**SERDP**

**INTERIM REPORT**

# A Multiscale Study of the Coupling Between Flow, Fire and Vegetation – Influence of Vegetation Distribution and Flow on Fire Behavior and Plume Development for Risk Mitigation in Prescribed Burns

Albert Simeoni
Muthu Selvaraj
***Worcester Polytechnic Institute***

Nicholas Skowronski
William Mell
Michael Gallagher
***US Forest Service***

Rodman Linn
***Los Alamos National Laboratory***

Craig Clements
***San Jose State University***

Rory Hadden
***University of Edinburgh***

**January 2024**

**SERDP Project RC20-1362**

**DISTRIBUTION STATEMENT A**
This document has been cleared for public release.

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*

**1. REPORT DATE** *(DD-MM-YYYY)*
03/01/2024

**2. REPORT TYPE**
SERDP Interim Report

**3. DATES COVERED** *(From - To)*
12/5/2020 - 12/15/2024

**4. TITLE AND SUBTITLE**
A Multiscale Study of the Coupling Between Flow, Fire and Vegetation – Influence of Vegetation Distribution and Flow on Fire Behavior and Plume Development for Risk Mitigation in Prescribed Burns

**5a. CONTRACT NUMBER**
21-C-0005

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Albert Simeoni and Muthu Selvaraj: Worcester Polytechnic Institute
Nicholas Skowronski, William Mell and Michael Gallagher: US Forest Service
Rodman Linn: Los Alamos National Laboratory
Craig Clements: San Jose State University
Rory Hadden: University of Edinburgh

Doug Aubrey

**5d. PROJECT NUMBER**
RC20-1362

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Worcester Polytechnic Institute
Fire Protection Engineering
50 Prescott St.
Worcester, MA 01605

**8. PERFORMING ORGANIZATION REPORT NUMBER**
RC20-1362

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Office of the Deputy Assistant Secretary of Defense (Energy Resilience & Optimization)
3500 Defense Pentagon, RM 5C646
Washington, DC 20301-3500

**10. SPONSOR/MONITOR'S ACRONYM(S)**
SERDP

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
RC20-1362

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

The project will address the following fundamental questions:

- How does the variability in vegetation structure and vegetation distribution at multiple scales influence fire and plume dynamics with regard to heat transfer and drag?
- How do fuel structure, distribution, age and seasonality influence fire dynamics and plume development in the field for different burn intensities?
- What physical processes are most relevant at different scales (thermal transfer, flow through vegetation, fire spread in heterogeneous fuels, near-field plume development, etc.)?

**15. SUBJECT TERMS**
wildland fires, Installation resilience, habitat, fire, Vegetation Distribution, Fire Behavior, Plume Development, Risk Mitigation, Prescribed Burns

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** |
|---|---|---|---|---|---|
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | | | Albert Simeoni |
| UNCLASS | UNCLASS | UNCLASS | UNCLASS | 20 | **19b. TELEPHONE NUMBER** *(Include area code)*<br>508-831-6333 |

**Standard Form 298** (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

# Index

# List of Figures

## 1. Objective

This project will fully respond to the first and third research objectives of the Statement of Needs: “Improve understanding of physical fire processes at spatial and temporal scales relevant to plume dynamics, fire behavior, and spotting” and “Advance understanding of fuel dynamics and structure, especially fuel moisture dynamics and the importance of fuel heterogeneity as it relates to fire intensity, ember production, emissions, and crown fire,” respectively. The specific objectives of the project will be to understand how the variability of vegetation influences fire behavior and plume development at multiple scales through drag and heat transfer. Several experiments will be conducted from the small laboratory scale to the large field scale in order to capture the feedback effects between vegetation, flow, fire and plume development. Then, this understanding will be used to test and improve CFD-based fire spread models. The project aims at developing a combined experimental and numerical platform that will extend the value of field data by completing the experiments by simulations that can systematically vary the critical parameters that influence fire and plume development.

The project will address the following fundamental questions:

- How does the variability in vegetation structure and vegetation distribution at multiple scales influence fire and plume dynamics with regard to heat transfer and drag?
- How do fuel structure, distribution, age and seasonality influence fire dynamics and plume development in the field for different burn intensities?
- What physical processes are most relevant at different scales (thermal transfer, flow through vegetation, fire spread in heterogeneous fuels, near-field plume development, etc.)?

## 2. Approach

A four-component approach is proposed to study the phenomena of interest for this call: small-scale laboratory experiments, large-scale laboratory experiments, field experiments, and multi-scale modeling. The approach will focus on the influence of vegetation on 1) the fluid dynamics in the vicinity of the combustion zone, 2) the fluid dynamics in the far field upstream and above the combustion zone, and 3) the coupling with thermal transfer and fire spread. The methodology underlying this project will be to first isolate the vegetation effects on drag and heat transfer within flow environments typical of prescribed fires and develop new understanding of the aspects of the vegetation that influence them. These components will then be systematically recombined to understand and characterize their multi-scale feedback with one another and how they impact fire behavior and plume core development. The approach will specifically seek to simplify known sources of uncertainty generated by the burning of natural vegetation to increase the repeatability of data gathered in a way relevant to the project objectives and to allow greater control of the range of fire intensities studied. An iterative approach is proposed between the laboratory scale, field burns, and modelling components that extends lessons learned from previously funded SERDP research (SERDP 2016). Figure 1 describes how the project will be organized to solve increasingly complex flow problems at different scales and how the activities will be linked together.

Figure 1: Overall project organization

## 3. Static pool fire tests – characterization of buoyant plume

The project focuses on using pool fires as a source for the buoyant plume at the lab- and field-scales. Pool fires were chosen as a fire source for two reasons: (1) The fire intensity can be easily controlled by varying the number of pans and their configuration and (2) Fuel flexibility (a wide range of fuels/fuel-mixtures can be used). The pool fires were fueled by a mixture of canola oil and diesel (1 gallon + 1 gallon). The fuels were chosen because the mixture had a steady burning rate of at least 10 minutes (canola oil burns slowly) while generating enough volume of sooty buoyant plume (diesel plumes are sooty enough to be visible in daylight, an important requirement in field experiments).

The objective of this project is to understand the influence of flow and fire on plume development and its interaction with vegetation. The distribution of vegetation also affects plume transport and dispersion. Therefore, the buoyant plume must be characterized before its interaction with vegetation. In this study, a series of point measurements of temperature, velocity, and heat flux have been carried out at several locations in the fire- and plume-zone above a laboratory-scale static pool fire. These experiments were conducted in the Fire Protection Engineering Laboratory at Worcester Polytechnic Institute (WPI).

## 4. Experimental Methodology

A rectangular pan with dimensions of 68 cm × 63 cm × 6.3 cm was used to generate a (diesel + canola oil, 1:1 by volume) pool fire. The rectangular shape has been chosen for generating larger fires in the future, by simply placing multiple pans together. Figure 2 presents a schematic and photograph of the experimental setup. The pan was filled with 2 gallons (7.56 liters) of fuel mixture to provide a steady burning time of around 10 min. The pan was placed over a load cell with an accuracy of 0.1 g for measuring the mass loss rate of the burning fuel. K-type thermocouple with a bead diameter of 0.5 mm were used for measuring the temperature in the flame and plume zones. Velocity measurements were carried out using bi-directional pressure probe. Heat flux sensors (both convective and radiative) were used for measuring the convective and radiative heat flux from the flame. The thermocouples and bi-directional pressure probes were located along the vertical direction (z-axis) 0.5 m from the ground and in arrays up to 3.75 m (see Fig. 2), while the heat flux sensors were located at 1.25, 1.75 and 2.25 m from the ground and were offset by 1.5 m in the y-direction (Fig. 2b). In the horizontal plane (x-axis), four arrays of thermocouples (a total of eleven thermocouples spaced by 15 cm in each array) were fixed at heights of 1.25, 2.25, 3.25, and 3.75 m from the ground. Similarly, two bi-directional pressure probes were located on each horizontal plane (8 in total) spaced 30 cm apart from either side of the central probe. Since the boiling point of the fuel mixture is quite high, a small amount (150 ml) of gasoline was added to the pool prior to ignition to facilitate the process. The pool ignited within two seconds when using a propane torch. Two different configurations, namely, a single pan and two pans placed together were tested. All the experiments were repeated thrice to ensure repeatability. Four Go-Pro cameras (two on the front-view and two on the side view) were located around the fire to capture the flame height and plume dynamics in the intermittent and plume zones.

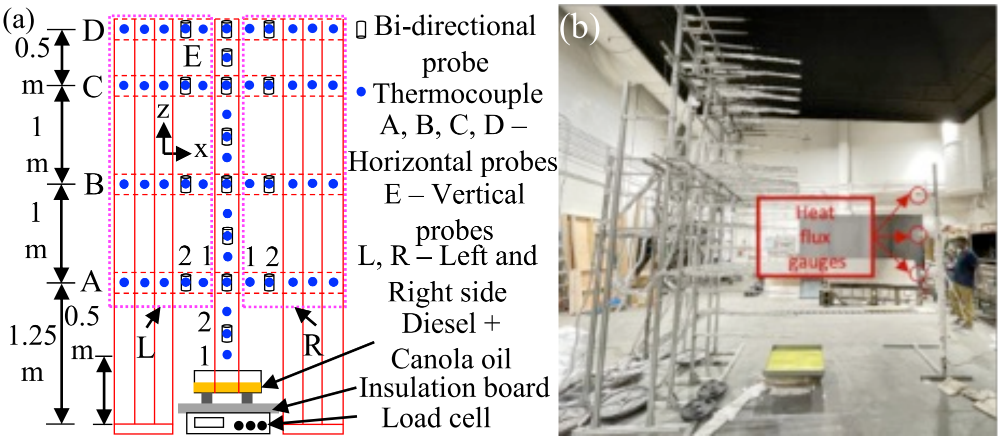

Figure 2: (a) Schematic (front view) and (b) Direct photograph (Side view) of experimental setup

## 5. Results and Discussion

### *5.1 Single pan experiments*

The instantaneous mass loss rate of fuel mixture is presented in Fig. 3a. Time zero denotes ignition. The fire develops slowly before attaining a steady burning rate (steady state 1) of around 8.3 g/s about 90 s after ignition. This mass loss rate (MLR) remains constant until 300 s after which a notable increase in MLR is observed. The MLR remains steady (steady state 2) around 9.3 g/s for the next five minutes (until 600 s). After the initial flame development regime, the fuel surface attains temperatures close to the boiling point of the mixture thus attaining a steady burning state 1. As the fuel is consumed, the thickness of the fuel layer decreases, and bulk boiling of the pool occurs due to conductive transfer. Hence, the MLR increases to a higher steady state value. Further in time, the MLR decreases until the flame is extinguished after 900 s.

A comparison of measured (time averaged) centerline temperature is plotted along with McCaffrey correlation for pool fires [1] as shown in Fig. 3b. The temperatures are averaged for a steady state burning duration of 240 s (120 s – 300 s). The data correlates well with the McCaffrey correlation in the continuous flame and the plume zones. In the intermittent flame regime, the correlations overpredict the experimental data.

Figure 4 shows the flame photographs and measured flame height over a steady state burn period of 120 s (120 s – 240 s). An in-house MATLAB code is used for image processing. It is observed that the continuous flame region is around 0.72 m high from the pan lip. The maximum and average flame height are around 1.2 m and 0.9 m, respectively. The intermittent flame height (with 50% intermittency) is 0.78 m.

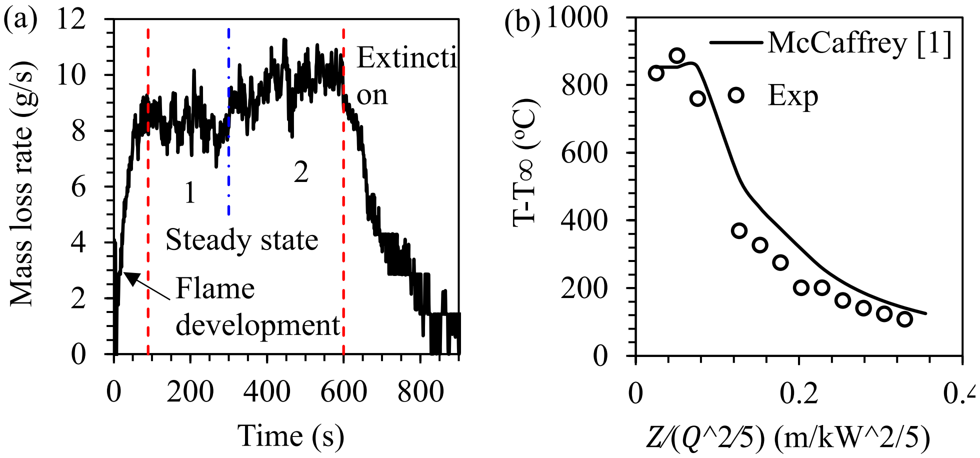

Figure 3: (a) Mass loss rate of canola oil – diesel mixture in a single pan pool fire as a function of time, (b) comparison of measured (symbols) centerline temperature (2 min. – 5 min.) with McCaffrey correlation [1]

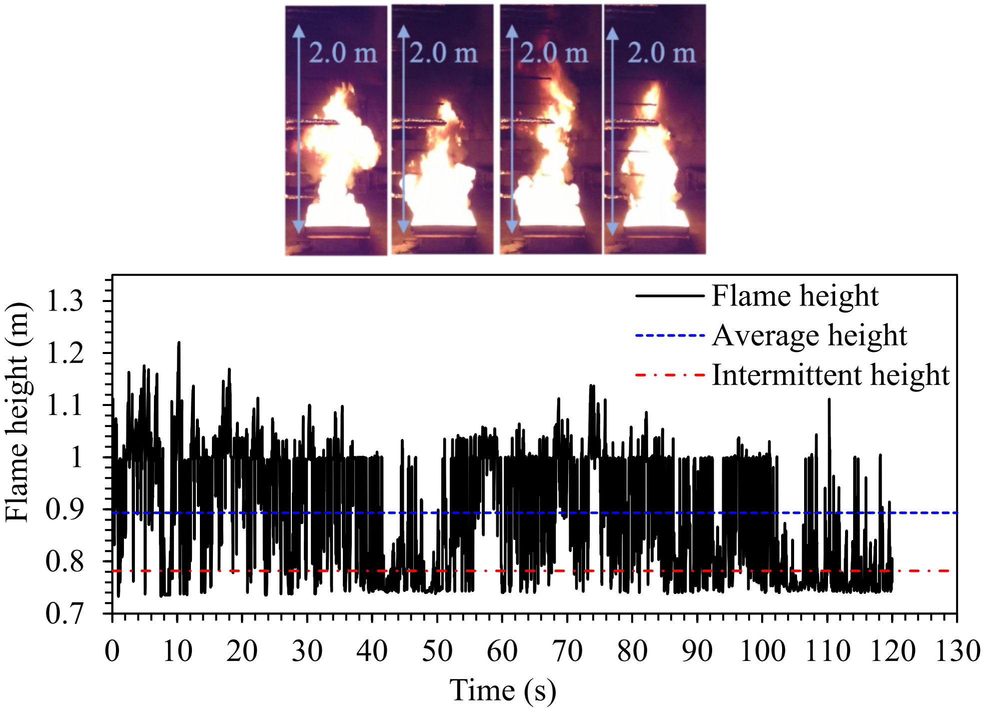

Figure 4: (Top) Photographs of flames at 120 s, 150 s, 180 s, and 240 s, (bottom) measured flame height in a single pan pool fire from image analysis (120 s – 240 s)

Figure 5a shows the temporal variation of measured temperature along the flame centerline. A constant temperature is maintained in the flame zone irrespective of the two steady states. In the intermittent zone, two peaks are observed in the profiles. After ignition, the flame develops slowly until it reaches the first peak temperature corresponding to steady state 1. It then decreases gradually due to the regression of fuel layer. The flame temperature rises again after the bulk boiling is initiated leading to a second peak in the temperature profile. The temperature decreases continuously until the flame is extinguished. A similar trend, but with lower peak values is observed in the temperature profiles in the plume zone (Transient temperature and velocity profiles at different locations can be found in Appendix A).

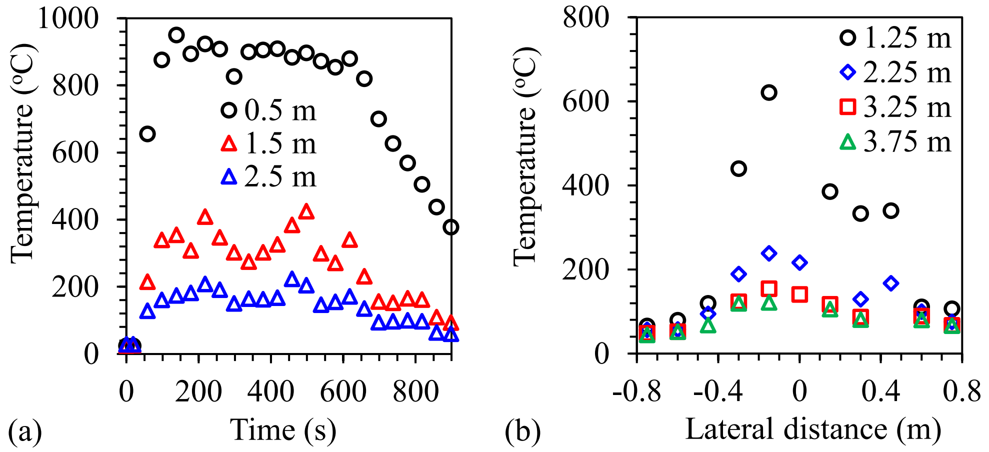

Figure 5: (a) Temporal variation of centerline temperature in the flame (0.5 m), intermittent (1.5 m), and plume (2.5 m) zones, (b) lateral variation of temperature during the steady state (120 s - 300 s) at heights 1.25 m, 2.25 m, 3.25 m, and 3.75 m from the ground.

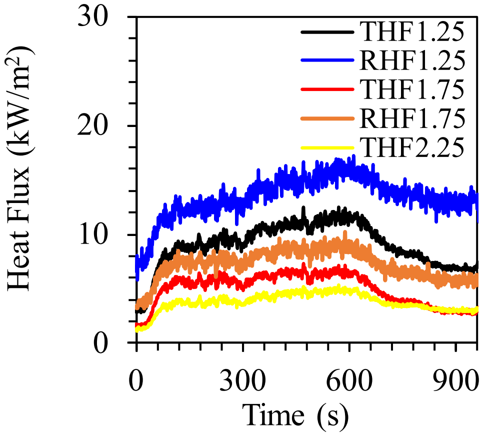

Figure 6: Total heat flux (THF) and radiative heat flux (RHF) profiles in a single pan pool fire at heights 1.25 m, 1.75 m, and 2.25 m. The gauges are located 1.5 m from the center of the pool.

The lateral temperature measurements for a steady state duration of 180 s are presented in Fig. 5b. It is observed that the peak temperatures are slightly offset to the left (negative sign) of the pan. However, the profiles show a gaussian temperature distribution at all locations as observed in the literature [1].

Figure 6 presents the total and radiative heat flux profiles at different heights. It is observed that the radiative heat flux is higher as compared to the total heat flux at all locations. This is expected as the gauges are located 1.5 m away from the center of the pan and the convective cooling by the entrained air reduces the total heat flux incident on the gauge.

### *5.2 Two pan experiments*

The instantaneous mass loss rate of fuel mixture in a two-pan pool fire is presented in Fig. 7a. Time zero denotes ignition. The mass loss rate of pan 1 and pan 2 shows opposite trends. The non-monotonous increase or decrease in MLR is determined by the heat feedback from the flame. The average mass loss rate of each pan is higher as compared to the MLR of a single pan in the experiment. There is no distinct steady state as observed in a single pan pool fire as the burning rate is significantly different for each individual pan.

Figure 7b depicts the measured (time averaged) centerline temperature in two-pan pool fires. The temperatures are averaged for a duration of 180 s (120 s – 300 s) similar to a single pan pool fire. The data shows a similar trend as observed with the McCaffrey correlations [1].

Figure 8 shows the flame photographs and measured flame height in a two-pan pool fire over a burn period of 120 s (120 s – 240 s). It is observed that the continuous flame region is around 0.67 m high from the pan lip. The maximum and average flame height are around 0.95 m and 0.765 m, respectively. The intermittent flame height (with 50% intermittency) is around 0.7 m. It is observed that the continuous, intermittent, and average flame heights are comparatively lower than a single pan pool fire. This may be due to the higher MLR, but reduced air entrainment around the periphery of the pool (since the pans are placed together, the overall perimeter is reduced). This results in an oxygen-starved (fuel rich) scenario leading to the excessive generation of smoke and pyrolysis products. Hence, the visible flame height is lower as compared to a single pan pool fire.

Figure 9a shows the temporal variation of measured temperature along the flame centerline. It is apparent that the temperature is distributed in the flame zone (0.5 m) due to variations in the burning rate of two pans. However, the intermittent and the plume zones show two distinct peaks as observed earlier.

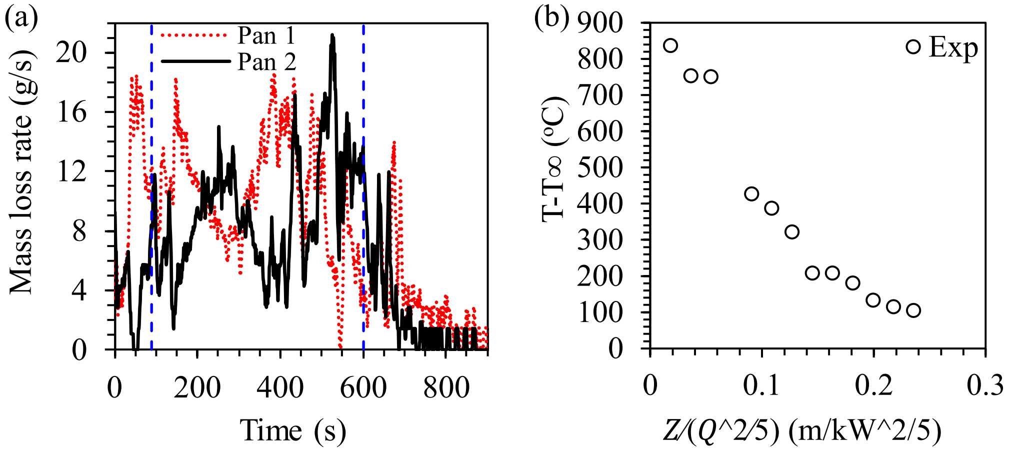

Figure 7: (a) Mass loss rate of canola oil – diesel two pan pool fire as a function of time, (b) measured (symbols) centerline temperature during the burn duration of 180 s (2 min. – 5 min.)

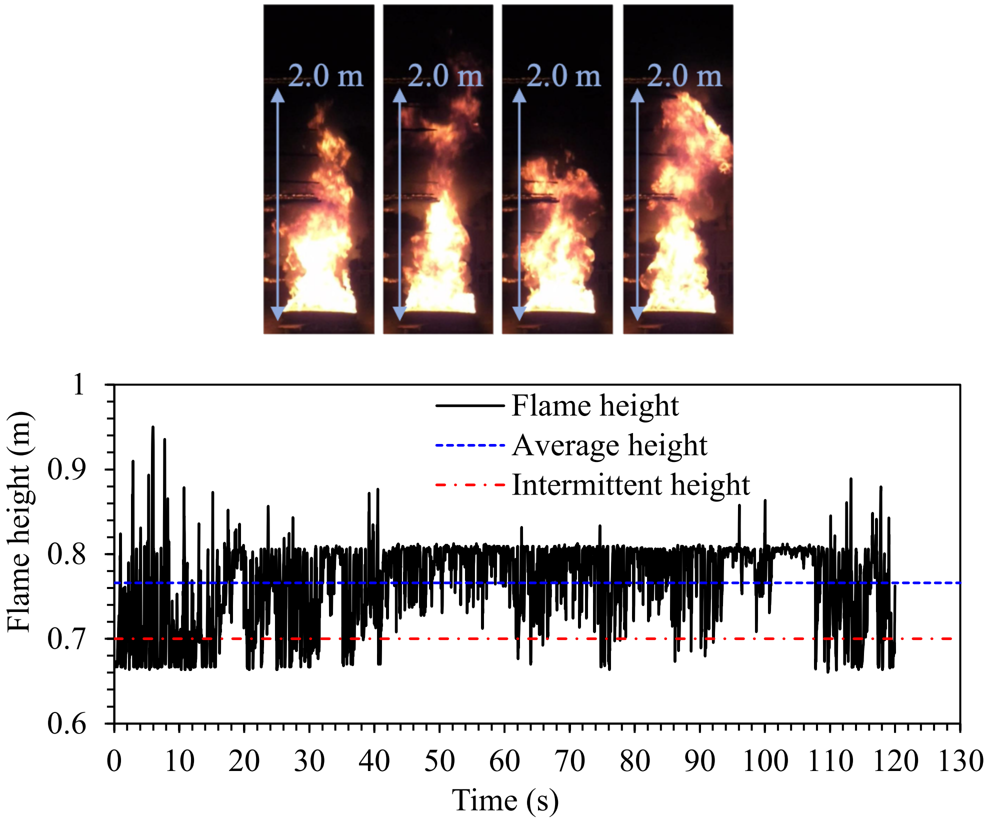

Figure 8: (Top) Photographs of flames at 120 s, 180 s, 240 s, and 300 s, (bottom) measured flame height in two-pan pool fire from image analysis (120 s – 240 s)

After ignition, the flame develops slowly and reaches a peak temperature and decreases further in time. A constant temperature region is observed between 120 s and 540 s before the temperature rises again due to bulk boiling of fuel mixture. With further increase in time, the temperature decreases gradually until the flame is extinguished (Transient temperature and velocity profiles for a two-pan pool fire at different locations can be found in Appendix B).

The lateral temperature measurements for a duration of 180 s are presented in Fig. 9b. It is observed that the peak temperatures are slightly offset to the left side (negative sign) of the pan. Above 2 m from the ground, the plume tilts away from the center and rises vertically leading to a second peak temperature at locations greater than 0.45 m.

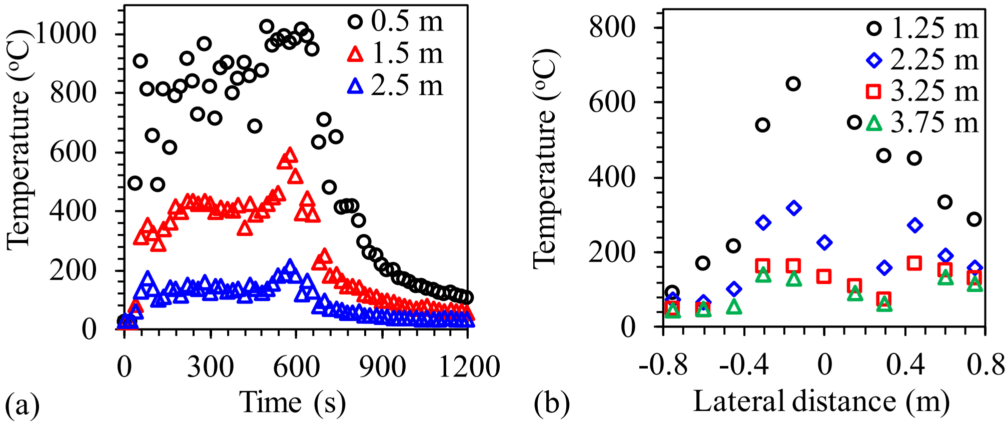

Figure 9: (a) Temporal variation of centerline temperature in the flame (0.5 m), intermittent (1.5 m), and plume (2.5 m) zones of two-pan pool fire, (b) lateral variation of temperature during 120 s - 300 s at heights 1.25 m, 2.25 m, 3.25 m, and 3.75 m.

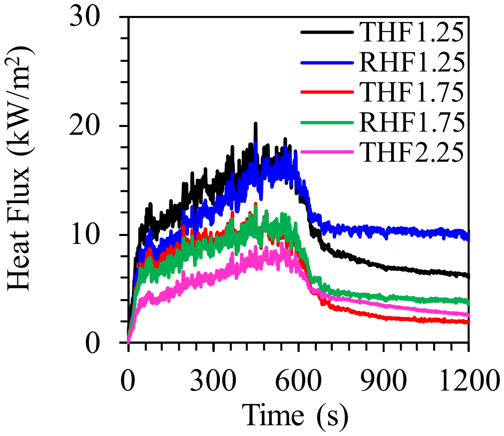

Figure 10: Total heat flux (THF) and radiative heat flux (RHF) profiles in a two-pan pool fire at heights 1.25 m, 1.75 m, and 2.25 m. The gauges are located 1.5 m from the center of the pool.

Figure 10 presents the total and radiative heat flux profiles in a two-pan pool fire at different heights above the ground. Both the total and radiative heat flux decreases with an increase in height. For a height of 1.25 m, the total heat flux is higher as compared to the radiative heat flux. This is due to higher mass loss rate and convective transfer from the flame zone. At 1.75 m above the ground, the total and the radiative heat flux are almost the same due to negligible convective heat flux from the flame.

## Conclusions

Lab scale pool fire experiments fueled by a mixture of canola oil and diesel were conducted to characterize the fire and plume. Single pan and two-pan pool fire experiments were done and point measurements of temperature, velocity, and heat flux were made along the centerline and at several lateral locations. The mass loss rate and visible flame height were recorded using load cells and cameras, respectively. Results show that there are two distinct steady state regimes present in a single pan pool fire (one before and one after the bulk boiling of the mixture). No distinct steady state was observed from the MLR curves of two-pan pool fire. For a single pan pool fire, the centerline temperature distribution correlated with the McCaffrey correlation and the lateral temperatures showed a gaussian distribution in the flame and plume zones. The radiative heat flux was higher than the convective heat flux at all heights due to convective cooling of the probe. In a two-pan pool fire, the centerline temperature showed similar distribution as in a single pan pool fire. The lateral temperature distribution showed two peaks in the plume zones due to the tilt and vertical rise of plume at these locations. The total and radiative heat fluxes were observed to be comparable with each other. These measurements will be used to validate a numerical model in FDS for simulating the plume and its interaction with the vegetation.

## References

[1] McCaffrey, Purely buoyant diffusion flames: some experimental results, NBSIR 79-1910, National Bureau of Standards. (1979).

## Appendix A

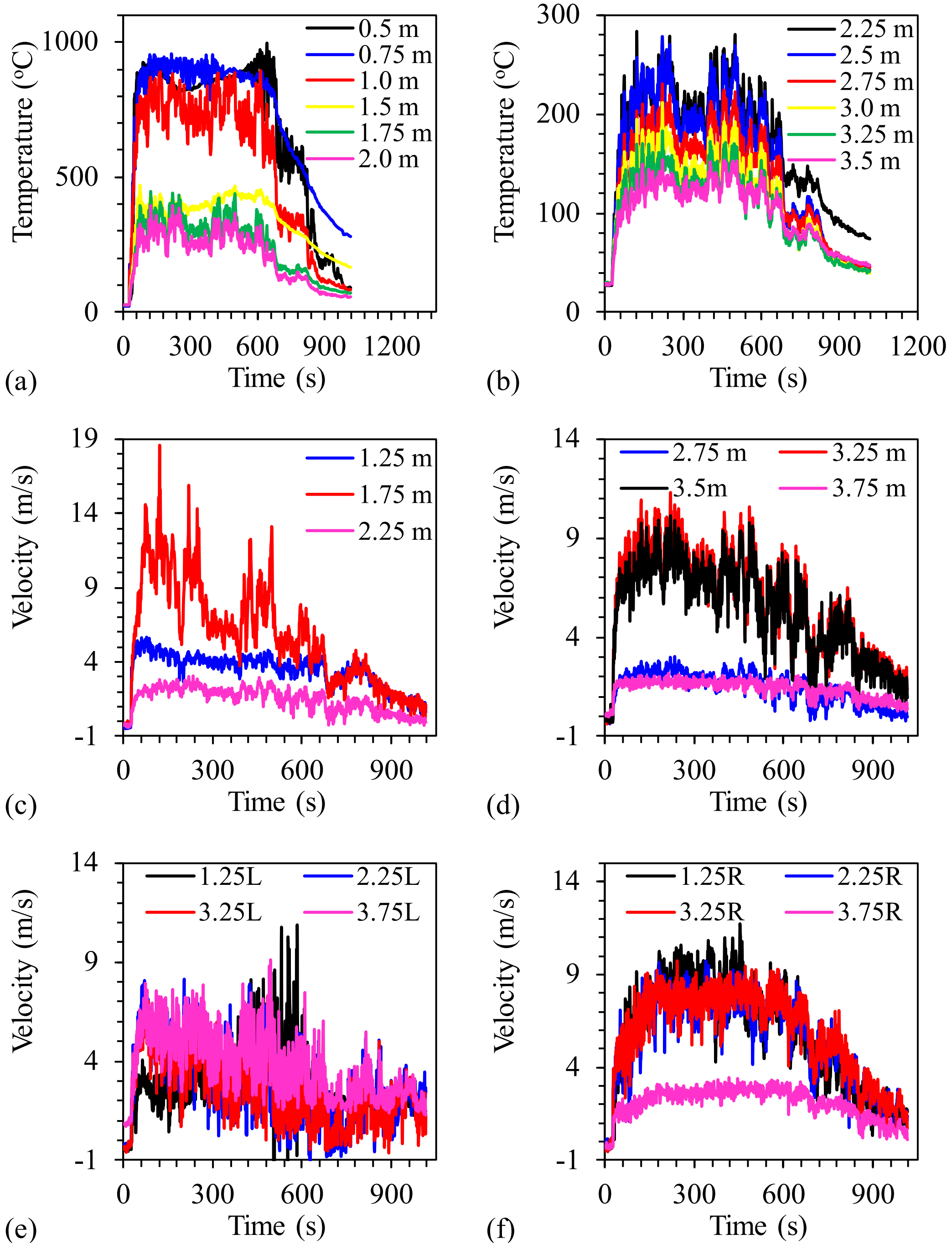

Figure A1: Temporal variation of (a), (b) centerline temperature, (c), (d) centerline velocity, and (e), (f) velocity at lateral locations (L – left side (-0.3 m), R – right side (0.3 m) from the pool center) at different heights from the ground.

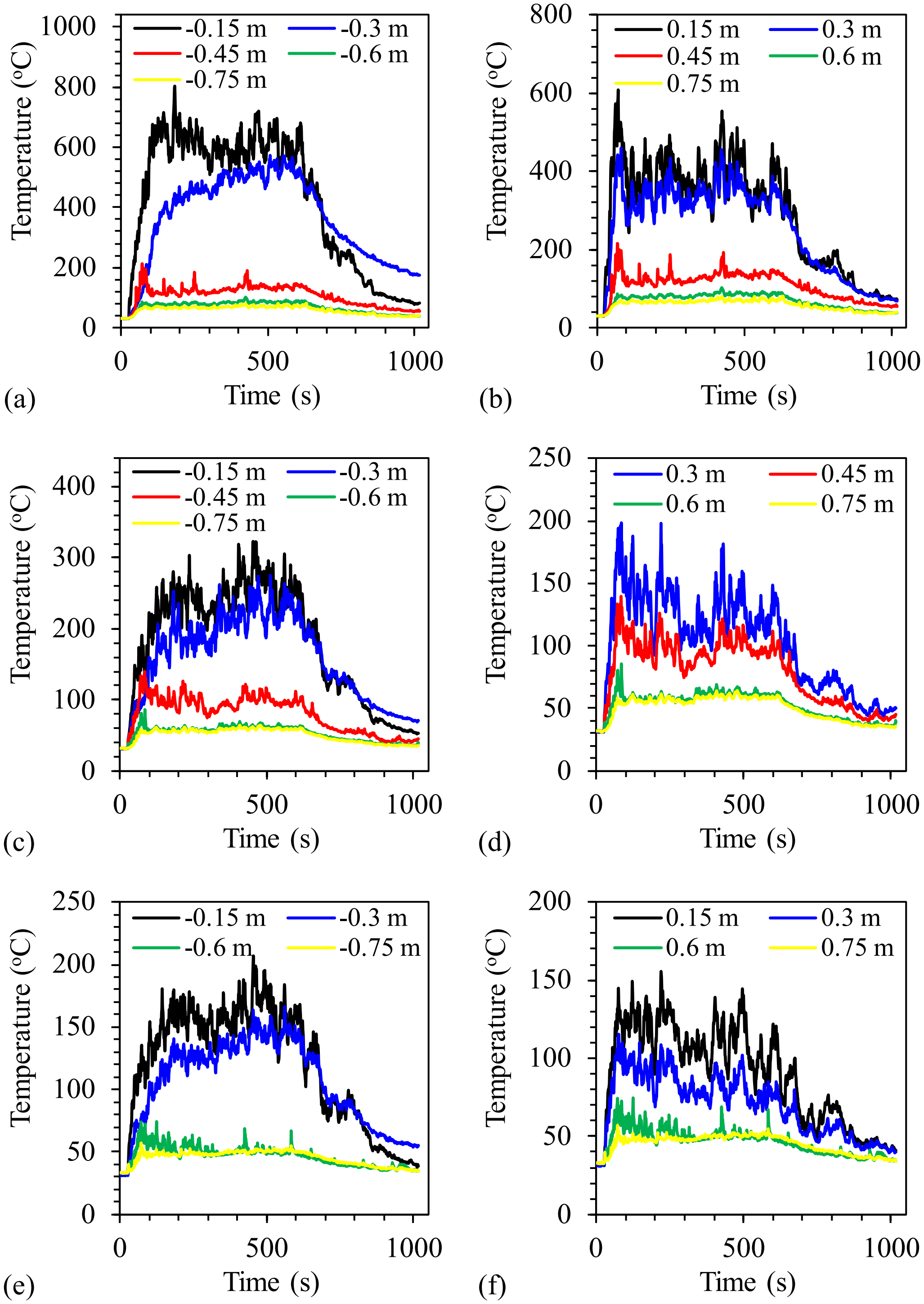

Figure A2: Temporal variation of lateral temperatures at a height of (a), (b)1.25 m, (c), (d) 2.25 m, and (e), (f) 3.25 m (negative sign represents the probe measurements on the left side and positive sign denotes the measurements on the right from the pool center) from the ground.

# Appendix B

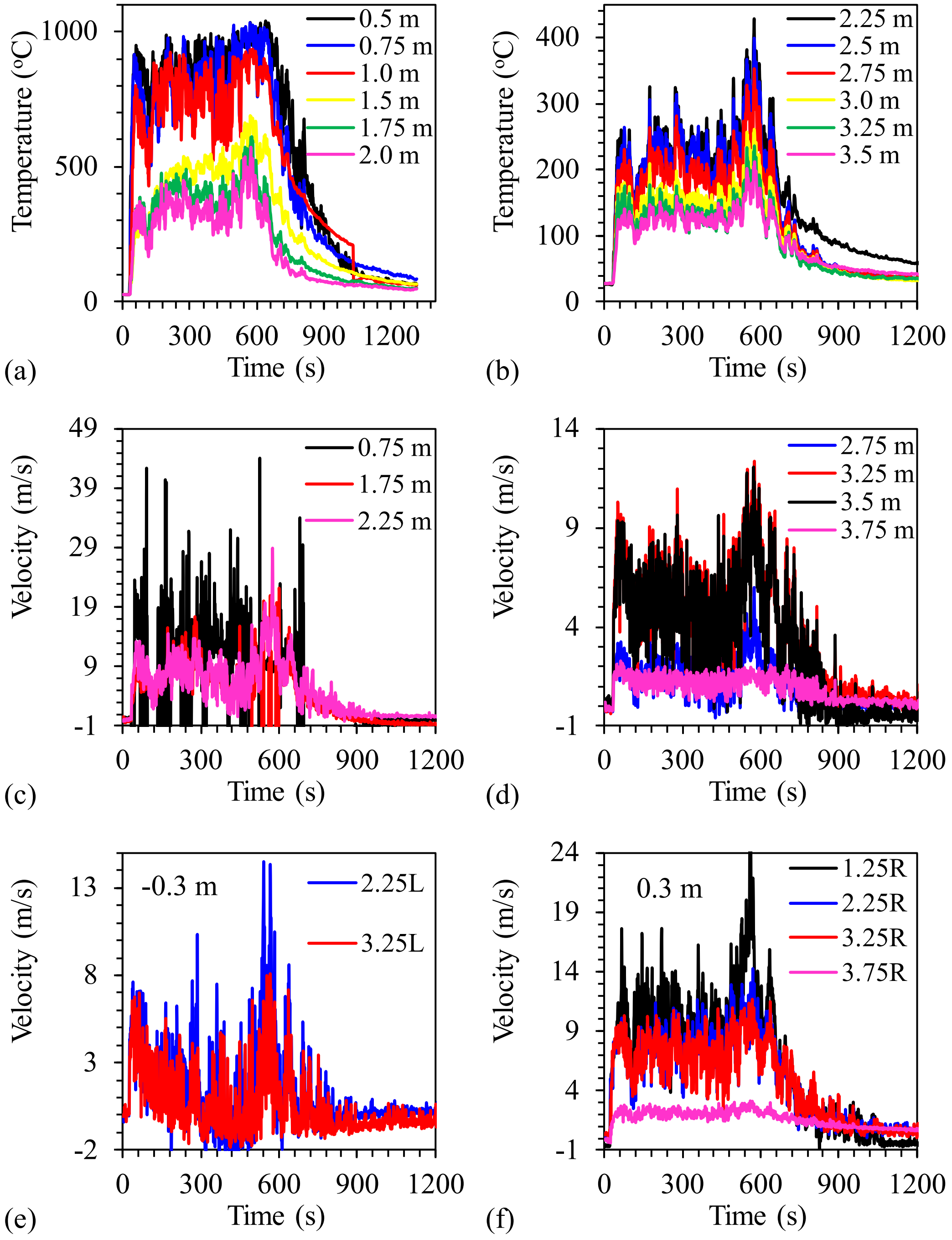

Figure B1: Temporal variation of (a), (b) centerline temperature, (c), (d) centerline velocity, and (e), (f) velocity at lateral locations (L – left side (-0.3 m), R – right side (0.3 m) from the pool center) at different heights from the ground.

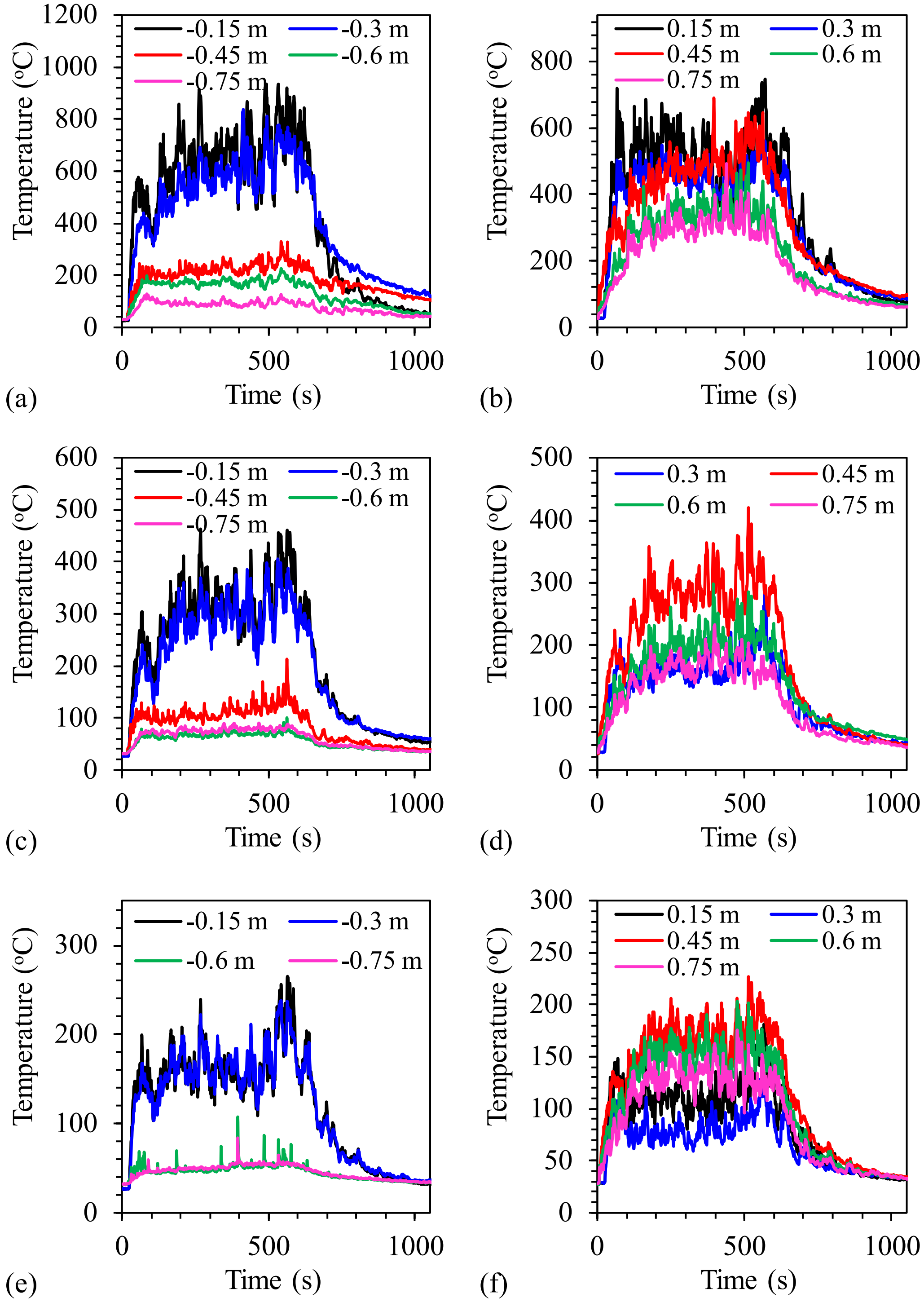

Figure B2: Temporal variation of lateral temperatures at a height of (a), (b)1.25 m, (c), (d) 2.25 m, and (e), (f) 3.25 m (negative sign represents the probe measurements on the left side and positive sign denotes the measurements on the right from the pool center) from the ground.