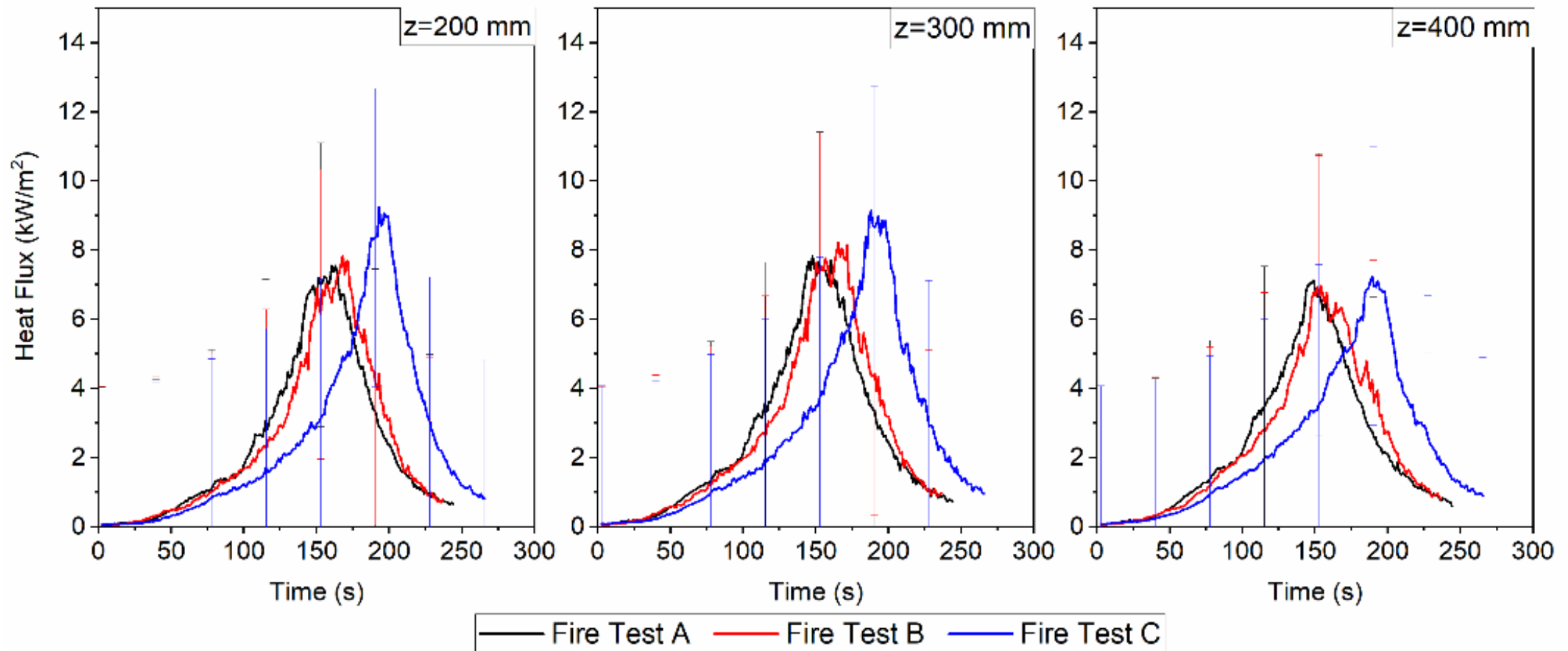
◇ 2nd Stage: Linear Ignition

- » Focus on **fire-induced flows**
- » 4 fire tests (repeatability tests)

Case	FMC	Slope	Fuel load	No. of tests
1	8%	0°	0.5 kg/m ²	x 1
2		10°		x 1
3		20°		x 3
4		30°		x 1
5	1%	0°	1.0 kg/m ²	x 3
6		0°		x 1

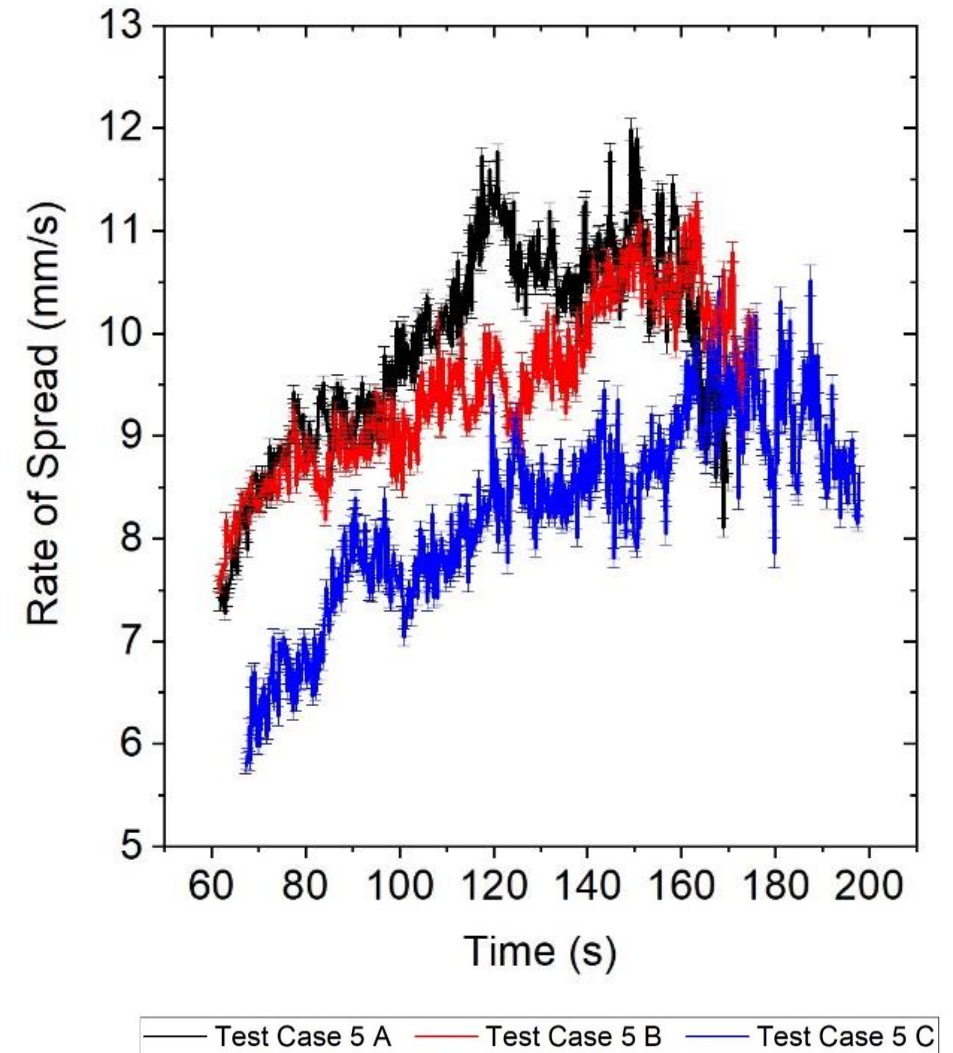
◇ Test Case 5 (0° Slope, 0.5 kg/m², FMC 1%)

» Measured heat flux (q'')



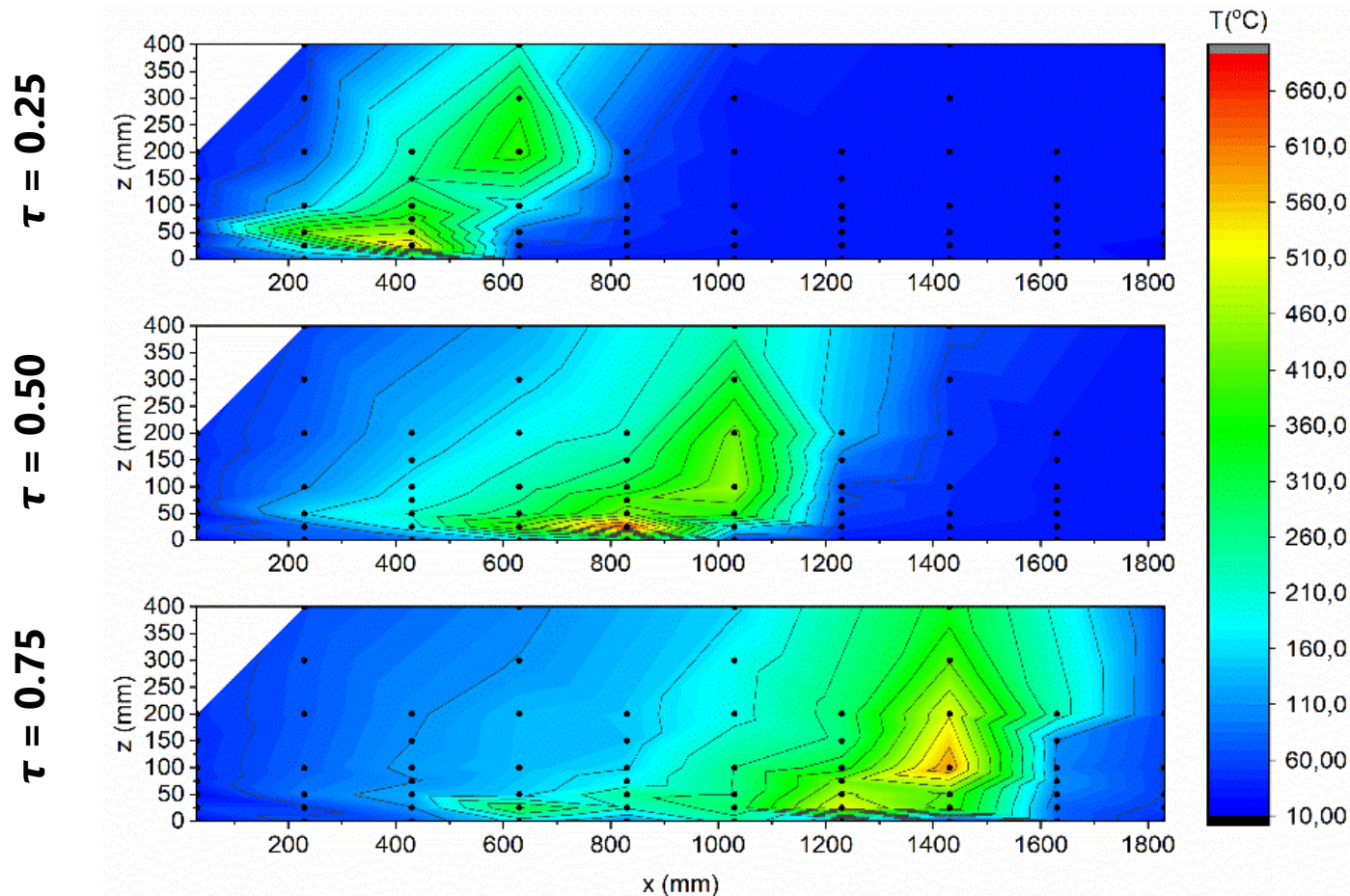
◇ Test Case 5 (0° Slope, 0.5 kg/m², FMC 1%)

- » Estimated Rate of Spread (R)
 - Larger discrepancies in temporal evolution (compared to the heat flux measurements)
 - Attributed to the inherently turbulent nature of the flame → Intense flame fluctuations
 - Similar time-averaged values



◇ Temporal Evolution of Temperature Profiles (Test Case 4)

» Normalized time: $\tau = t/t_{end}$



Temporal evolution of fire front developing at 0° slope angle
(x64 time)



Temporal evolution of fire front developing at 30° slope angle
(x64 time)

◇ Parametric Study: Temperatures ($\tau = 0.25$)

» Increasing Slope (Test Case 1 $\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ 4)

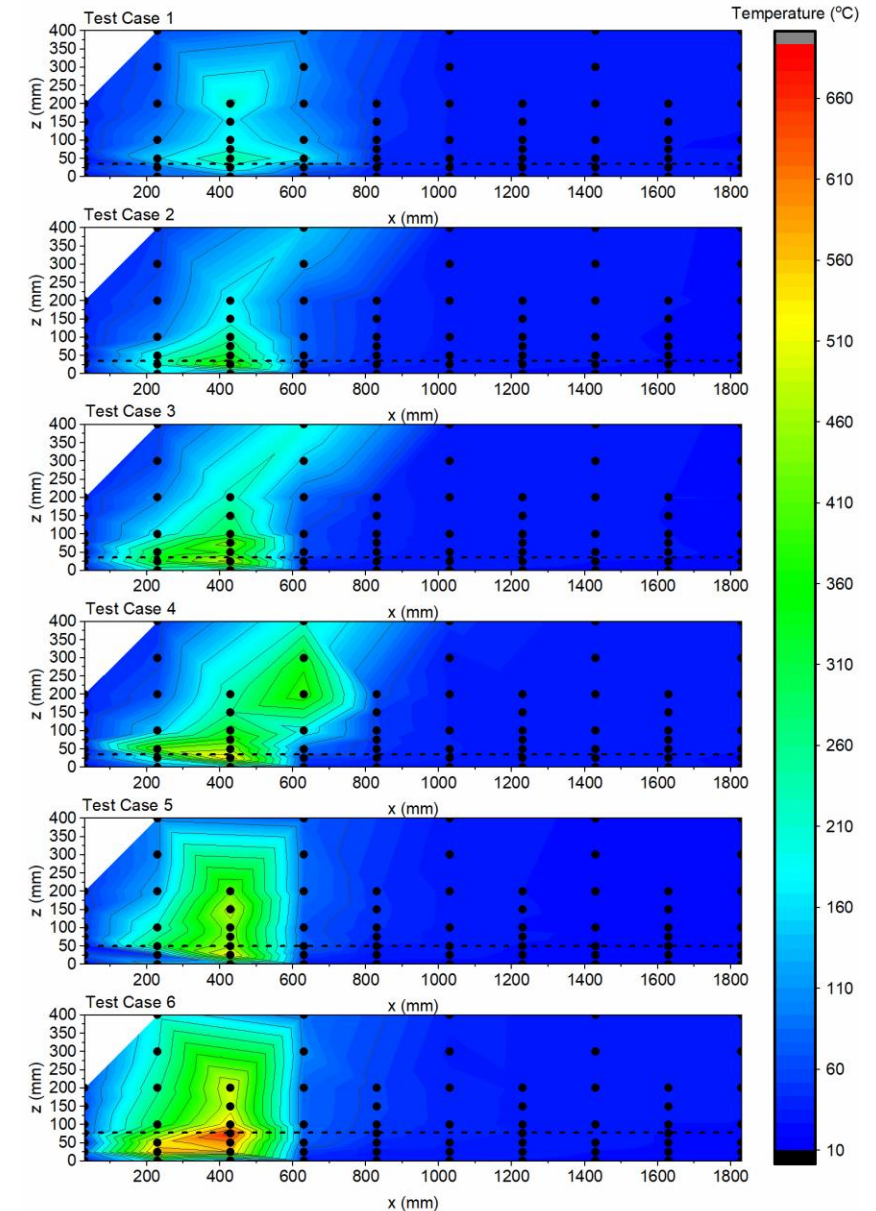
- Slightly increasing temperatures
- The length of the “thermal tail” behind the flame front is increased, due to extended smoldering combustion

» Increasing FMC (Test Case 5 $\rightarrow$ 1)

- Decreasing temperatures (moisture acts as a heat sink)

» Increasing Fuel Load (Test Case 5 $\rightarrow$ 6)

- Increasing temperatures, mainly inside the higher fuel bed



◇ Parametric Study: Temperatures ($\tau = 0.50$)

» Increasing Slope (Test Case 1 $\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ 4)

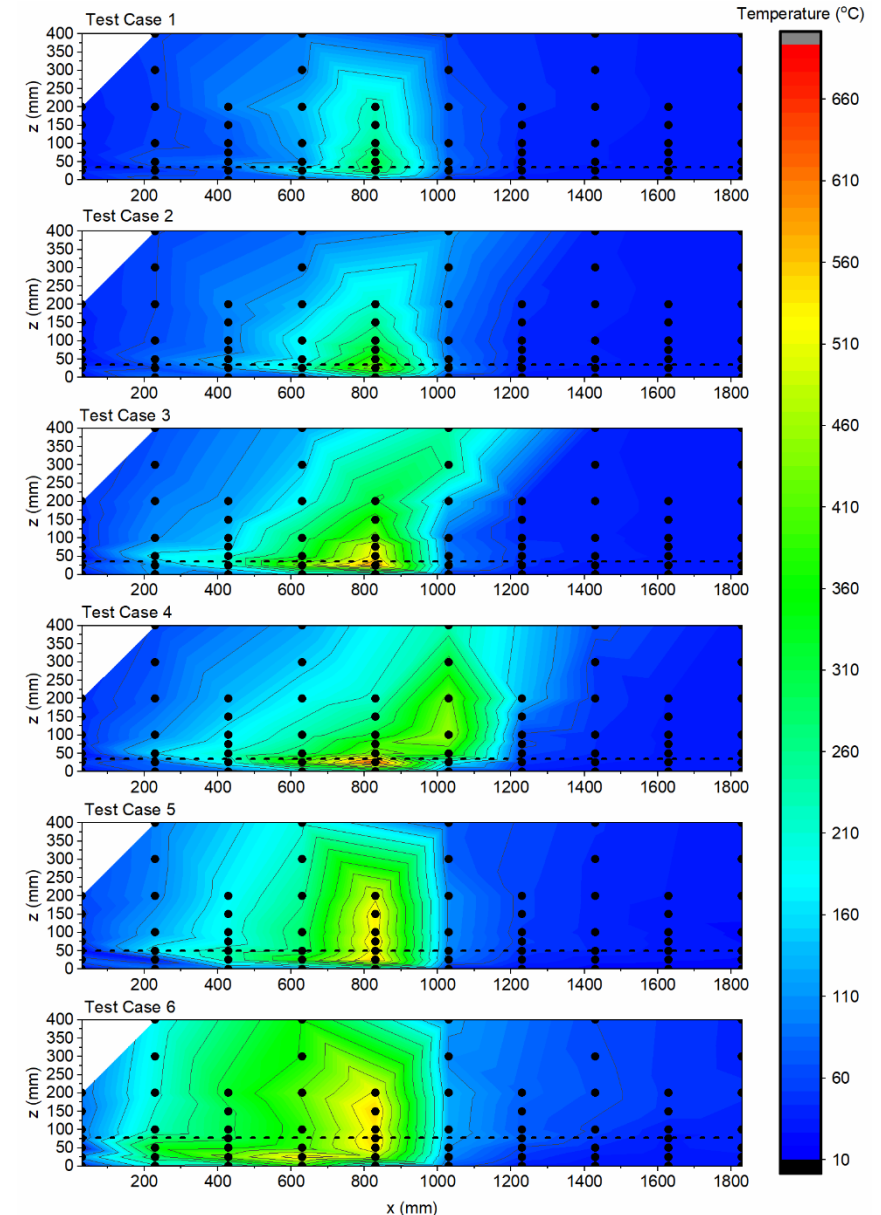
- Slightly increasing temperatures
- The length of the “thermal tail” behind the flame front is increased, due to extended smoldering combustion

» Increasing FMC (Test Case 5 $\rightarrow$ 1)

- Decreasing temperatures (moisture acts as a heat sink)

» Increasing Fuel Load (Test Case 5 $\rightarrow$ 6)

- Increasing temperatures, mainly inside the higher fuel bed



◇ Parametric Study: Temperatures ($\tau = 0.75$)

» Increasing Slope (Test Case 1 → 2 → 3 → 4)

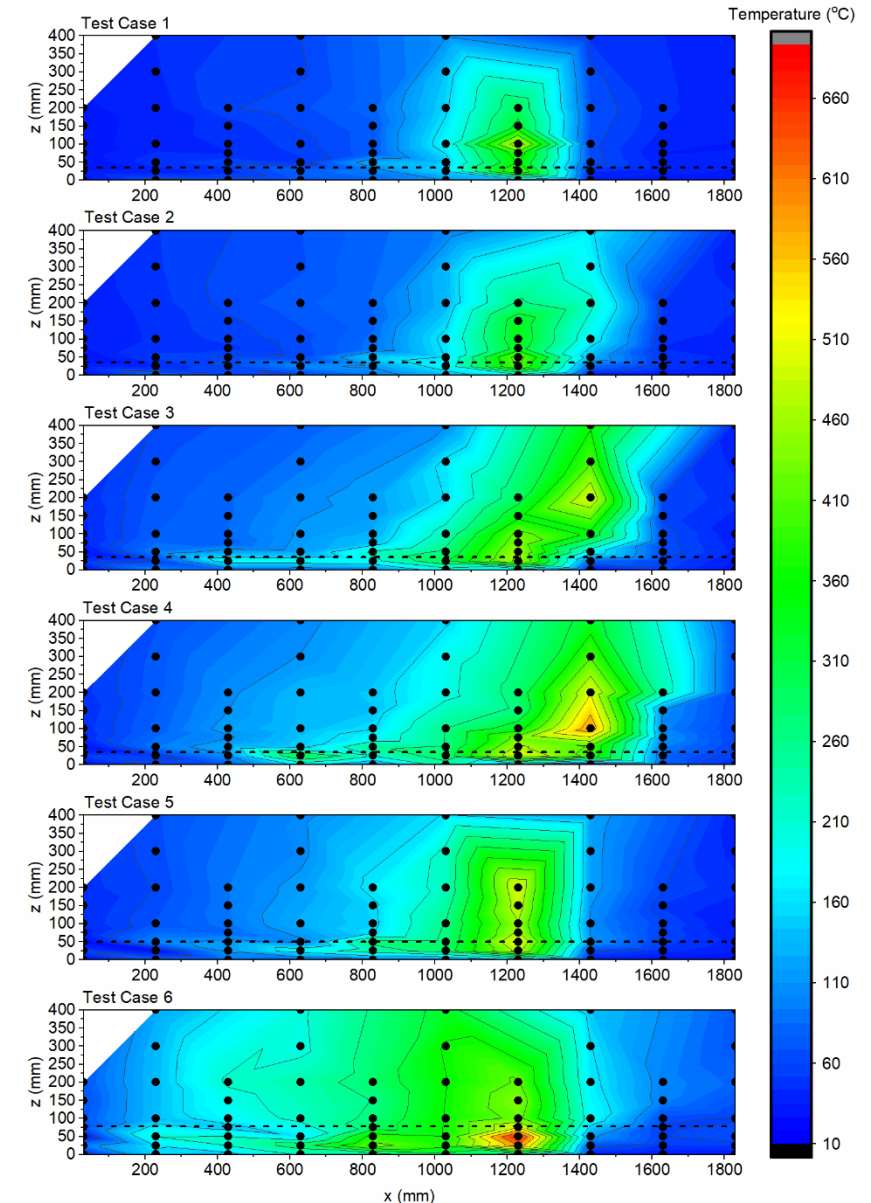
- Slightly increasing temperatures
- The length of the “thermal tail” behind the flame front is increased, due to extended smoldering combustion

» Increasing FMC (Test Case 5 → 1)

- Decreasing temperatures (moisture acts as a heat sink)

» Increasing Fuel Load (Test Case 5 → 6)

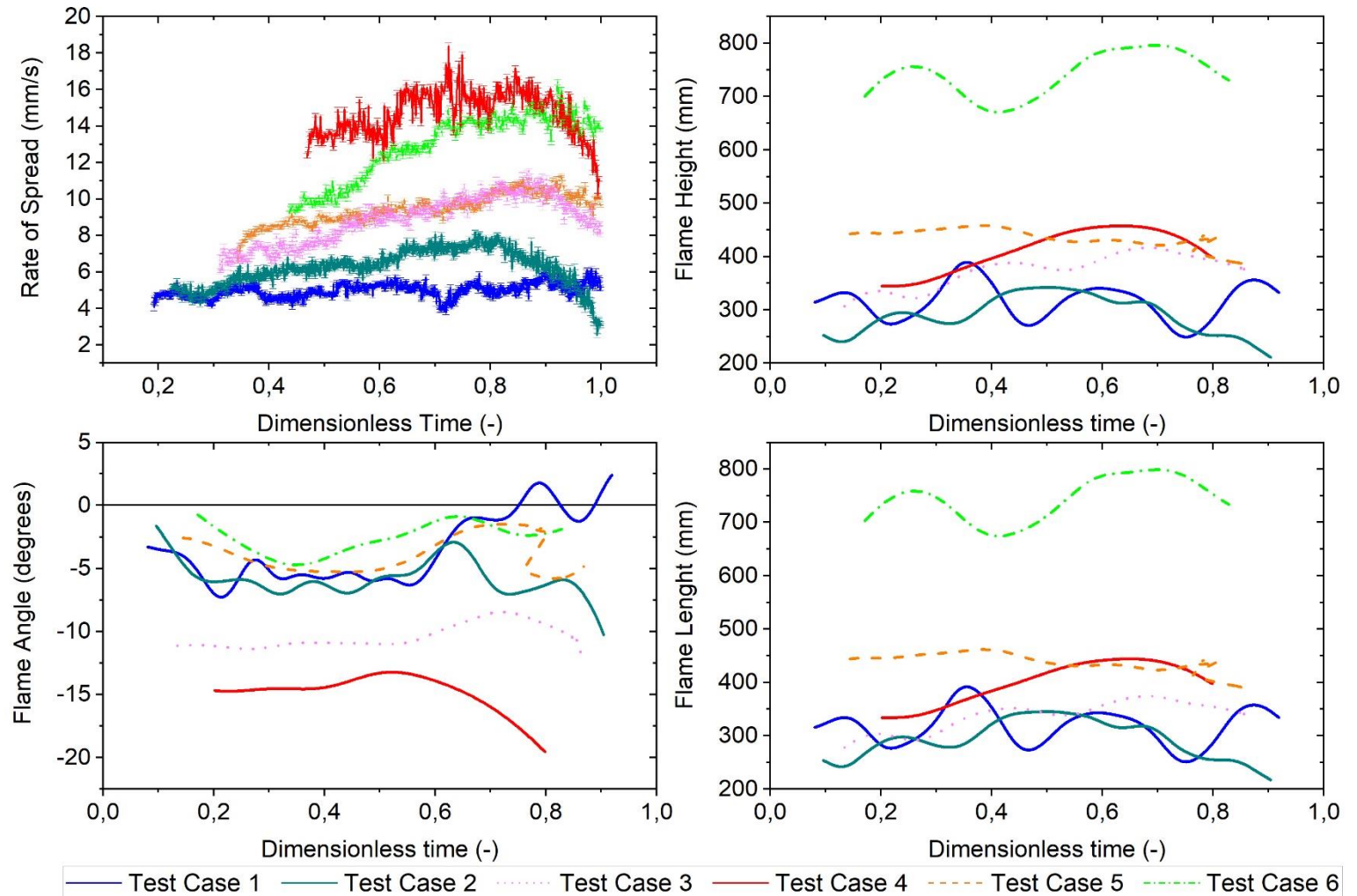
- Increasing temperatures, mainly inside the higher fuel bed



◇ Parametric Study: Rate of Spread and Flame Geometry

» Increasing Slope

- 0° to 10°:
 - » Increase in R
 - » H and α are unaffected
- 10° to 20°:
 - » Increase in R
 - » Slight increase in H
 - » Slight decrease in α
- 20° to 30°:
 - » High increase in R
 - » Increase in H
 - » Decrease in α



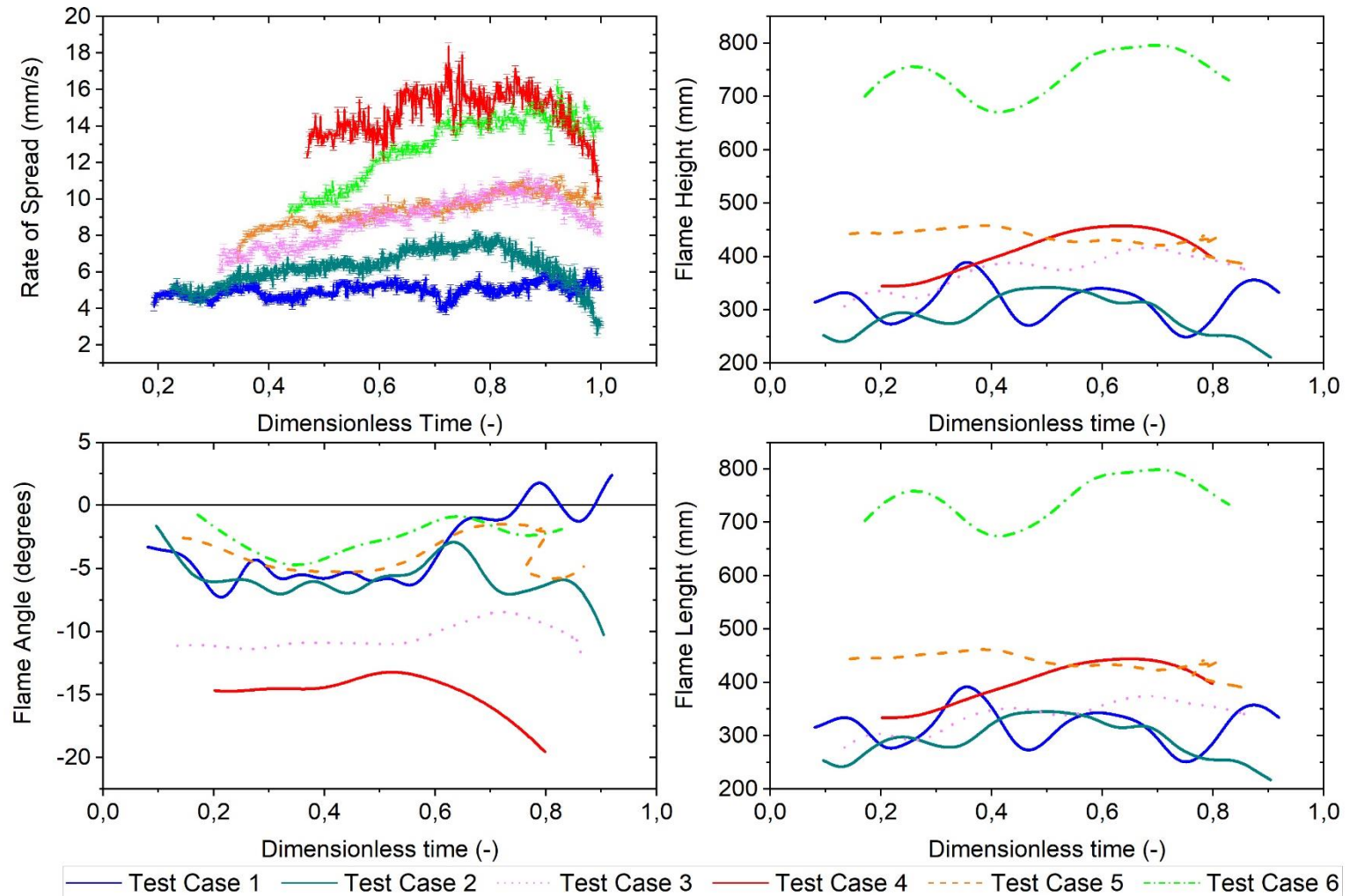
◇ Parametric Study: Rate of Spread and Flame Geometry

» Increasing FMC

- From 1% to 8%
 - » Decrease in R
 - » Decrease in H
 - » α is unaffected

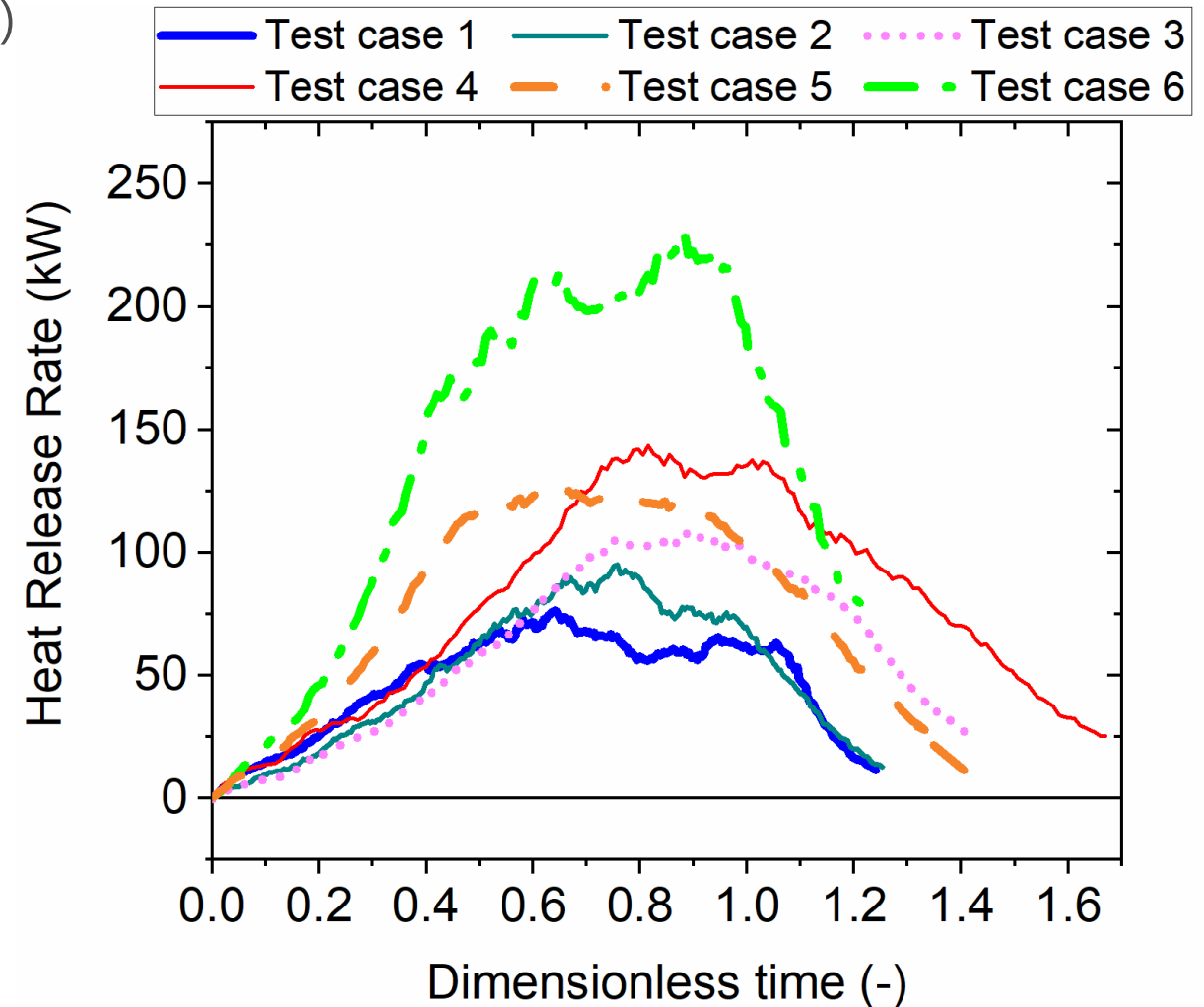
» Increasing Fuel Load

- From 0.5 to 1.0 kg/m²
 - » Increase in R
 - » Increase in H
 - » α is unaffected



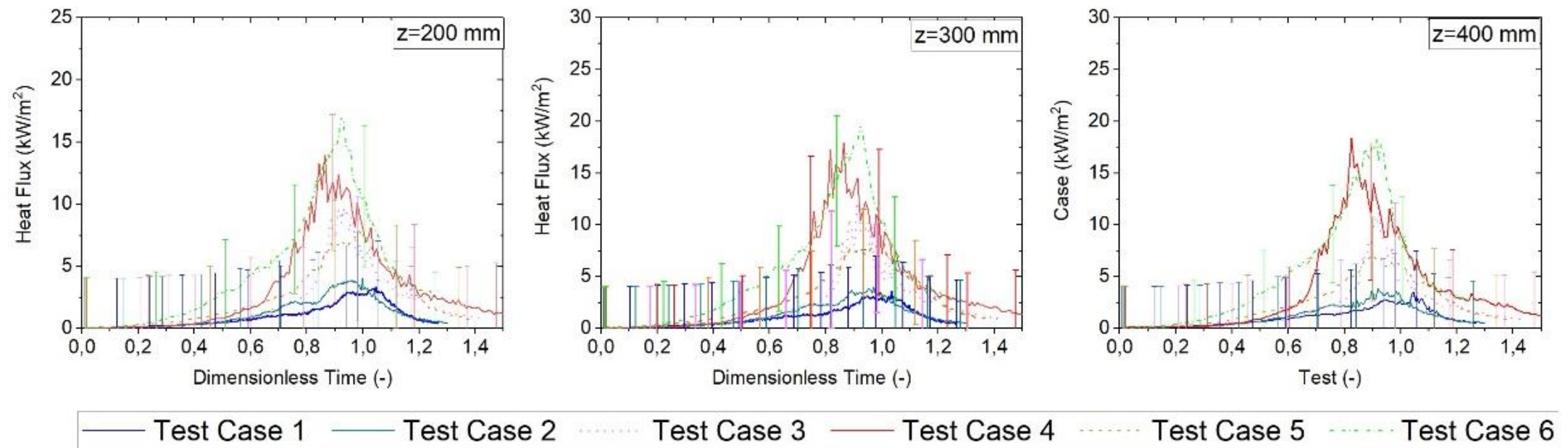
◇ Parametric Study: Heat Release Rate

- » **Increasing Slope (Test Case 1 → 2 → 3 → 4)**
 - HRR increases
- » **Increasing FMC (Test Case 5 → 1)**
 - The HRR peak value is decreased by ~65%
- » **Increasing Fuel Load (Test Case 5 → 6)**
 - Significant increase of the HRR



◇ Parametric Study: Heat Flux

- » **Increasing Slope:** Increasing heat flux, due to decreasing flame tilt angle (angle between the flame front and the terrain)
- » **Increasing FMC:** Decreasing heat flux
- » **Increasing Fuel Load:** The heat flux is almost doubled when the fuel load is doubled, mainly attributed to the increase of flame height



◇ Increasing Slope

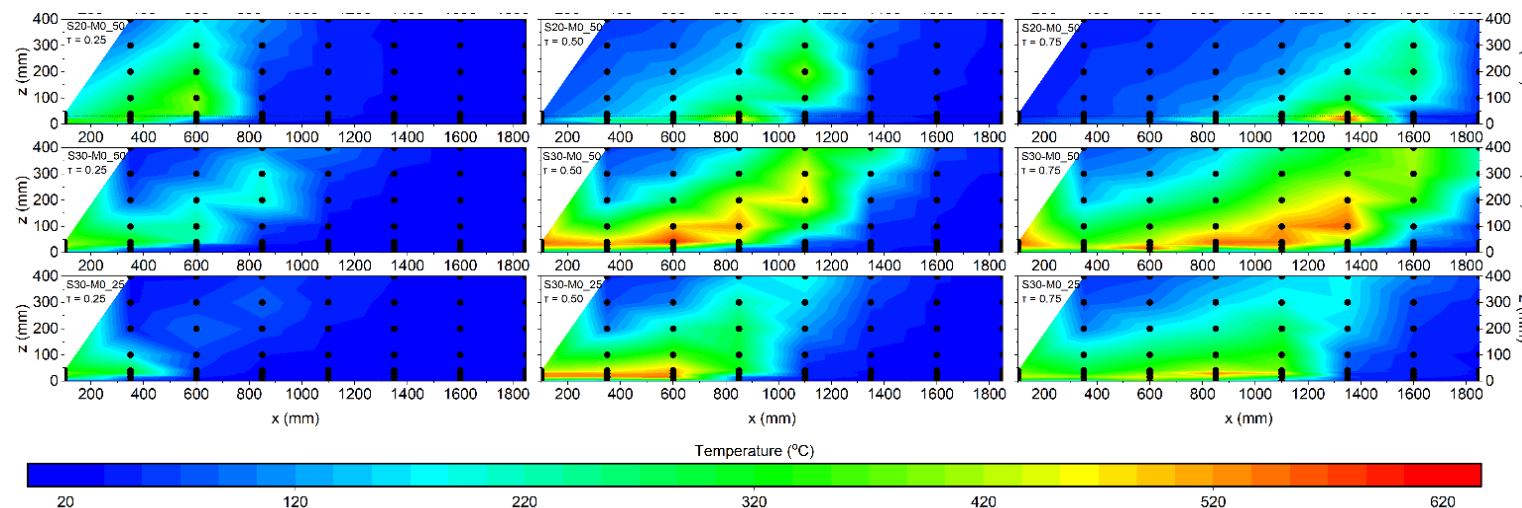
- » Increasing R
- » Increasing HRR
- » Increasing heat flux

◇ Increasing Fuel Load

- » Increasing R
- » Increasing HRR
- » Increasing heat flux
- » Increasing flame height

◇ Increasing FMC

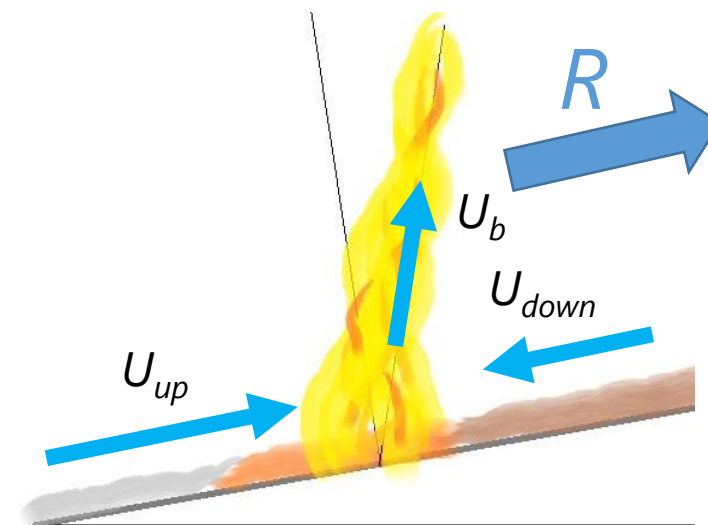
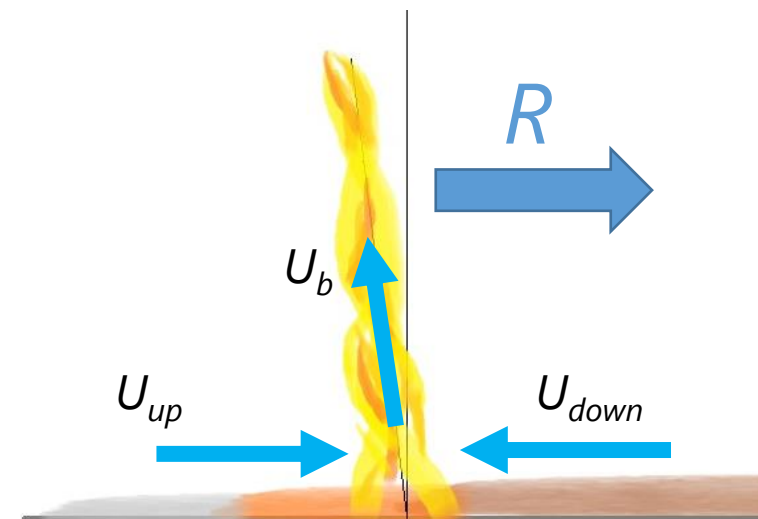
- » Noticeable decrease in all the above quantities



Increase in	ROS	HRR	Heat Flux	Flame Height	Flame Angle
Slope	↗	↗	↗	(↗)	(↘)
Fuel Load	↗	↗	↗	↗	-
FMC	↘	↘	↘	↘	-

◇ Fire-Induced Flows

- » **Thermal buoyant flow:** Hot combustion product stream
- » **Air entrainment flows** appear upstream (U_{up}) and downstream (U_{down}) of the flame front
 - **Stationary flame:** Symmetrical flows ($U_{down} = U_{up}$)
 - **Advancing flame front:** Asymmetrical flows ($U_{down} > U_{up}$)
 - » Smoldering region behind the flame front
- » **Horizontal Terrain**
 - The downstream entrainment flow cools the unburnt fuel
- » **Sloped Terrain**
 - The upstream flow can introduce an acceleration-deceleration cycle of fire spread

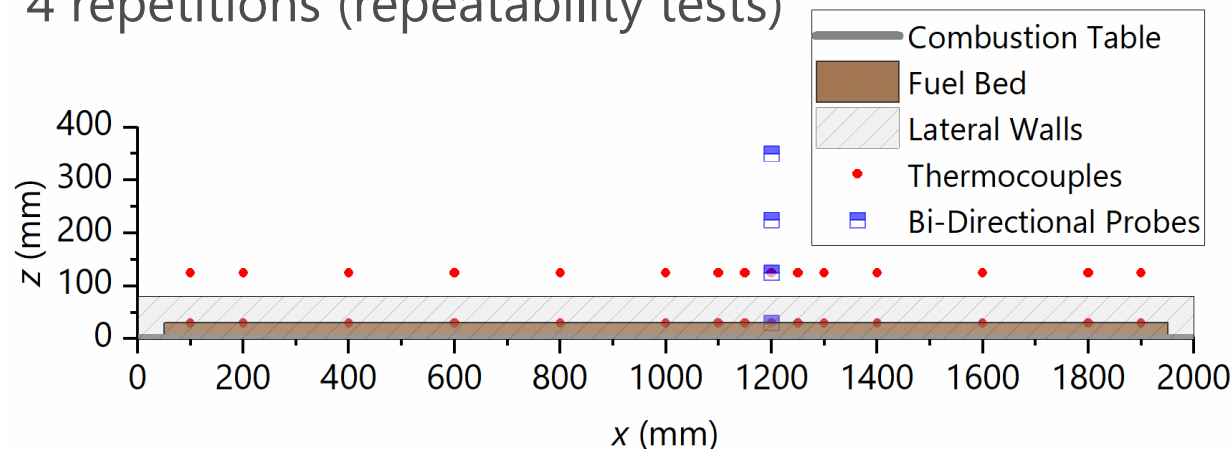


◇ Main Aim

- » Experimental characterization of the developing entrainment velocities upstream and downstream of an advancing flame front as a function of height (z)

◇ Inclinable Combustion Table

- » Area: 2 m x 1 m
- » Linear ignition
- » Lateral walls to simulate an “infinite linear front”
- » 4 repetitions (repeatability tests)

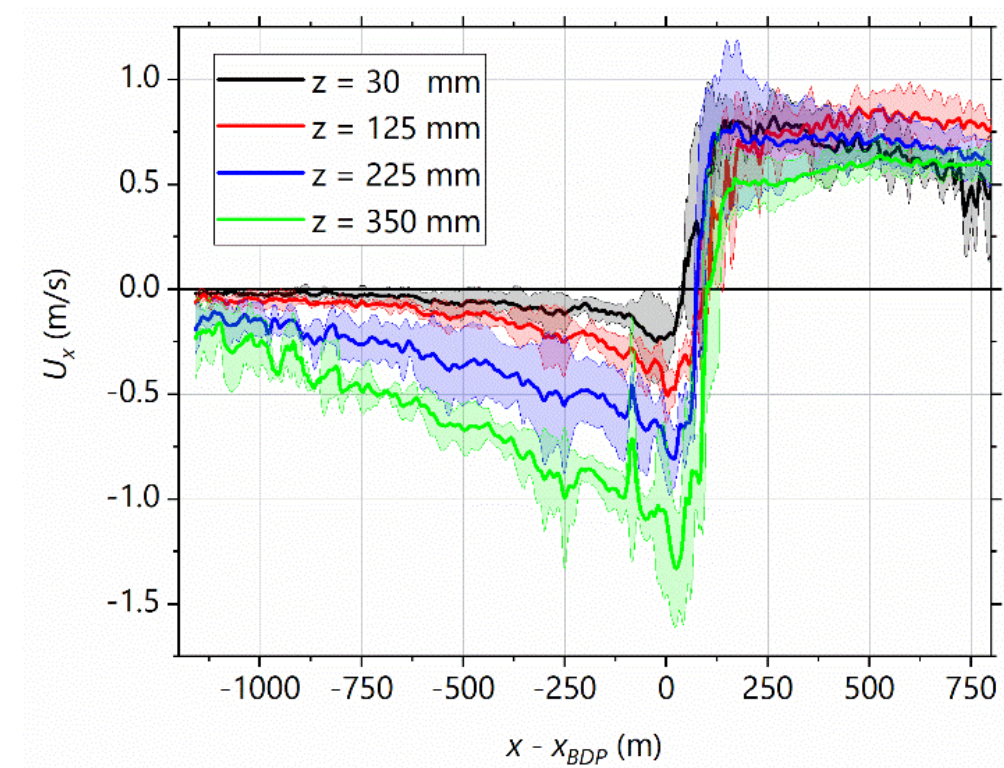
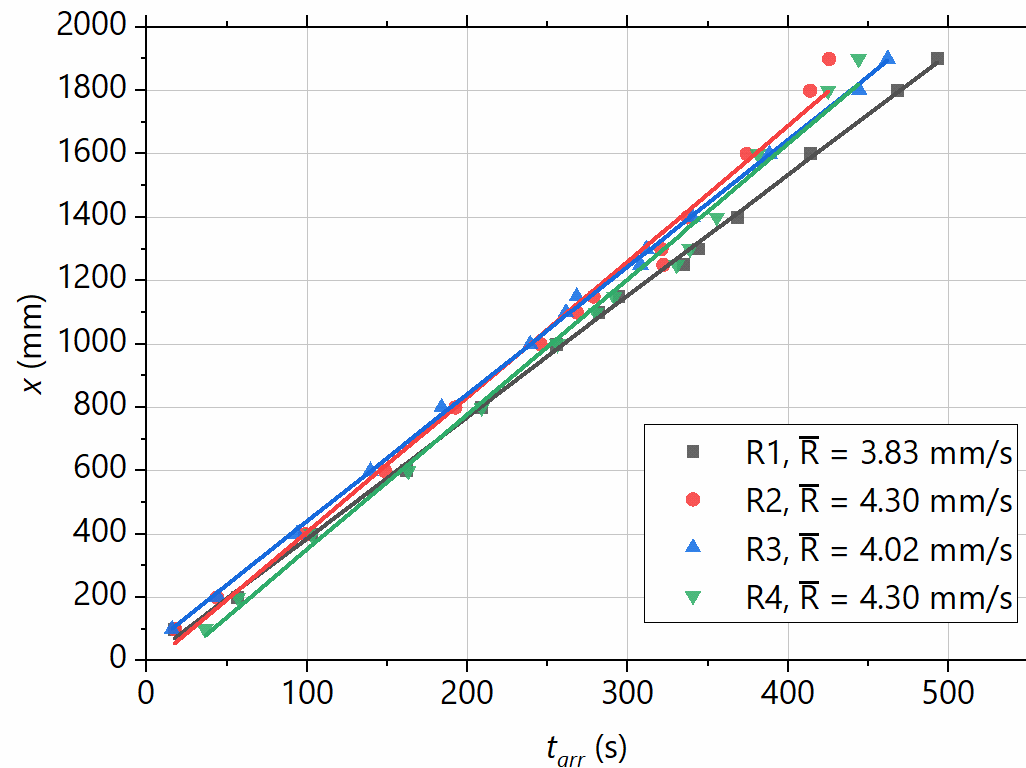


◇ ROS estimation

» Small discrepancies among 4 repeatability tests

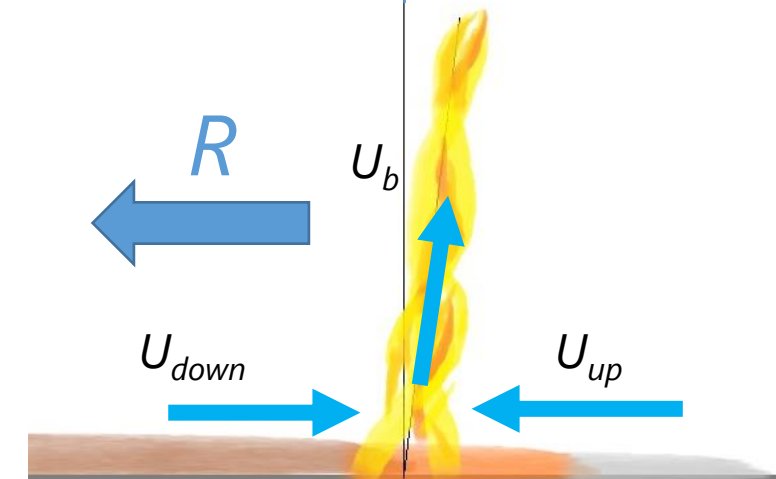
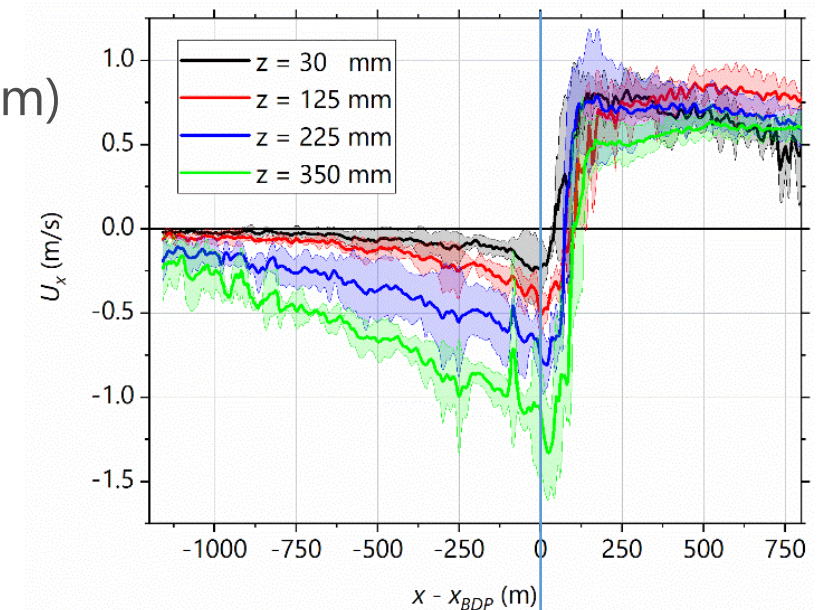
◇ Velocity measurements

» Average values and measurement uncertainties



◇ Vertical profile of Axial Velocities

- » $x - x_{BDP}$: Distance between flame and BDP ($x_{BDP} = 1200$ mm)
 - **Positive values:** BDP upstream of flame front (U_{up})
 - **Negative values:** BDP downstream of flame front (U_{down})
- » U_x : Axial velocity
 - **Positive values:** Direction of flame spreading
 - **Negative values:** Direction against flame spreading



◇ Absolute Values

» Generally, $|U_{down}| < |U_{up}|$ (except @ $z = 350$ mm)

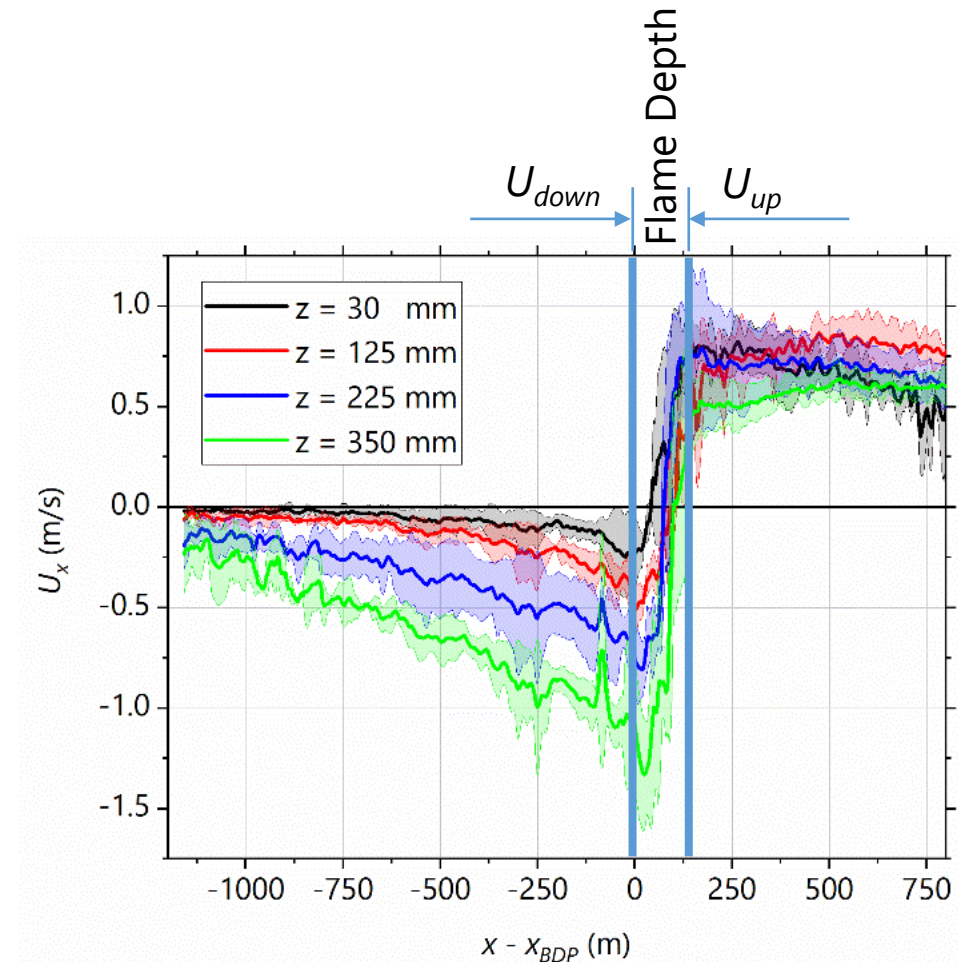
◇ Vertical Profile

» U_{down} increases with height

» U_{up} seems relatively insensitive to height

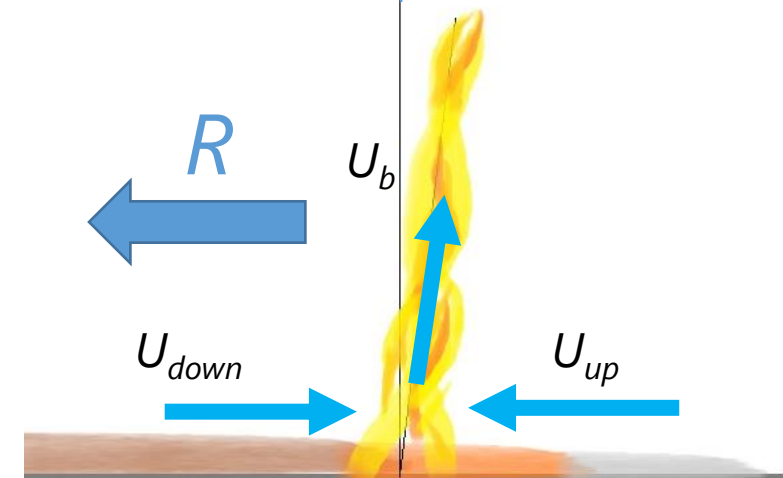
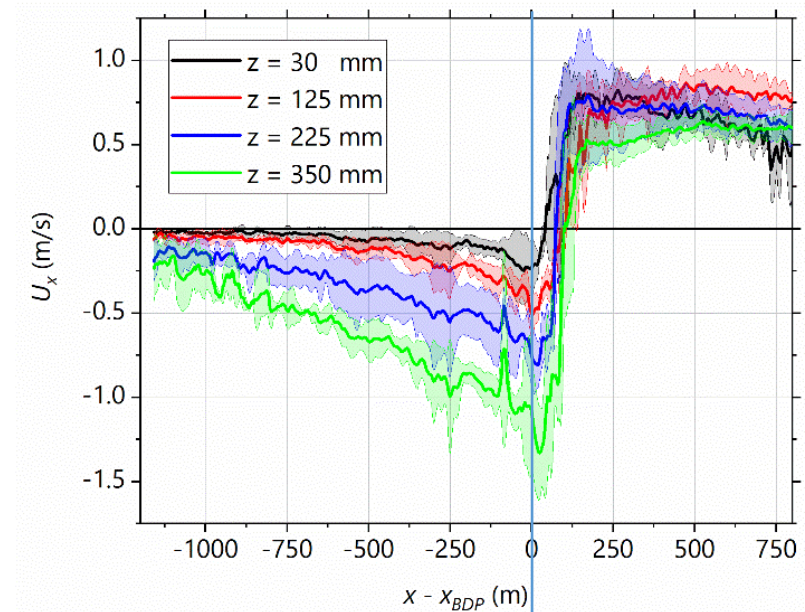
◇ Horizontal “entrainment influence range”

» For U_{down} , the distance from the flame that the entrainment flow is non-zero increases with height → Flame plume diameter increases with height



◇ Asymmetry of Entrainment Flows

- » U_{down} : Velocity magnitude and horizontal “entrainment influence range” increase with height
- » U_{up} : Velocity magnitude is relatively insensitive to height
- » The observed asymmetry is most likely owed to the smoldering region behind the flame front, resulting in higher temperatures



◇ NTUA – Athens, Greece (27/10/2006)

- **J.C. del Alamo**, The large-scale organisation of turbulent channels (Winner)
- **K. Argyriadi**, Liquid film flow: effects of disturbance characteristics and wall morphology
- **P. Schlatter**, Large-eddy simulation of transition and turbulence in wall-bounded shear flow
- **D. Kolaitis**, Development of computational tools for multiphase, multi-component, reactive flows-application to cool flames
- **T.U. Werder**, Multiscale simulation of Carbon nanotubes in aqueous environments



◇ D. Kolaitis

- » Tel. (+30) 210-7724002
- » e-mail: dkol@central.ntua.gr
- » Laboratory of Heterogeneous Mixtures and Combustion Systems
- » Building O, School of Mechanical Engineering, NTUA
- » Iroon Polytechnείου 9, Zografou 15772, Athens, Greece



$S = 0^\circ$, $R_{mean} = 3.7$ mm/s



$S = 20^\circ$, $R_{mean} = 9.8$ mm/s



$S = 30^\circ$, $R_{mean} = 40$ mm/s