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Revealing the orientation threshold and optimum contact surface in flame formation, thermal processes, and combustion behaviour of moisturized solid fuel

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ABSTRACT

The ignition of small fuel elements plays a crucial role in fire propagation. These fine fuels are often the first to ignite and serve as a bridge for fire spread to larger scenarios. The moisture content of these fuels significantly affects their flammability and thermal behaviour. In this study, the effect of fuel moisture content (FMC) and orientation on the drying, pyrolysis, ignition, and thermal processes of a cellulose solid fuel is investigated through a series of numerical simulations. In addition, experimental ignition-time measurements were conducted at the U.S. Forest Service Missoula Fire Sciences Laboratory to provide an independent assessment of model performance. The simulations represent a leaf-scale fuel element allowed to heat up and ignite in a hot upwards-directed (convective) airflow. The leaf is considered in three different orientations of vertical, horizontal, and inclined at a 45° angle, and with five different FMC values between 4% and 63%. The simulations are conducted with FireFOAM, using Large Eddy Simulation (LES). Simulation results are validated against available experimental measurements, using the time evolution of the fuel mass loss. The results indicate the inclined orientation has the highest temperature increase among the three orientations, suggesting a critical angle exists for optimal convective heat transfer. Furthermore, the inclined orientation exhibited the highest drying and pyrolysis rates. This suggests that the angle between the airflow direction and the leaf surface normal critically influences the boundary layer development around the leaf.

1. Introduction

Even the largest and most destructive conflagrations often find their origin in the ignition and combustion of small, leaf-sized fuel elements. These fuels burn, promoting the ignition and further burning of larger fuel elements as the fire grows in scale through a variety of complex physical and chemical processes [1]. The behaviour and growth of a fire are driven by topographic and atmospheric conditions [2–5], fuel-structure interactions [6–8], and the effect of fuel moisture content (FMC) [9–12].

One significant factor mentioned is fuel moisture content (FMC), a crucial parameter in thermal behaviour and combustion dynamics [13]. FMC represents the ratio of water mass to the total mass of dry fuel [14]. Fuel moisture content (FMC) stands out as a highly dynamic factor affecting the flammability of vegetative solid fuels and can exhibit rapid changes across time and space. The type and condition of fuel also play a pivotal role in the initiation and spread of fire.

The susceptibility of FMC to weather changes, such as variations in relative humidity, air temperature, and precipitation, strongly influences the initial moisture level of fuels, which consequently affects their ignition and combustion behaviour. [15–17]. Pickett et al. [18] presented an experimental investigation of the combustion of moist foliage and found that moisture remained within the foliage even after ignition, which contradicts the classical combustion mechanism, as it applies to dry fuels, for example. Yashwanth et al. [19] performed a numerical investigation on the effect of FMC on pyrolysis and thermal responses of moist fuels with moisture contents varying from 30% to 200%. In their study, thin cellulosic fuels exposed to a radiant heat source demonstrated that fuels with lower moisture content ignited earlier and produced higher solid and gas phase temperatures. In

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another investigation, Moinuddin et al. [11] studied the effect of relative humidity and fuel moisture content on fire propagation. Their findings demonstrated that fuels with lower moisture content burned with higher intensity and rate of spread. In the work of Morvan [9], it was shown that higher fuel moisture content can significantly reduce fire spread due to a combination of evaporative heat demands and the effect of evaporated water on the local concentration of oxygen, which can extinguish fires in high-moisture scenarios.

Recent studies have also utilized numerical modelling and advanced simulation tools to explore the complex interactions in the pyrolysis and combustion of solid fuels under varied conditions. Liu et al. [20] conducted a numerical investigation on the pyrolysis of moist wood using FireFOAM. The authors reported, similar to the real scenario, by increasing the thickness of wood, the time to heating the entire wood sample increases, and results in increasing the evaporation time for the moisture. The ignition, combustion, and burning process were neglected in their work. Borujerdi et al. [21] carried out a numerical investigation into the thermal processes and combustion behaviour of fine fuels exposed to a convective heat source, considering various levels of fuel moisture content. In their work, combustion and pyrolysis of a solid fuel of manzanita were numerically investigated. Their outcomes showed that an increase in fuel moisture content results in a delay in the ignition time. Also, a significant amount of moisture remained in the leaf after the ignition.

An investigation of vertically positioned leaves exposed to a convective heater with a setup similar to [22] was carried out by Prince [23]. In their work, four different fuel moisture content values of 4% (dry dead), 26% (rehydrated dead), 34% (dehydrated live), and 63% (fresh live) were investigated. The observations illustrated that the edges of solid fuel ignited earlier than the other locations of the leaves. It was also found that dead leaves released mass sooner than leaves with higher fuel moisture contents. Engstrom et al. [24] investigated the combustion behaviour of small samples of leaf-scale solid fuels. The results showed that the ignition temperature did not vary significantly with changes in size and shape for each type of sample. However, the ignition time was notably influenced by the size, shape, and orientation of the sample, indicating that these physical characteristics play a crucial role in how quickly materials ignite [25].

The combustion characteristics and thermal responses of wood, particularly in relation to its fuel moisture content, are critical for understanding and predicting fire behaviour. Fuel moisture content effects on the ignition and thermal decomposition of wood were experimentally and numerically investigated by Gong et al. [26]. They reported an ignition temperature of 395 °C, which was used as the ignition criterion. Their results indicated that by decreasing the heat flux and increasing the fuel moisture content, the ignition time increased for fuel moisture content lower than 25%.

The orientation of small fuel elements, such as leaves, relative to a heat source critically influences their combustion behaviour, affecting how quickly and effectively they ignite and burn. In the work of Engstrom et al. [24], the effect of leaf orientation on combustion behaviour was explored. The results showed that when leaves were oriented vertically, they ignited at the edge closest to the flame and the fire propagated to the top edge of the leaf, regardless of other shape differences. Conversely, leaves held horizontally exhibited a more uniform ignition around their perimeter. This research highlights how the orientation of leaves relative to a heat source directly influences the dynamics of ignition and subsequent combustion patterns. Such findings provide insights into the way fires propagate and behave, potentially aiding in the development of more accurate predictive models for fire spread and combustion processes.

The reviewed investigations help to shed light on our understanding of the influence of fuel moisture content on ignition and pyrolysis processes. Combined influence and potential interaction of FMC and spatial configuration have not yet been examined. This oversight highlights a significant gap in our fundamental understanding of how these factors affect the burning properties of single fine fuel. Additionally, this study reveals the critical role of an optimum angle for pyrolysis efficiency and flame formation when exposed to a convective heat source, exploring how orientation and moisture content interact to affect combustion dynamics.

The aim of this research is to investigate the effect of spatial configuration, and different amounts of FMC, on the drying process, rate of pyrolysis, ignition, and burning of a solid fuel exposed to a convective heat source, at five different fuel moisture content levels of 4, 10, 26, 34, and 63%, and three different orientations of horizontal, inclined (45° angle), and vertical. The selected FMC values represent a wide range of moisture conditions observed in vegetative solid fuels, covering four distinct categories: dry dead (4%), rehydrated dead (26%), dehydrated live (34%), and fresh live (63%) [23,27]. The three leaf orientations (horizontal, inclined, and vertical) are chosen to provide a systematic approach for analysing the influence of alignment on convective heat transfer and ignition behaviour. A set of experimental ignition-time measurements was conducted at the U.S. Forest Service Missoula Fire Sciences Laboratory, to provide a validation data for the simulated results. While leaf positioning in natural conditions is more complex, these orientations allow for a fundamental investigation into the key physical mechanisms governing heat transfer and combustion, providing insights that can be extended to more intricate fire spread conditions.

2. Physical model

This research examines a cellulose leaf [10] as a solid fuel, with different levels of fuel moisture content, namely 4%, 10%, 26%, 34%, and 63%. Although leaves in natural scenarios contain hemicellulose and lignin, the simplified model enables a focused investigation of the existence of an orientation threshold and assessment of the effect of the contact surface on pyrolysis and flame formation. The leaf is subjected to convective heating, in three different orientations: horizonal, vertical, and inclined at a 45° angle. The convective heat source produces hot gases at a constant velocity. Fig. 1 illustrates the computational domain with dimensions of 0.18 m (x) × 0.25 m (y) × 0.32 m (z). A solid fuel leaf is positioned at the centre of the computational domain, elevated 0.04 m above the lower surface. The leaf has dimensions of 23.7 mm × 0.51 mm × 23.7 mm.

A structured mesh is employed, featuring a region of high resolution near the leaf and in proximity to the convective heat source. The convective heat source introduces a mixture with 10 mol% O_2 at a temperature of 1273 K and a velocity of 0.6 m/s, mirroring the experimental conditions outlined by [23].

The model presented in this study incorporates a set of reactions and corresponding kinetic parameters, which are detailed in Table 1.

The rate of reaction is determined using the Arrhenius equation:

$$k = Ae^{\frac{-E_a}{RT}} \tag{1}$$

In this expression, k represents the reaction rate, A shows the pre-exponential factor, E_a denotes activation energy, R stands for universal gas constant, T indicates temperature, and ΔHr represents the enthalpy of the reaction.

This study focuses on conducting a comparative investigation among different orientations, and studies heat-transfer coupling, desiccation, and early-stage ignition processes, rather than long-term char burnout. Accordingly, the solid-phase reactions in the model are moisture evaporation and cellulose pyrolysis, and char oxidation is not considered. [20,21,29,30].

While there is some indication that moisture can indeed influence the gas-phase combustion chemistry [31], these effects have not been fully elucidated and are therefore not included in this work.

To model the chemical combustion reaction of pyrolysis gases, a single-step reaction involving air and methane is employed and presented in Eq. (2). This is due to the fact that the main pyrolysis gas of

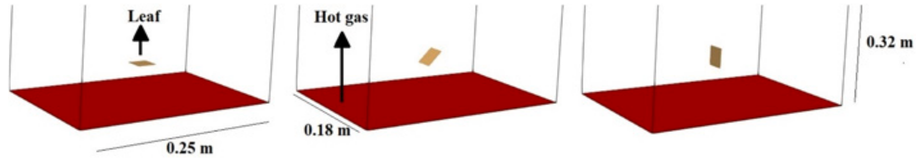

Fig. 1. Schematic of the computational domain for the three cases with horizontal, inclined, and vertical orientations.

Table 1
Pyrolysis and moisture evaporation reactions used in the present study with their corresponding kinetic parameters [28].

Reaction	A (s^{-1})	E_a (J mol $^{-1}$)	Reaction order	ΔHr (J g^{-1})
Moisture → Vapor	5.13×10^{10}	8.8×10^4	1	-2.44×10^3
Cellulose→ Char + Pyrolysate	7.83×10^{10}	1.27×10^5	4.86	-1.41×10^3

vegetative fuels is CH_4 [10,21]. Methane has been used as a surrogate fuel for wildland fire modelling in the work of Dahale et al. [32]. Similarly, in this study we also employ methane as a surrogate to simplify the modelling process.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{2}$$

3. Mathematical and reaction models

In this present investigation, the resolution of the governing equations is achieved by the utilization of FireFOAM, an open-source solver of the OpenFOAM [33] framework. FireFOAM is a useful and effective platform for simulating the dynamic behaviour of fires and pyrolysis reactions, as indicated by *Le* et al. [34]. Additionally, FireFOAM is advantageous due to its incorporation of various Computational Fluid Dynamics (CFD) sub-models, enabling the simulation of diverse fire dynamic issues, including radiant and convective heating effects, pyrolysis, and turbulent and laminar combustion.

In the present study, prior to ignition, the Reynolds number indicates a laminar flow regime. However, after ignition, combustion causes a significant increase in local temperature and pressure, generating localized vorticity and flow instabilities and disturbances in the region above the burning leaf. These effects lead to the formation of localized turbulence, which influences the convective heat transfer and combustion dynamics. To accurately capture these effects, the Large Eddy Simulation (LES) [35] model is employed. While LES is generally applied to fully turbulent flows, its use here allows for the resolution of turbulent structures generated post-ignition, which would not be effectively captured using purely laminar flow models. Furthermore, the wall-adapting local eddy (WALE)-viscosity approach [36] is utilized specifically for large-eddy simulation (LES) in turbulent boundary layers during transitional flow. This method is chosen for its ability to accurately represent the asymptotic decay of eddy viscosity near a solid wall in the turbulent boundary layer [37].

In this study, the Finite Volume Discrete Ordinates Method (fvDOM) [38,39] is utilized to model thermal radiation. This method discretises the radiation field into multiple solid angles and calculates the radiation intensity along these directions. The total irradiation is then obtained by integrating the intensity over all solid angles [40]. While convective heat transfer is the dominant mode of energy transfer [41], the application of fvDOM ensures an accurate representation of radiative heat exchange within the computational domain.

For the combustion modelling of methane involving a single-step reaction, the infinitely fast chemistry combustion model [21,42] is implemented which assumes that gas-phase combustion occurs instantaneously once pyrolysis gases and sufficient energy are available. The ignition process is driven by heat transfer to the leaf, which is influenced by both fuel moisture content (FMC) and orientation. As heat is transferred from the convective heat source to the leaf, a portion of the energy is absorbed for moisture evaporation, regulating the temperature increase of the solid fuel. Once the temperature reaches the pyrolysis threshold, cellulose decomposition initiates, leading to the release of pyrolysis gases. The amount of emitted pyrolysis gases and the available energy determine the onset of gas-phase combustion. Since the interaction between heat transfer, pyrolysis, and gas-phase combustion is fully captured in this study, the infinitely fast chemistry approach provides an efficient and reliable framework for comparing the burning behaviour of leaf-scale fuel elements under different FMC conditions and orientations. This assumption was adopted to focus the analysis on the coupled heat transfer and flow dynamics that govern ignition and early flame formation, rather than the detailed gas-phase reaction kinetics. The infinitely fast chemistry model provides a computationally efficient means of capturing the onset of combustion and the associated thermal response to the solid phase. It neglects intermediate species formation, pollutant emission, and finite-rate reaction effects, which beyond of the scopes of the current work. The research primarily aims to reveal the influence of orientation and fuel moisture content on the heat transfer mechanisms and ignition behaviour, rather than to resolve the detailed emission characteristics. Nevertheless, future extensions of this work could incorporate finite-rate or multi-step chemical kinetics to further evaluate the effects of detailed chemistry on gas-phase combustion.

In the current investigation, the solid matrix volume is assumed constant to focus on the effects of FMC and orientation on initial stage of fire development. While real leaves undergo structural changes, the early stage is primarily governed by heat transfer, drying, and pyrolysis, which is accurately captured. This assumption also enhances computational efficiency, ensuring a focused and effective analysis.

The kinetic parameters, such as activation energy and pre-exponential factors, were selected from established literature [28,29,43] to ensure a balance between computational efficiency and accuracy. Moisture normalisation in the equations allows consistent treatment of varying fuel moisture levels, facilitating meaningful comparisons. The governing equations for the pyrolysis and vaporisation are as follows [26,29,44–46]:

$$\frac{\partial(\rho_s Y_{cellulose})}{\partial t} = \dot{\omega}_{cellulose} \tag{3}$$

$$\frac{\partial(\rho_s Y_{moisture})}{\partial t} = \dot{\omega}_{moisture} \tag{4}$$

$$\dot{\omega}_{wood} = \left[\frac{\rho_s Y_{cellulose}}{(\rho_s Y_{cellulose})_0}\right]^n (\rho_s Y_{cellulose})_0 A_{cellulose} \exp\left(-\frac{E_{a,cellulose}}{RT}\right) \tag{5}$$

$$\dot{\omega}_{moisture} = \left[\frac{\rho_s Y_{moisture}}{(\rho_s Y_{moisture})_0}\right]^n (\rho_s Y_{moisture})_0 A_{moisture} \exp\left(-\frac{E_{a,moisture}}{RT}\right) \tag{6}$$

where and E_a and A stand for the activation energy and pre-exponential factor, respectively. Y represents the mass fraction of cellulose and moisture species, $\dot{\omega}$ denotes the mass consumption rate, and T and ρ_s refer to the temperature and averaged density of the species. The symbol n represents the reaction order, R is the universal gas constant, and the subscript 0 indicates the initial condition of the problem.

The governing equations in the fluid region are outlined below

[43,47,48]:

$$\frac{\partial \overline{\rho}}{\partial t}+\frac{\partial\left(\overline{\rho}\widetilde{u}_i\right)}{\partial x_i}=0 \tag{7}$$

$$\frac{\partial\left(\overline{\rho}\widetilde{u}_i\right)}{\partial t}+\frac{\partial\left(\overline{\rho}\widetilde{u}_i\widetilde{u}_j\right)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\overline{\rho}(\upsilon+\upsilon_t)\left(\frac{\partial\left(\widetilde{u}_i\right)}{\partial x_j}+\frac{\partial\left(\widetilde{u}_j\right)}{\partial x_i}-\frac{2}{3}\frac{\partial\left(\widetilde{u}_k\right)}{\partial x_k}\delta_{ij}\right)\right]-\frac{\partial\left(\overline{P}\right)}{\partial x_i}+\overline{\rho}\,g_i \tag{8}$$

$$\frac{\partial\left(\overline{\rho}\widetilde{h}\right)}{\partial t}+\frac{\partial\left(\overline{\rho}\widetilde{u}_j\widetilde{h}\right)}{\partial x_j}=\frac{D\overline{P}}{Dt}+\frac{\partial}{\partial x_j}\left[\overline{\rho}\left(\alpha_t+\frac{\upsilon_t}{Pr_t}\right)\left(\frac{\partial\widetilde{h}}{\partial x_j}\right)\right]+\dot{q}'''-\nabla.\dot{q}_r'' \tag{9}$$

$$\frac{\partial\left(\overline{\rho}\widetilde{Y}_m\right)}{\partial t}+\frac{\partial\left(\overline{\rho}\widetilde{u}_j\widetilde{Y}_m\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\overline{\rho}\left(D_c+\frac{\upsilon_t}{Sc_t}\right)\frac{\partial\left(\widetilde{Y}_m\right)}{\partial x_j}\right]+\overline{\omega}_m \tag{10}$$

$$\overline{P}=\overline{\rho}R\widetilde{T} \tag{11}$$

here, h denotes the total enthalpy, symbols "∼" and "¯" represent Favre filtering and spatial averaging, respectively. Y_m stands for the mass fraction of species m, g represents gravitational acceleration, and P is the static pressure, $D_c, Pr_t, \delta, \upsilon_t, \rho, Pr_t, \upsilon, \alpha_t, R, Sc_t$, and ω_m are correspond to the laminar diffusion coefficient, turbulent Prandtl number, Kronecker delta, turbulent viscosity, density, turbulent Prandtl number, laminar viscosity, thermal diffusion coefficient, gas constant, turbulent Schmidt number, and production/sink rate of species m due to gas reaction, respectively. The computational domain is discretised using a structured grid, with a region of high-resolution refinement near the leaf surface to accurately capture convective heat transfer effects. The simulations employ a wall-resolved approach, ensuring that boundary layer effects are directly resolved without reliance on wall functions. The grid resolution was chosen to maintain sufficiently low y + values, allowing for accurate treatment of near-wall velocity gradients and convective heat transfer.

4. Results

For different leaf orientations (horizontal, inclined, and vertical), the mesh configuration was adapted to ensure proper alignment with the airflow direction while preserving the refined resolution near the leaf surface. This adaptation was necessary to maintain consistency in boundary layer resolution and to account for variations in the interaction between the leaf and the convective heat source. A grid independence study was conducted to confirm that the chosen spatial resolution provides numerical accuracy without grid-dependent effects. The computational domain was discretised into three different grid sizes of 324,000, 554,000, and 736,000 cells. Subsequently, the results obtained from each simulation were compared [49]. Increasing the mesh from 324,000 to 554,000 led to a noticeable change in the normalised mass of the solid fuel, while the difference between 554,000 and 736,000 was minimal. As a result, the mesh with 554,000 cells was chosen for the remaining simulations as a compromise between accuracy and computational cost. The outcomes from each simulation were then compared and are illustrated in Fig. 2.

In order to validate the simulations, Fig. 3 displays the time history diagram of the normalised mass of the leaf, considering a fuel moisture content of 4, 26, 34, and 63%. The figure presents the computational outcomes from the current investigation alongside the experimental data obtained by [23]. The figure illustrates a satisfactory agreement between the numerical simulations and the experimental findings. The

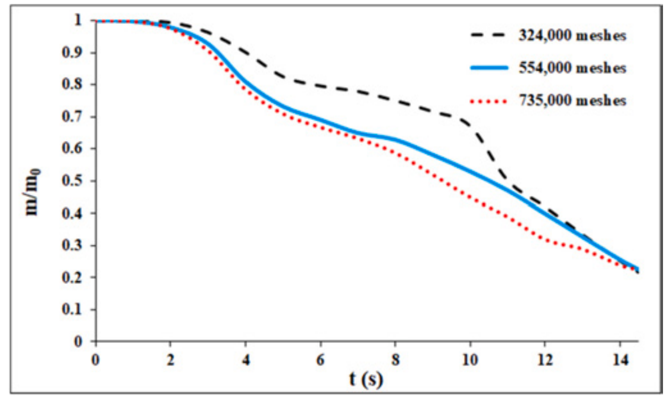

Fig. 2. Effect of mesh resolution on normalised fuel mass.

discrepancy observed between the simulated data and experimental measurements is attributed, in part, to the solid fuel employed in this study. The present simulations are based on cellulose, which was selected to isolate the fundamental mechanisms of drying and pyrolysis under convective heating. However, in the experiment conditions, the vegetative fuel contain cellulose, hemicellulose, and lignin and small fractions of proteins and lipids [50].

To have another validation of the simulation results, a series of auto-ignition experiments was conducted at the Missoula Fire Sciences Laboratory (U.S. Forest Service). The experiments employed an apparatus consisting of a 16 cm-diameter vertical outlet connected with two 6.5 kW electrical air heaters (Fig. 4). The heaters raised the airflow temperature to 1048.15 K, sufficient to achieve auto-ignition of moist cellulosic fuel samples positioned in the outlet stream. A ceramic manifold merged the two heater flows and directed them through a 90° bend to achieve the vertical discharge. A series of screens then evened out the flow profile. The airstream was dried with a desiccant and its flow rate precisely regulated using dual Omega FMA-2612 A mass-flow controllers. Temperature control was achieved with K-type thermocouple placed immediately at the outlet of the airtorches to monitor the hot stream.

Solid fuels are square-shaped cellulosic leaves (25.4 × 25.4 × 1.5 mm) prepared at two fuel moisture contents: 3.9% and 10.3%. The low-moisture condition (3.9%) was obtained by oven-drying at 70 °C, while the higher moisture condition (10.3%) was achieved using a conditioning chamber held at 18 °C and 40% relative humidity (RH). During the tests, the outlet stream was maintained at 1048.15 K with a total flow of 562.6 L min^{-1}, corresponding to a velocity of 1.67 m/s at the test temperature. Each orientation case was repeated three times for both FMC levels to minimise experimental error.

To minimise moisture exchange with ambient laboratory air between conditioning and testing, only two to three samples were removed at a time and immediately sealed in a zip-lock bag. All tests were completed within approximately 2–3 min of removal, and the samples remained sealed until moments before ignition; no pre-exposure to the hot stream was applied prior to insertion. So, the sealed storage and short transfer interval were used specifically to minimise any FMC change prior to ignition.

A sliding mechanism equipped with steel clips was used to secure the fuel samples and move them directly into the hot airflow at the outlet of the manifold. Ignition was detected using a dual-camera system: a high-definition visible camera recording at 60 frames s^{-1} and a FLIR SC6811 infrared camera (calibrated to 1500 °C) with a detection range of 3.0–5.0 μm. The infrared system provided thermal imaging to capture precise ignition timing, while visual observations were used to confirm flame appearance (Fig. 5). Ignition time was defined as the first appearance of a sustained visible flame, identified from high-definition video recordings. The measured ignition times are presented in Fig. 6

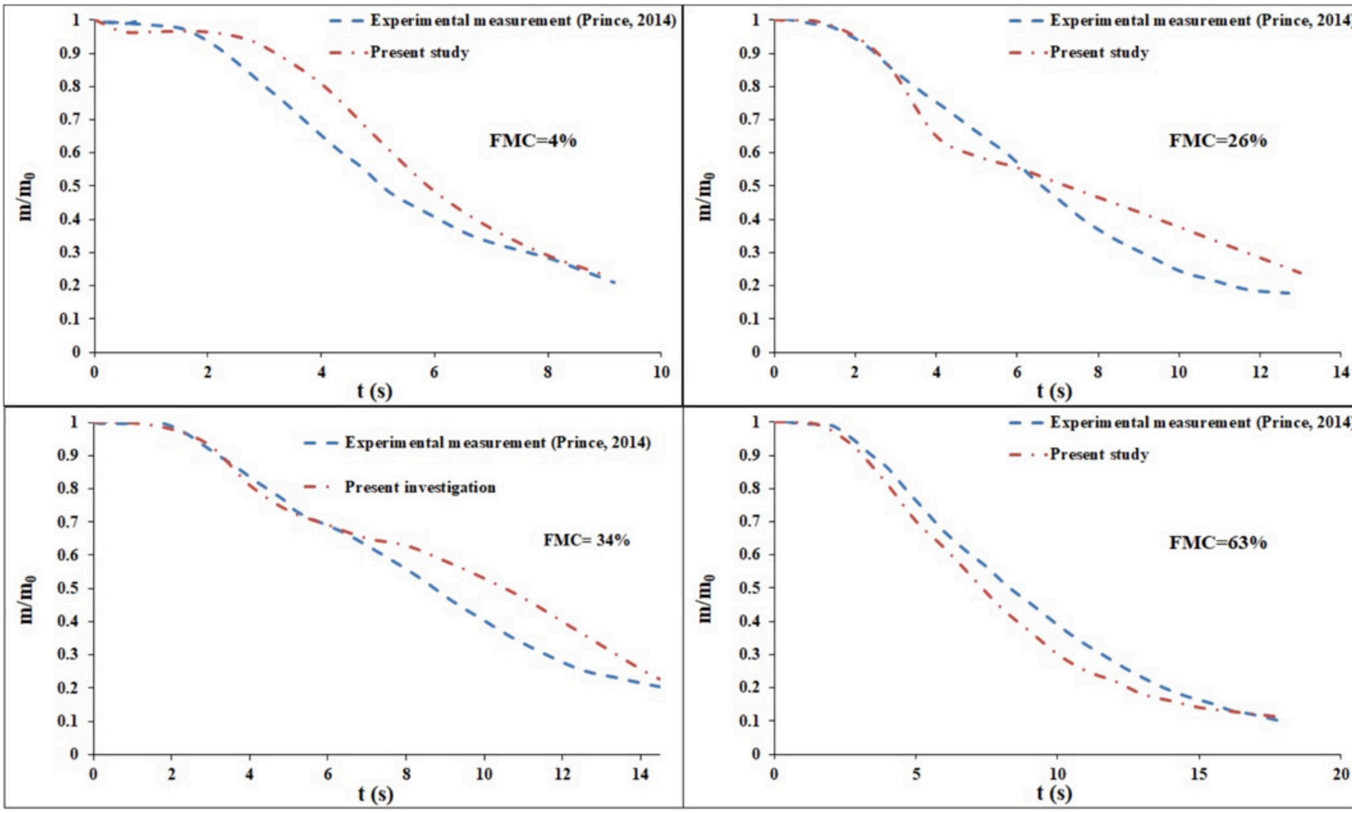

Fig. 3. Graph depicting the temporal evolution of the normalised mass of the leaf in the current study, contrasted with the experimental data from [23], for the scenario with a fuel moisture content of 4, 26, 34, and 63%.

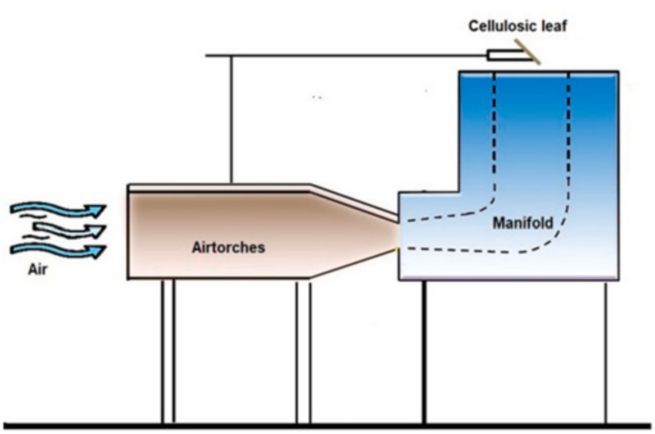

Fig. 4. Schematic of the experimental setup.

and compared with the numerical simulations.

Fig. 6 compares ignition times from experimental measurements and numerical simulations at two FMC levels (3.9% and 10.3%) across three orientations. In both cases, the inclined orientation exhibits the shortest ignition time, which is attributed to the asymmetric flow field around the leaf, and the intensified interaction on the windward side of the leaf that enhances convective heat transfer and accelerates the thermal response. This mechanism will be examined in detail further in Fig. 7 through analysis of the streamline pattern. However, horizontal and vertical orientations show longer ignition times, with the differences more evident at higher FMC due to the additional energy required for moisture evaporation. The simulations capture the general trends of the experiments, and show a good agreement with the experimental data, demonstrating that the model reproduces the combined effects of orientation and FMC on ignition behaviour and thermal responses. Both experimental and numerical results reveal the existence of a threshold angle between the airflow and the leaf, beyond which convective heat transfer is maximised. This is due to the inclined leaf's optimal exposure to the hot airflow, considering both factors of velocity and direction of the flow.

Fig. 7 illustrates the vector and streamline patterns and velocity distribution around the leaf for three different orientations: horizontal, inclined, and vertical. The figure highlights the flow behaviour and boundary layer development near the leaf surface, showcasing the impact of orientation on the convective heat transfer mechanism.

In the horizontal orientation, a stagnation point forms directly above the leaf's centre, resulting in a symmetric flow pattern with reduced velocity near the surface. This stagnation zone limits convective heat transfer in the central region while enhancing it toward the leaf's edges, as evidenced by the increased streamline density and higher velocities at the corners. The flow separation at the edges leads to divergent flow paths, which contribute to lower overall heat flux at the central region.

In the inclined orientation, the streamline pattern indicates an asymmetrical flow, with higher velocities observed along the windward side of the leaf. This orientation minimizes stagnation effects and promotes stronger convective heat transfer across the leaf surface due to the enhanced airflow interaction. The inclined orientation also induces a recirculation region downstream of the leaf, which affects the distribution of pyrolysis gases and the overall combustion dynamics.

In the vertical orientation, the flow remains aligned with the leaf's surface, resulting in the formation of a thinner velocity boundary layer near the lower edge. The streamline density increases near the lower part of the leaf, indicating higher convective heat transfer in this region. However, the flow interaction weakens as it moves upward along the leaf, leading to reduced convective heat transfer at the upper edge.

Overall, the streamline analysis confirms the significant influence of leaf orientation on the velocity distribution and convective heat transfer

Fig. 5. Experimental measurement of ignition of inclined cellulosic leaf in 1048 K, captured by HD and IR camera.

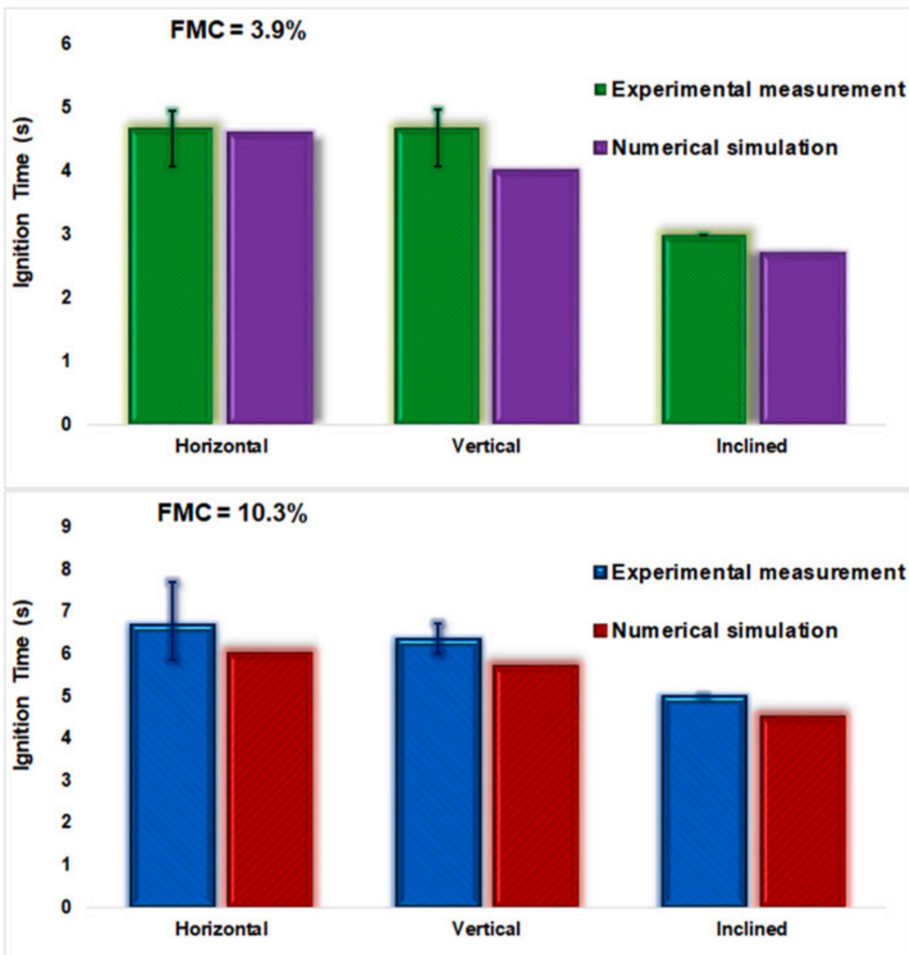

Fig. 6. Ignition time for three fuel orientations (horizontal, vertical, and inclined) at two FMC levels (3.9% and 10.3%), comparing experimental measurements with numerical simulations.

mechanisms. The inclined orientation exhibits the most favourable conditions for convective heat transfer, while the horizontal and vertical orientations demonstrate reduced heat transfer efficiency due to stagnation and limited airflow interaction, respectively.

Fig. 8 highlights the heat input rate (HIR) dynamics for the three leaf orientations, horizontal, inclined, and vertical, providing insights into their influence on heat transfer mechanisms and combustion efficiency.

The inclined orientation consistently exhibits the highest peak HIR and the fastest rise to the peak across all cases. This is attributed to the optimal angle of attack, which enhances convective heat transfer by maximizing airflow interaction with the leaf surface. The inclined position also reduces stagnation effects, ensuring uniform heat distribution across the leaf and efficient energy transfer.

The horizontal orientation, in contrast, demonstrates the lowest peak HIR and a delayed ignition response. The stagnation zone beneath the leaf, where airflow velocity is minimal, significantly reduces convective heat transfer efficiency. This orientation also exhibits uneven heat distribution, with higher heat flux concentrated at the edges of the leaf,

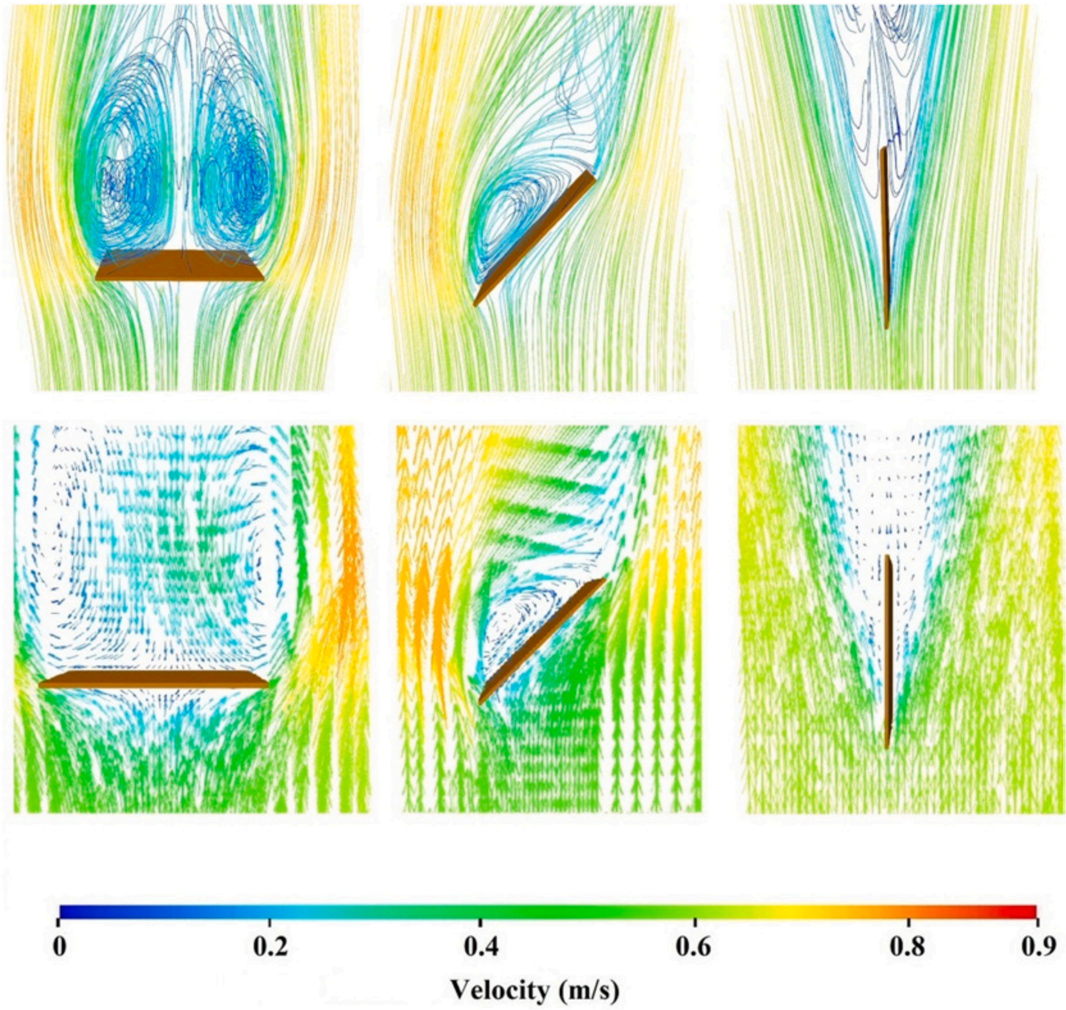

Fig. 7. Vector and streamline patterns and velocity distribution, for the three different orientations, prior to ignition.

resulting in slower and less uniform combustion.

The vertical orientation exhibits intermediate behaviour, with peak HIR values lower than the inclined orientation but higher than the horizontal case. The vertical position allows for better airflow along the leaf's surface compared to the horizontal orientation. However, the alignment of the leaf surface parallel to the airflow leads to reduced heat transfer efficiency at the upper part of the leaf, as the convective heat transfer decreases in this region.

Looking at Fig. 8 in more detail, as the fuel moisture content (FMC) increases, the peak heat input rate (HIR) tends to increase across all orientations. This behaviour can be attributed to the additional energy required to evaporate the higher moisture content before combustion. While higher FMC levels delay the ignition process and prolong the drying phase, the energy supplied during this extended phase results in a more pronounced peak HIR once combustion is fully established. This trend underscores the complex interplay between moisture evaporation, ignition dynamics, and heat transfer efficiency.

Overall, the inclined orientation consistently outperforms the other orientations in terms of heat transfer efficiency and ignition dynamics, making it the most favourable configuration for convective heating. The horizontal and vertical orientations, while less effective, provide useful insights into the role of stagnation zones and flow alignment in influencing heat transfer rates.

Temperature distribution in the leaf at $t = 3.5$ s, for different cases with FMC $= 4, 10, 26, 34, 63\%$ and three different orientations is shown in Fig. 9. As can be seen, in each orientation, by increasing the amount of fuel moisture content, the temperature of the leaf decreases. This is due to the heat absorbed in vaporizing the moisture content of the leaf. The leaf with a horizontal orientation exhibited the lowest temperature, primarily warming up from its corners. This is attributed to the presence of a stagnation point under the leaf centre, resulting in lower convective heat transfer. The vertically oriented leaf exhibited higher temperatures at its lower part due to greater exposure to the hot airflow, while its upper part remained cooler. The inclined orientation exhibited the highest temperature increase among the three orientations, suggesting a critical angle for optimal convective heat transfer due to the combined effects of airflow velocity and direction.

The area-weighted temperature at $t = 3.5$ s, and the cases with FMC 4% for the vertical, inclined, and horizontal orientations are 561 K, 603 K, and 545 K, respectively. The same parameter, for the cases with fuel moisture content of 34% at the time of 3.5 s, for vertical, inclined, and horizontal leaf are 451, 520 K, and 418 K, respectively.

Graphs depicting the temporal evolution of the heat release rate are shown for various scenarios, featuring FMC values of 4, 10, 26, 34, and 63%, along with three different orientations are shown in Fig. 10. Quite evidently, in all the scenarios, the case with inclined orientation starts releasing heat earlier than the other orientations and also its maximum HRR is higher than others. Consequently, the HRR in the inclined case finishes earlier than the other orientations, as the cellulose has been consumed at a higher rate. Additionally, by increasing the FMC, the maximum amount of HRR decreases. The time at which the maximum Heat Release Rate (HRR) occurs varies with increasing Fuel Moisture

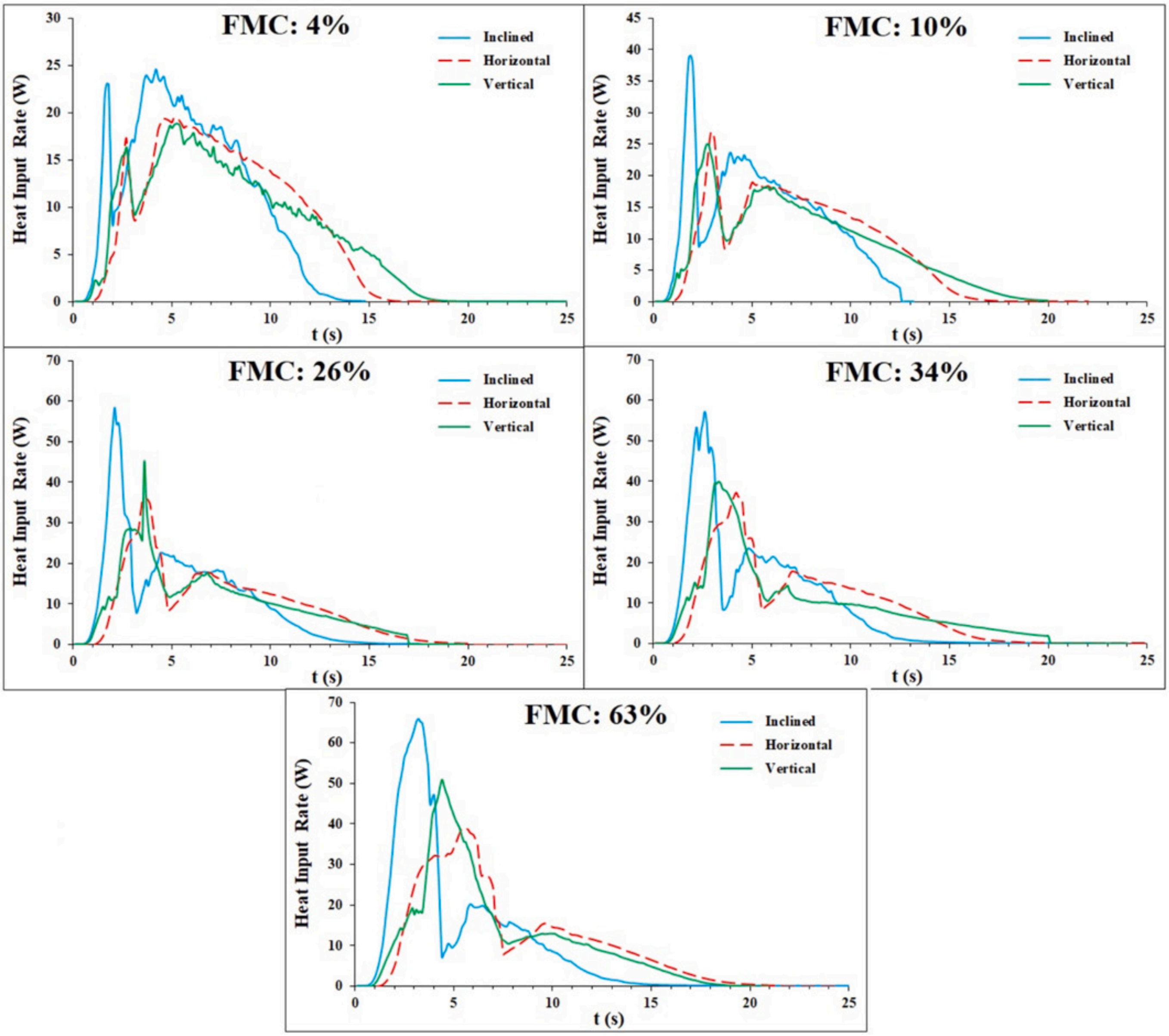

Fig. 8. Time series of the heat input rate for different cases with FMC = 4, 10, 26, 34, 63% and three different orientations.

Content (FMC). Table 2 provides the maximum HRR values and the corresponding times for each case.

Fig. 11 shows the contours of temperature at the fluid domain around the leaf at $t = 3.5$ s, for different cases with FMC = 4, 10, 26, 34, 63% and three different orientations. As can be seen, after 3.5 s of heating, the cases with lower fuel moisture have more progress in the burning process. Since the flame is still in the transient state and has not reached a steady state, cases with higher Fuel Moisture Contents (FMCs) exhibit lower flame heights. This is attributed to the delay in ignition caused by the moisture. For instance, at that moment, t = 3.5 s, the case with horizontal orientation and 63% FMC has not ignited yet. Looking at Fig. 11 in more detail, especially the case with FMC 34% and horizonal orientation, the case with inclined and vertical orientations and FMC 63%, the ignition location can also be seen. For the horizontal cases, the ignition happens at the corners of the leaf above it. Moreover, for the case with vertical orientation, it happens at the vicinity of lower part of the leaf.

The distribution of pyrolysis gas mass fraction around the leaf at a time of 3.5 s is examined for various scenarios, considering different levels of FMC at 4%, 10%, 26%, 34%, and 63%, and across three different orientations is graphically represented in Fig. 12. Leaves with lower FMC showed greater advancement in combustion, emitting more pyrolysis gas, which is consistent with the observed temperature distributions. Higher FMC levels resulted in lower pyrolysis gas emissions, indicating slower combustion progress.

Normalised mass diagrams are studied to eliminate the influence of variations in the initial mass of the fuel, ensuring consistent and meaningful comparisons across different cases. This approach allows the focus to remain on the impact of key parameters, such as orientation and contact surface, on pyrolysis dynamics and flame formation, without interference from differences in sample size or initial conditions. Fig. 13 thus depicts the progression of normalised mass of dry fuel over time for various scenarios, encompassing different levels of FMC at 4%, 10%, 26%, 34%, and 63%, along with three distinct orientations. The highest rate of the cellulose consumption is for the cases with inclined orientation due to the highest convection heat transfer.

Looking at Fig. 13 in more detail, interestingly, it can be seen that at later times, the horizontal configuration “outburns” the vertical one.

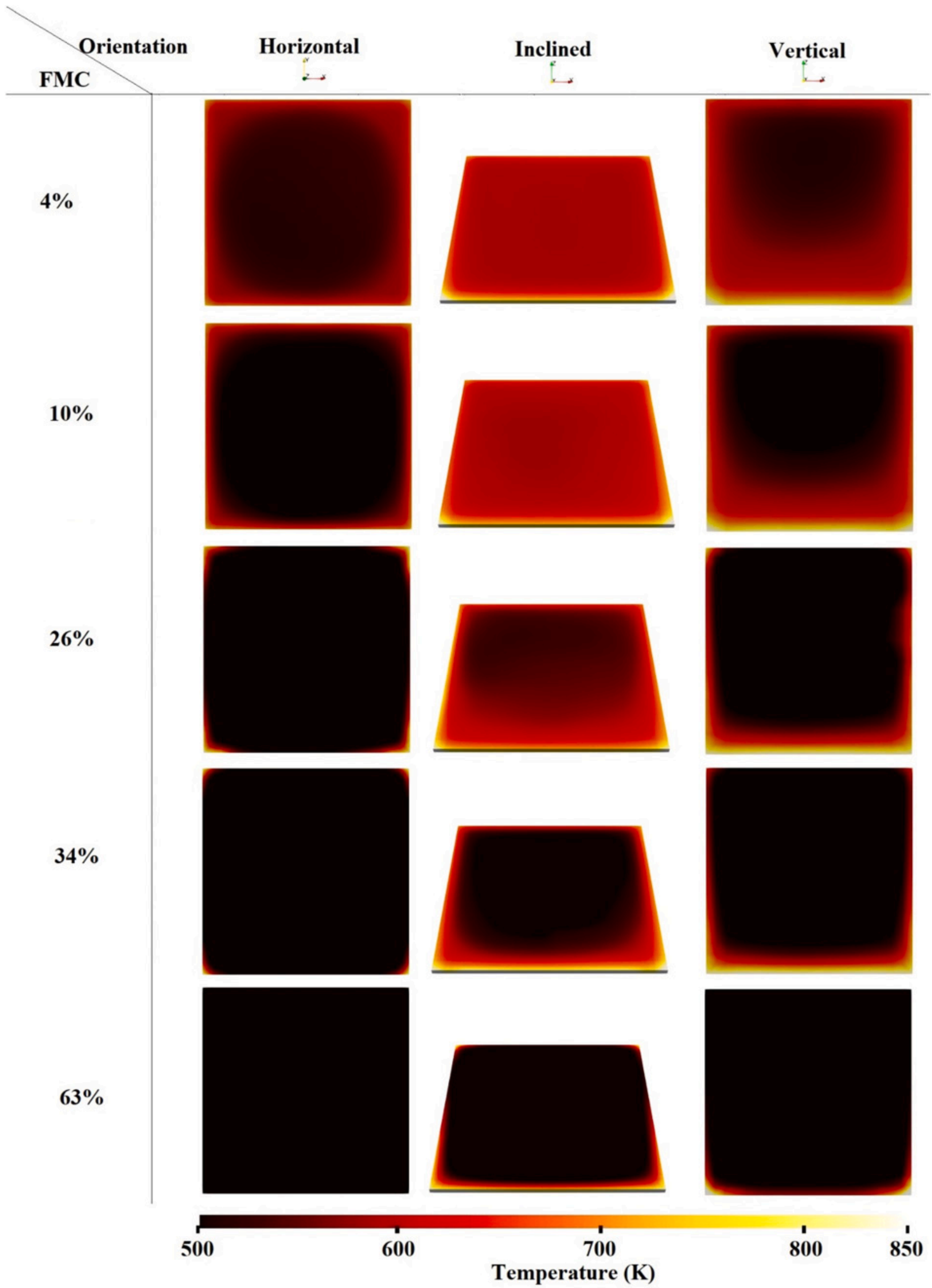

Fig. 9. Temperature distribution in the leaf at t = 3.5 s, for different cases with FMC = 4, 10, 26, 34, 63% and three different orientations.

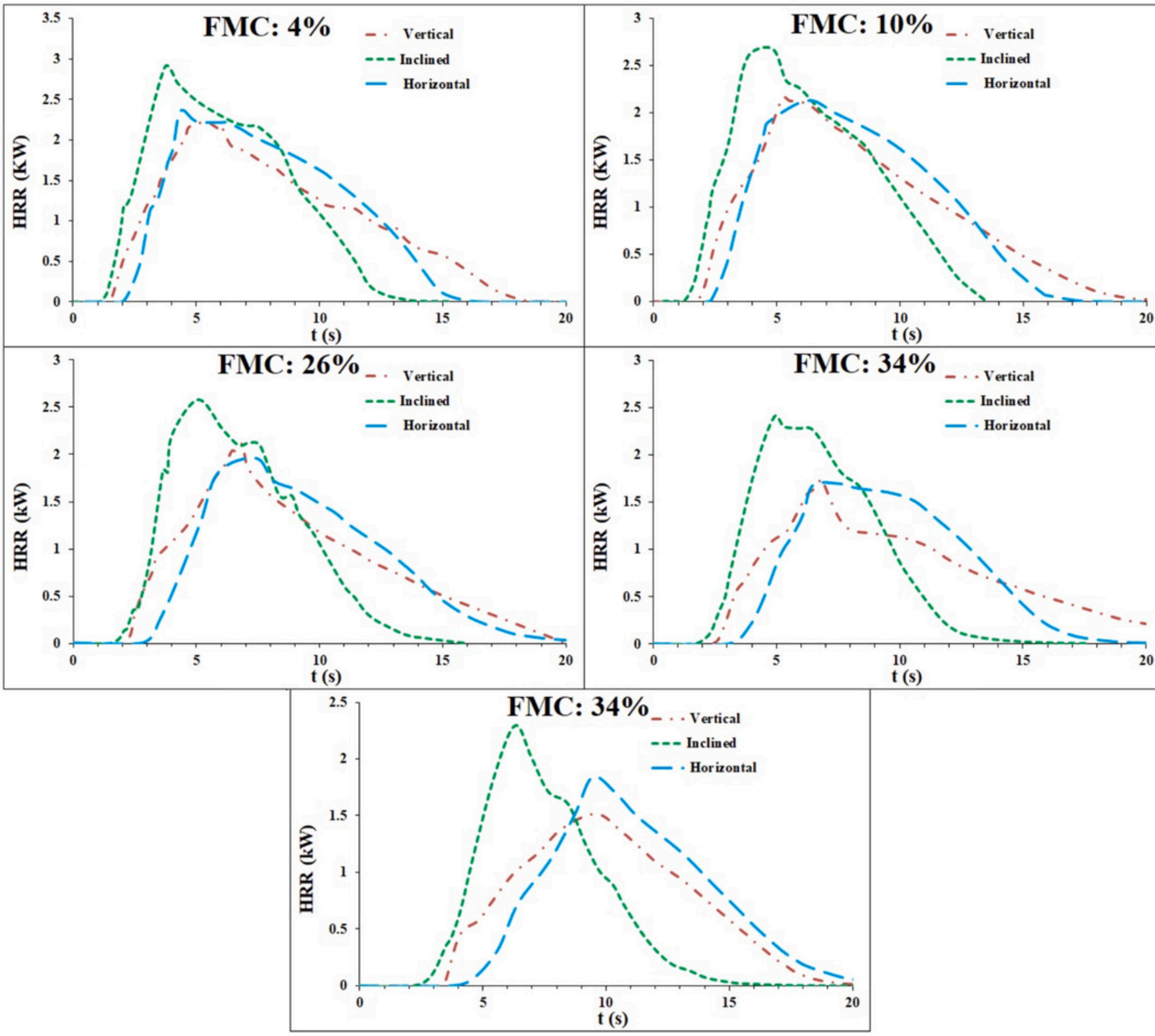

Fig. 10. Time history diagram of the heat release rate for different cases with FMC = 4, 10, 26, 34, 63% and three different orientations.

Table 2
Maximum HRR values and their corresponding occurrence times for various FMC levels and three different orientations.

FMC	Orientation	Maximum HRR (kW)	Occurrence time (s)
	Vertical	2.23	5.43
4%	Inclined	2.89	3.7
	Horizontal	2.36	4.36
	Vertical	2.08	6.3
10%	Inclined	2.67	4.8
	Horizontal	2.12	6.2
	Vertical	2.11	6.8
26%	Inclined	2.58	5.6
	Horizontal	1.96	7.4
	Vertical	1.75	6.83
34%	Inclined	2.4	4.9
	Horizontal	1.7	7.5
	Vertical	1.51	9.6
63%	Inclined	2.3	6.3
	Horizontal	1.84	9.44

This behaviour arises from differences in the effect of different heat-transfer mechanisms acting on each orientation. The cumulative effect of sustained convective exposure at vertical fuel compared to enhanced radiative heat transfer received by the horizontal fuel after ignition. In the vertical case, the projected area of the fuel is smaller, then the flame heats faster, and the ignition occurs earlier. In contrast, the horizontal fuel, although igniting slightly later, experiences a larger radiative view factor and retains the flame in closer proximity during the later stages of burning. This prolonged exposure to hot gases and radiation accelerates mass loss, causing the horizontal leaf to outburn the vertical at later times.

Moisture normalisation is considered to ensure consistent comparisons across cases with different initial moisture levels. This approach eliminates the influence of varying starting conditions, allowing the study to focus on the effects of orientation and contact surface on pyrolysis efficiency and flame formation. The drying process for the leaf with three different orientations of horizontal, inclined, and vertical and various fuel moisture content levels is indicated in Fig. 14. The highest drying rate is for the case with FMC 4% and inclined orientation. The

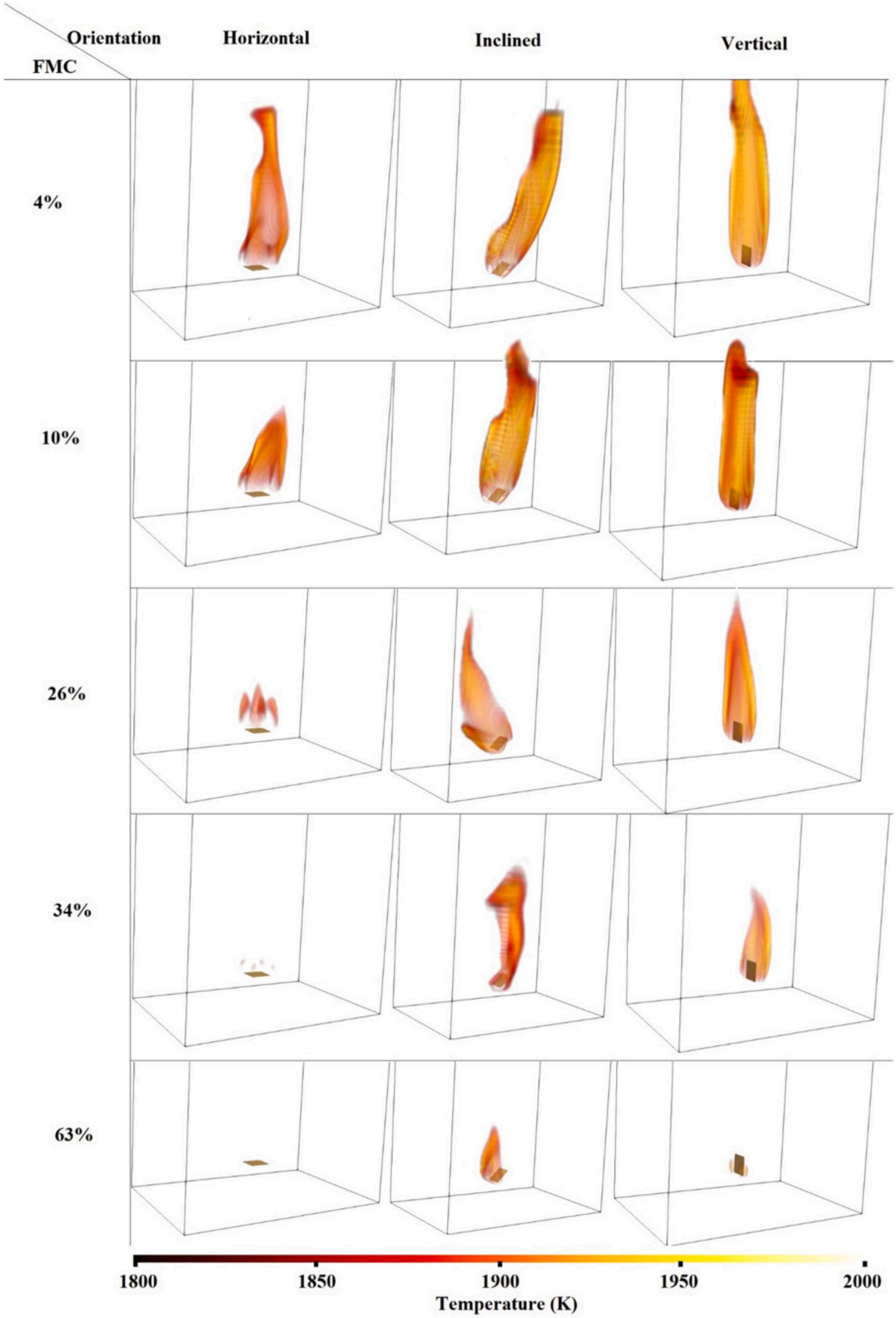

Fig. 11. Temperature distribution around the leaf at $t = 3.5$ s, for different cases with FMC = 4, 10, 26, 34, 63% and three different orientations.

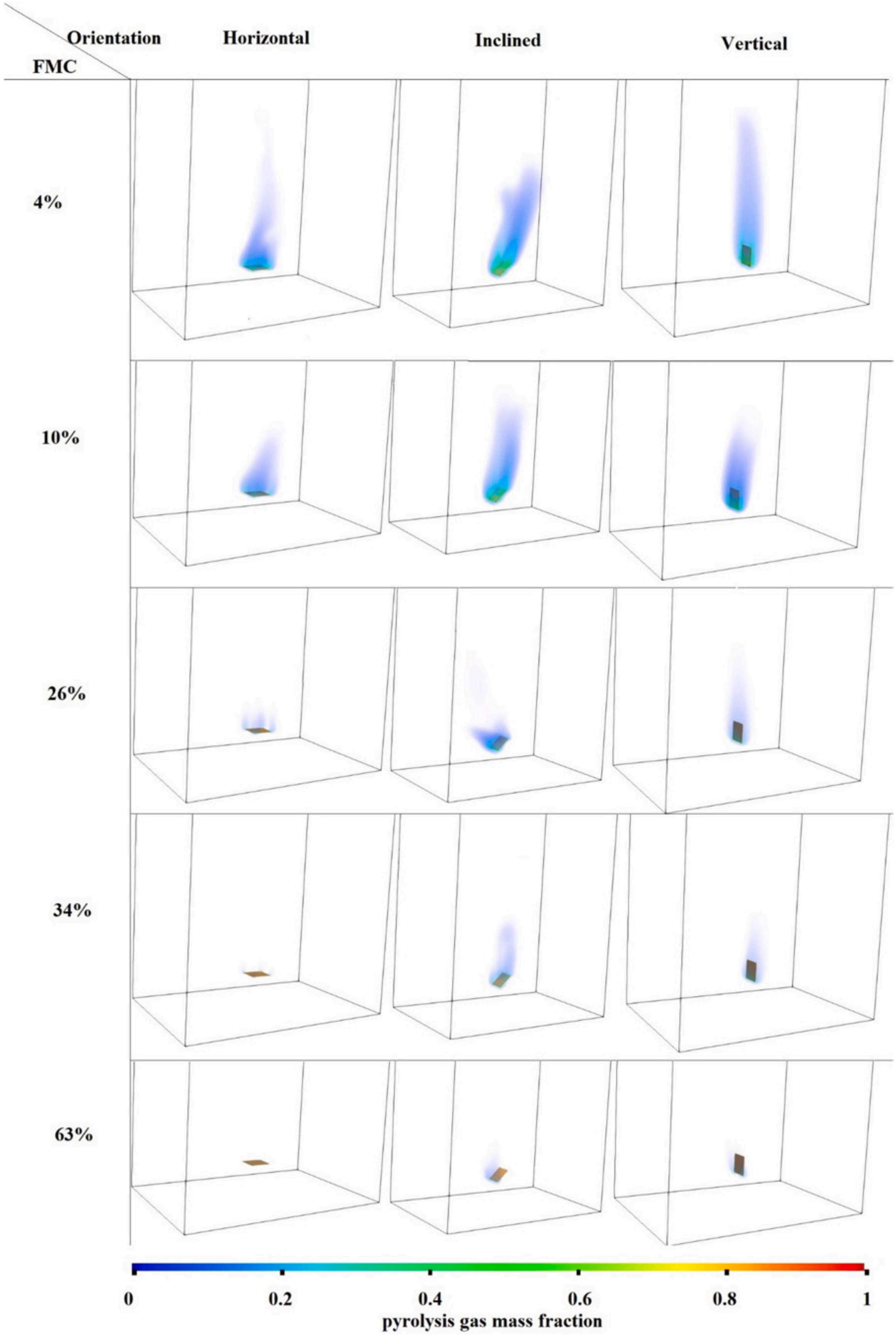

Fig. 12. Pyrolysis gas mass fraction distribution around the leaf at t = 3.5 s, for different cases with FMC = 4, 10, 26, 34, 63% and three different orientations.

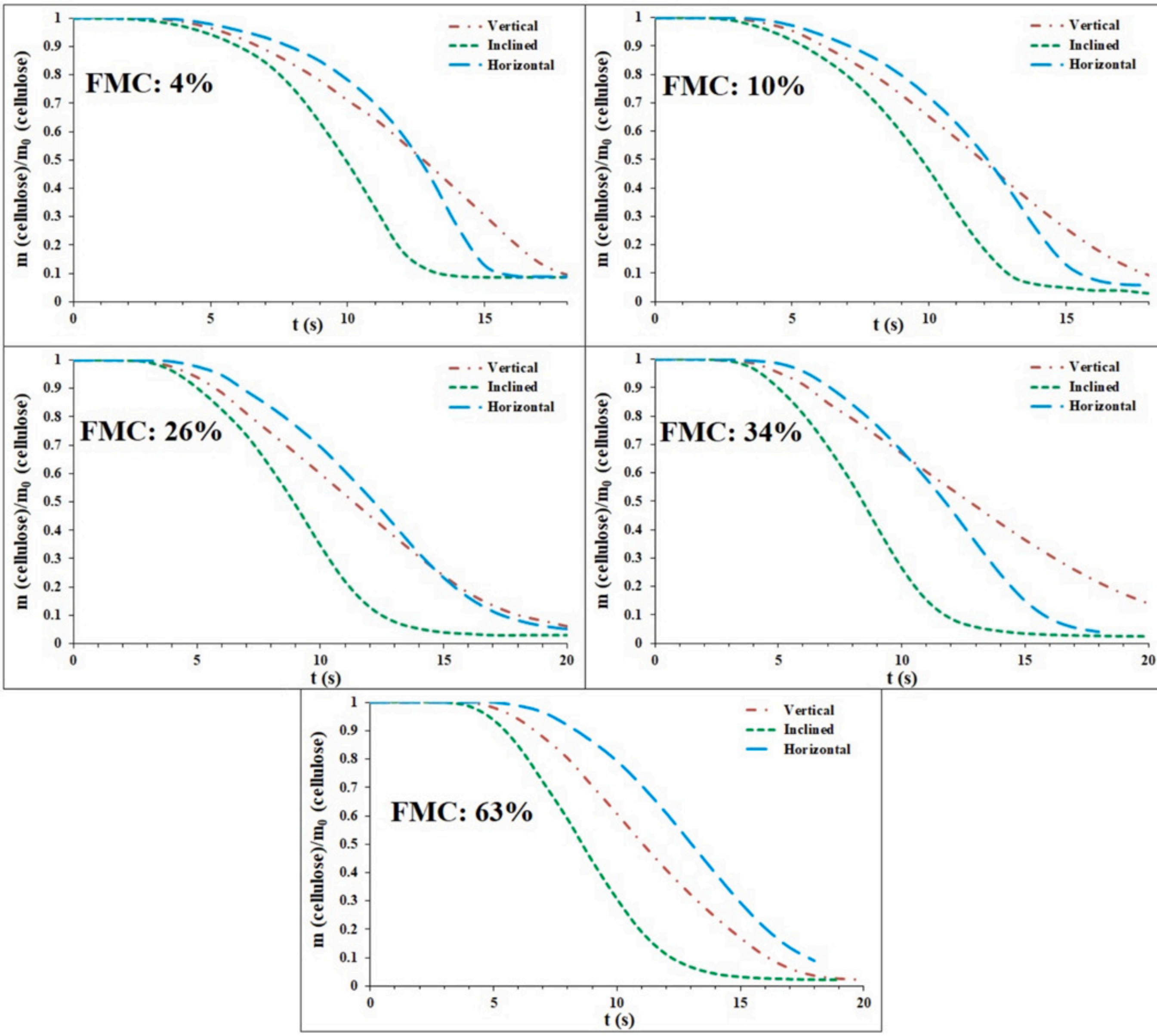

Fig. 13. Time evolution diagram of the dry fuel normalised mass for different cases with FMC = 4, 10, 26, 34, 63% and three different orientations.

case with horizonal orientation and FMC of 63% remained wet until 7.2 s.

In this study, the “burnout time” is defined as the duration between the onset of gas-phase combustion and the point at which the combustion process ceases. Furthermore, the term “dryout time” is defined as the period from the initiation of leaf heating until the point at which the moisture level reaches zero. Ignition time is defined using a temperature threshold, whereby the onset of sustained gas-phase combustion was assumed when the local gas temperature exceeded 1300 K and remained above this level for a sustained period. Similar temperature thresholds have been widely adopted in CFD studies to delineate flame regions and combustion zones [51–53].

The diagrams depicting ignition time, burnout time, and dryout time in relation to fuel moisture content across three distinct orientations are shown in Fig. 15. As can be seen, by increasing the FMC, the ignition and dryout time increases almost linearly. Nevertheless, the impact on burnout time, particularly beyond a moisture content of 26%, is relatively mild when increasing the moisture content. Hence, for the vertical cases, increasing the FMC from 4% to 63% results in a 105% increase in ignition time, a 13% increase in burnout time, and a 143% increase in dryout time. For the inclined case, the ignition time increases by 107% with the same FMC increase. Burnout time for the inclined case rises by 6%, while dryout time increases by 175%. In the horizontal leaf orientation, increasing FMC from 4% to 34% leads to a 114% increase in ignition time, an 8% increase in burnout time, and a 134% increase in dryout time.

5. Discussion

The results of this study highlight the critical influence of fuel moisture content and orientation on the drying, pyrolysis, ignition, and combustion processes of leaf-scale fuel elements. The results indicate that there is minimal if any interaction between FMC and orientation, both have an effect on burning characteristics, but they act independently.

As shown in Fig. 9, for each orientation, an increase in fuel moisture content leads to a decrease in the leaf temperature. The heat transferred by the hot flow helps to vaporize the moisture within the leaf. Therefore,

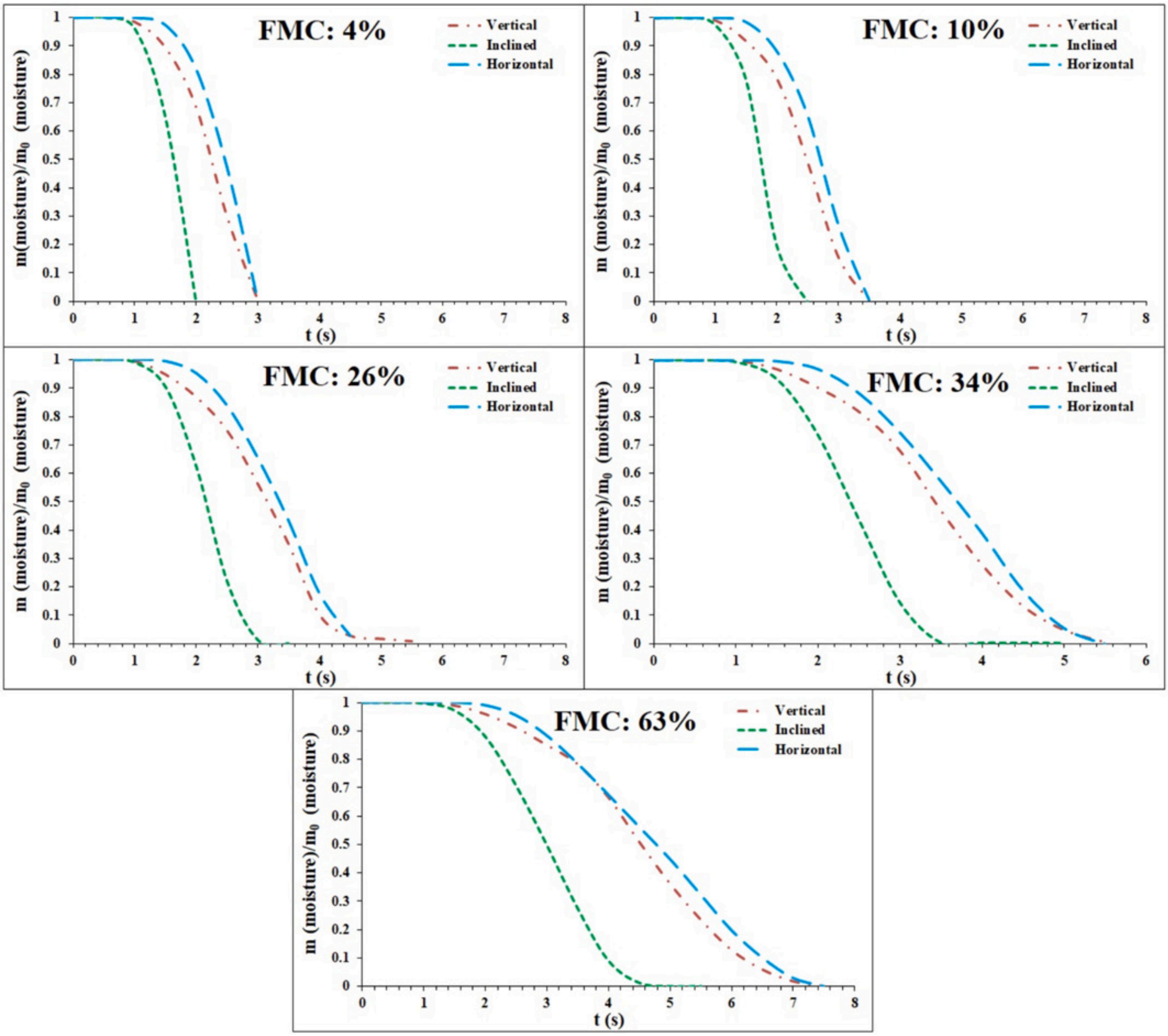

Fig. 14. Temporal diagram of moisture normalised mass for different cases with FMC = 4, 10, 26, 34, 63% and three different orientations.

higher FMC results in a lower temperature of the leaf. On the other hand, by changing the orientation of the leaf with the same FMC, the temperature distribution over the leaf changes. The leaf with horizontal orientation has the lowest overall temperature and starts warming up from its corners. This is due to the presence of a stagnation point under the leaf at the centre, producing a point with near zero air velocity that results in lower convective heat transfer. The case with vertical orientation has the second highest overall temperature. Its lower part has the highest temperature because of its more direct exposure to the hot air, while its upper part has the lowest temperature. More interestingly, the case with inclined orientation exhibits the highest overall temperature among the three different orientations. This suggests that there is a threshold in the angle between the air flow and the leaf, regarding the convective heat transfer. This is due to the highest exposure of the leaf to the hot air considering both factors of velocity and direction of the flow. The case with the horizontal orientation has the perpendicular direction to the hot flow, which helps the convective heat transfer, but has the stagnation point and low velocity flow. On the other hand, the case with vertical orientation has a higher air velocity at its vicinity, but its direction to the hot flow is parallel. Overall, the results indicate that the angle of attack (θ), which is defined as the angle between the direction of the fluid flow and the leaf surface normal, is of key importance in convective heat transfer. The angle of attack (θ) influences the development of the boundary layer around the leaf. Moreover, changing the angle of attack leads to the creation of recirculating flow and turbulence, affecting the overall dissipation of convective heat in the vicinity of the leaf. In other words, the divergence of flow and stagnation point affects the convective heating below the leaf. So, the case with the inclined (45° angle) orientation has the highest convective heat transfer, compared to vertical and horizontal cases.

In other terms, the variation of the convective heat transfer coefficient (h_{conv}) with the angle of attack (θ) exhibits a non-monotonic trend driven by the competing effects of tangential and normal flow components. When the angle of attack increases from the vertical position ($\theta = 0^{\circ}$) to the inclined configuration, the normal velocity component ($U_n = U\sin\theta$) increases (impingement effect), which enhances convective heat transfer across the surface. This condition promotes asymmetric flow over the leaf, with higher velocities along the windward side and the

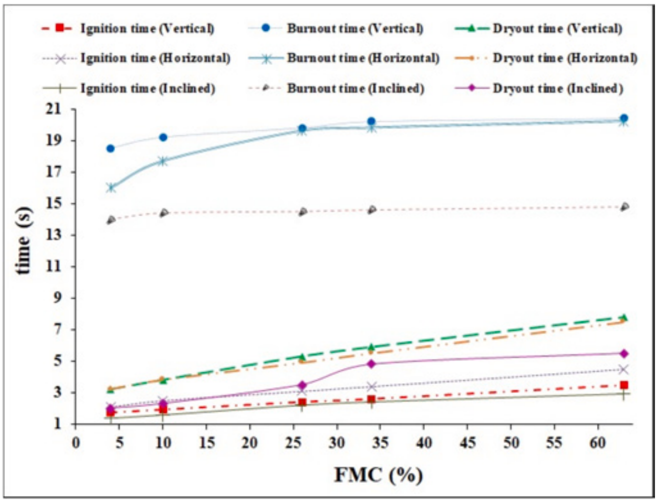

Fig. 15. Diagram of ignition time, burnout time, and dryout time, versus fuel moisture content, for the three different orientations.

formation of a downstream recirculation region, both of which strengthen heat transfer and accelerate drying, pyrolysis, and ignition. However, as the angle of attack continues to increase toward the horizontal orientation ($\theta \rightarrow 90^\circ$), the tangential component of velocity ($U_t = U\cos\theta$) diminishes, causing a stagnation point to develop at the central region of the leaf, leading to reduced near-surface velocity and localized heat transfer despite a strong impingement effect at the centre. This stagnation zone limits the convective heat transfer in the central region while slightly enhancing it toward the edges due to local flow separation. Consequently, the overall heat flux becomes lower and less uniform compared with the inclined case. Consequently, h_{conv} first increases with θ, reaching a maximum at an inclined angle where both tangential sweeping and normal impingement are balanced, and then decreases as stagnation effects dominate, confirming the existence of a threshold angle that optimizes convective heat transfer. Therefore, as the angle of attack increases from vertical → inclined → horizontal, the convective heat transfer first increases, reaches a maximum (at approximately the inclined case), and then decreases.

The HRR analysis, illustrated in Fig. 10, reveals that leaves with lower FMC ignite faster and release heat more rapidly. This is consistent with the understanding that drier fuels combust more intensely and quickly due to lower heat absorption requirements for moisture evaporation, allowing more energy to be used for combustion [54,55]. The inclined orientation was not only associated with accelerated onset of HRR but also achieved higher peak values compared to the vertical and horizontal orientations. This suggests that in vegetative fire scenarios, leaf-like fuel elements are more susceptible to ignition when they are inclined at an angle to the convective flow.

Looking at Fig. 12, after exposing the leaf to the hot air flow and allowing 3.5 s to elapse, it is observed that cases with lower fuel moisture exhibit greater advancement in the combustion process, which matches the results in Fig. 11. After heating the leaf to a temperature of approximately 300 °C [56], the cellulose starts to emit pyrolysis gases around the leaf, initiating the burning process and flame formation around the leaf. The cases with higher FMC levels emit the lowest amount of pyrolysis gas after 3.5 s. The spatial distribution of these pyrolysis gases is crucial for understanding flame propagation patterns. FMC and leaf orientation significantly impact pyrolysis gas release, highlighting the importance of considering both factors.

The pattern of flame formation varies based on the orientation of the leaf. In the horizontal orientation, a stagnation point with zero air velocity is present at the central bottom, causing the flow to diverge toward the corners. Consequently, flames begin to form above the corners of the leaf. In the vertical orientation, flames form at the lower edge of the leaf, which is the hottest part. For an inclined case, the pressure deficit and turbulent effects at the back side, downstream, result in an intermittent flame that forms at the lower part of the leaf.

As shown in Fig. 15, the ignition, dryout, and burnout times for the inclined leaves are shorter than those for other orientations. This indicates that all combustion processes occur more rapidly in inclined leaves compared to the horizontal and vertical leaves. Given this observation, along with the fact that FMC has a slight delaying effect on the combustion process, it is important to highlight that in the initial stages of combustion (at approximately 3.5 s, as shown in Fig. 11), the flame height for inclined leaves is greater than that for other orientations when higher FMC is present.

Examining Fig. 15 in greater detail, the linear increase in ignition and dryout times with higher FMC emphasizes the role of moisture in prolonging the pre-ignition phase. The relatively minor impact of FMC on burnout time beyond 26% indicates a threshold where additional moisture does not significantly delay combustion completion. This is consistent with operational doctrine, which state that the ideal FMC for prescribed burning is 9–16%, whereas an FMC of 25–30% is too wet to support sustained burning [55].

The FMC has a significant relation with the ignition process, which influences fire formation. The current study helps to understand how solid fuels ignite and the relationship of burning characteristics with factors such as moisture content and orientation to the convective heat source. The findings of this study enhance our theoretical understanding of how FMC and leaf orientation affect the ignition, drying, and burning processes of leaf-like fuel elements. These results shed light on the intricate physical mechanisms governing leaf combustion, offering a more detailed perspective on the factors influencing ignition times and burnout durations. Specifically, the study reveals that inclined leaves ignite and burn out more rapidly than those in horizontal or vertical orientations, highlighting the significant impact of orientation on combustion dynamics.

By elucidating these effects, our research contributes valuable knowledge to the field of fire behaviour modelling. The insights gained from this study can help refine theoretical models and potentially improve predictions of fire behaviour in various environmental conditions. This deeper understanding is essential for advancing fire science and enhancing our ability to model and predict combustion behaviour effectively. The outcomes of this study pave the way for further research in this field. Future studies could explore a broader range of orientations and moisture levels to gain a more nuanced understanding of fire dynamics. Additionally, investigating the effects of varying airflow velocities and directions could provide deeper insights into fundamental fire behaviour. For example, research could delve into the effects of turbulent flow around the leaf, examining turbulence factors and their impact on convective heating. Exploring different angles could help identify the threshold between different flow regimes around the leaf and hence different convective heating regimes. Understanding these dynamics can provide deeper insights into how air movement influences heat transfer and combustion processes. Incorporating other environmental factors, such as wind speed and humidity, would further enhance our fundamental understanding of ignition and combustion processes.

Natural vegetative fuels contain additional constituents such as hemicellulose, lignin, and minor organic compounds, and moisture migration and vapor transport within porous structures can influence local thermal gradients and ignition characteristics. The use of pure cellulose in this study was an intentional simplification adopted to isolate and examine the fundamental physical mechanisms, namely the influence of orientation on convective heat transfer, drying, and pyrolysis. Such an approach is well established in combustion research for decoupling geometric and thermal effects from the complexity of heterogeneous fuel composition [10,57–59].

The model does not explicitly include internal vapor transport; however, the evaporative energy sink and surface moisture removal processes are directly represented in the governing equations, allowing the simulations to capture the dominant thermal influence of FMC on ignition delay and heat-transfer dynamics. Importantly, the study does not aim to reproduce a specific vegetation species, but to establish fundamental knowledge and generalizable trends in how the alignment of thin fuel elements with an external flow controls the convective heating rate, ignition time, and flame evolution. The findings offer foundational insights with broader applicability beyond wildland fires to engineering applications, potentially informing fuel arrangement in combustion systems, drying technologies [60,61], thermal management [62], heat exchanger design and optimisation [63], and thermally driven material processes where spatial configurations influence heat and mass transfer. The current framework represents an approximation of biomass fuels, and that future work will extend the model to include multi-component solid composition and in-depth moisture transport to improve quantitative prediction under realistic fuel conditions.

6. Conclusions

This investigation systematically examined the influence of fuel moisture content (FMC) and orientation on the drying, pyrolysis, ignition, and combustion of leaf-scale solid fuels exposed to a convective heat source. The findings address a gap in existing models, where the influence of orientation on combustion dynamics has been overlooked, offering new insights into the role of orientation in pyrolysis behaviour. The key findings can be summarised as follows:

- This investigation reveals the presence of an optimum contact surface and angle of attack, demonstrating that inclined orientations enhance pyrolysis rates and flame formation more effectively than horizontal or vertical positions.
- There is a threshold angle between the airflow and the leaf that affects convective heat transfer due to the leaf's highest exposure to hot air, considering both velocity and direction of flow.
- Changing the leaf's orientation at a constant FMC alters the temperature distribution on the leaf, with the inclined orientation experiencing the highest temperature rise.
- In the horizontal cases, ignition occurs above the corners of the leaf, while in vertical cases, it occurs along the lower edge.
- The simulations also confirmed that increasing the FMC decreases the maximum HRR and changes the time of its occurrence.
- While ignition and dryout times grow almost linearly with increasing FMC, the effect on burnout time is less pronounced, especially beyond 26% moisture content.

Overall, this study provides new insight into how orientation and moisture jointly influence leaf-scale combustion dynamics. The results emphasis the role of geometry-induced convective interaction in determining ignition thresholds and flame evolution, contributing to improved understanding and modelling of fine-fuel behaviour.

Nomenclature

g	acceleration of gravity
P	Pressure
T	Temperature
E_a	Activation energy
u_i	Component of velocity in the i direction
Sc_t	Turbulent Schmidt number
R	Gas constant
δ	Kronecker delta
υ	Laminar viscosity
A	pre-exponential factor
h_{conv}	convective heat-transfer coefficient
WALE	Wall-Adapting Local Eddy-viscosity model
FMC	fuel moisture content
$\sim$	Favre (density-weighted) filter
HRR	heat release rate
$y+$	dimensionless wall distance
$\dot{\omega}$	mass consumption rate
ρ_s	averaged density of the species
Y_m	Mass fraction of species m
k	Reaction rate
h	Enthalpy
Pr_t	Turbulent Prandtl number
D_C	Laminar diffusion coefficient
ϕ	Viscous shear stress
e	Exponential function
α_t	Thermal diffusion coefficient
c_p	Specific heat
fvDOM	finite-volume Discrete Ordinates Method
LES	Large-Eddy Simulation
	spatial/filter average
HIR	heat input rate
μ	dynamic viscosity

CRediT authorship contribution statement

Ali Edalati-nejad: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sara McAllister:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Investigation. **Maryam Ghodrat:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Jason J. Sharples:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] S. Verma, A Large Eddy Simulation Study of the Effects of Wind and Slope on the Structure of a Turbulent Line Fire, University of Maryland, College Park, 2019.
[2] A.L. Sullivan, J.J. Sharples, S. Matthews, M.P. Plucinski, A downslope fire spread correction factor based on landscape-scale fire behaviour, Environ. Model Softw. 62 (2014) 153–163.
[3] A. Edalati-nejad, M. Ghodrat, J.J. Sharples, On the interaction of wind, fire intensity and downslope terrain with implications for building standards in wildfire-prone areas, Int. J. Wildland Fire. 32 (11) (2023) 1619–1632.
[4] J.J. Sharples, An overview of mountain meteorological effects relevant to fire behaviour and bushfire risk, Int. J. Wildland Fire 18 (7) (2009) 737–754.
[5] A. Edalati-nejad, M. Ghodrat, S.A. Fanaee, A. Simeoni, Numerical simulation of the effect of fire intensity on wind driven surface fire and its impact on an idealized building, Fire 5 (1) (2022) 17.
[6] W.W. Dillon, D. Hiatt, S.L. Flory, Experimental manipulation of fuel structure to evaluate the potential ecological effects of fire, For. Ecol. Manag. 482 (2021) 118884.

[7] C.R. Gosper, S.M. Prober, C.J. Yates, Multi-century changes in vegetation structure and fuel availability in fire-sensitive eucalypt woodlands, For. Ecol. Manag. 310 (2013) 102–109.
[8] R. Tangney, R. Miller, J. Fontaine, W. Veber, K. Ruthrof, B. Miller, Vegetation structure and fuel dynamics in fire-prone, Mediterranean-type Banksia woodlands, For. Ecol. Manag. 505 (2022) 119891.
[9] D. Morvan, Numerical study of the effect of fuel moisture content (FMC) upon the propagation of a surface fire on a flat terrain, Fire Saf. J. 58 (2013) 121–131.
[10] B. Yashwanth, B. Shotorban, S. Mahalingam, C. Lautenberger, D. Weise, A numerical investigation of the influence of radiation and moisture content on pyrolysis and ignition of a leaf-like fuel element, Combust. Flame 163 (2016) 301–316.
[11] K. Moinuddin, N. Khan, D. Sutherland, Numerical study on effect of relative humidity (and fuel moisture) on modes of grassfire propagation, Fire Saf. J. 125 (2021) 103422.
[12] A. Edalati-nejad, M. Ghodrat, J.J. Sharples, Quantifying downstream proximity effects on the thermal and combustion dynamics of cellulosic leaves in a convective flow, Int. J. Heat Fluid Flow 117 (2026) 110065.
[13] W. Ma, L. Zhai, A. Pivovaroff, J. Shuman, P. Buotte, J. Ding, B. Christoffersen, M. Moritz, C.D. Koven, L. Kueppers, Assessing climate change impacts on live fuel moisture and wildfire risk using a hydrodynamic vegetation model, Biogeosci. Discuss. 2020 (2020) 1–35.
[14] M.I. Asensio, J.M. Cascón, P. Laiz, D. Prieto-Herráez, Validating the effect of fuel moisture content by a multivalued operator in a simplified physical fire spread model, Environ. Model Softw. 164 (2023) 105710.
[15] T.M. Ellis, D.M. Bowman, P. Jain, M.D. Flannigan, G.J. Williamson, Global increase in wildfire risk due to climate-driven declines in fuel moisture, Glob. Chang. Biol. 28 (4) (2022) 1544–1559.
[16] T. Hu, L. Ma, Y. Gao, J. Fan, L. Sun, Modification and comparison of methods for predicting the moisture content of dead fuel on the surface of *Quercus mongolica* and *Pinus sylvestris* var. mongolica under rainfall conditions, Fire 6 (10) (2023) 379.
[17] J. Fan, T. Hu, J. Ren, Q. Liu, L. Sun, A comparison of five models in predicting surface dead fine fuel moisture content of typical forests in Northeast China, Front. For. Glob. Chang. 6 (2023) 1122087.
[18] B.M. Pickett, C. Isackson, R. Wunder, T.H. Fletcher, B.W. Butler, D.R. Weise, Experimental measurements during combustion of moist individual foliage samplesA, Int. J. Wildland Fire 19 (2) (2010) 153–162.
[19] B. Yashwanth, B. Shotorban, S. Mahalingam, D. Weise, A Numerical Investigation of the Effect of Moisture Content on Pyrolysis and Combustion of Live Fuels, 2014.
[20] H. Liu, C. Wang, A. Zhang, Numerical simulation of the wood pyrolysis with homogenous/heterogeneous moisture using FireFOAM, Energy 201 (2020) 117624.
[21] P.R. Borujerdi, B. Shotorban, S. Mahalingam, A computational study of burning of vertically oriented leaves with various fuel moisture contents by upward convective heating, Fuel 276 (2020) 118030.
[22] J.R. Gallacher, The Influence of Season, Heating Mode and Slope Angle on Wildland Fire Behavior, Brigham Young University, 2016, p. 28105514. Theses and Dissertations.
[23] D.R. Prince, Measurement and Modeling of Fire Behavior in Leaves and Sparse Shrubs, Brigham Young University, 2014.
[24] J.D. Engstrom, J.K. Butler, S.G. Smith, L.L. Baxter, T.H. Fletcher, D.R. Weise, Ignition behavior of live California chaparral leaves, Combust. Sci. Technol. 176 (9) (2004) 1577–1591.
[25] P.J. Zylstra, Forest Flammability: Modelling and Managing a Complex System, UNSW Sydney, 2011.
[26] J. Gong, J. Cao, C. Zhai, Z. Wang, Effect of moisture content on thermal decomposition and autoignition of wood under power-law thermal radiation, Appl. Therm. Eng. 179 (2020) 115651.
[27] D.R. Prince, T.H. Fletcher, Differences in burning behavior of live and dead leaves, part 1: measurements, Combust. Sci. Technol. 186 (12) (2014) 1844–1857.
[28] M. Chaos, M.M. Khan, N. Krishnamoorthy, J.L. de Ris, S.B. Dorofeev, Evaluation of optimization schemes and determination of solid fuel properties for CFD fire models using bench-scale pyrolysis tests, Proc. Combust. Inst. 33 (2) (2011) 2599–2606.
[29] Y. Ding, C. Wang, S. Lu, Modeling the pyrolysis of wet wood using FireFOAM, Energy Convers. Manag. 98 (2015) 500–506.
[30] A.G. Bradbury, Y. Sakai, F. Shafizadeh, A kinetic model for pyrolysis of cellulose, J. Appl. Polym. Sci. 23 (11) (1979) 3271–3280.
[31] A. Atreya, T. Crompton, J. Suh, A study of the chemical and physical mechanisms of fire suppression by water, Fire Saf. Sci. 6 (2000) 493–504.
[32] A. Dahale, S. Ferguson, B. Shotorban, S. Mahalingam, Effects of distribution of bulk density and moisture content on shrub fires, Int. J. Wildland Fire 22 (5) (2013) 625–641.
[33] OpenFOAM Foundation. OpenFOAM: The Open Source CFD Toolbox, 2009. https://openfoam.org.
[34] D. Le, J. Labahn, T. Beji, C.B. Devaud, E.J. Weckman, A. Bounagui, Assessment of the capabilities of FireFOAM to model large-scale fires in a well-confined and mechanically ventilated multi-compartment structure, J. Fire Sci. 36 (1) (2018) 3–29.
[35] Y. Wang, P. Chatterjee, J.L. de Ris, Large eddy simulation of fire plumes, Proc. Combust. Inst. 33 (2) (2011) 2473–2480.
[36] N. Ren, Y. Wang, S. Vilfayeau, A. Trouvé, Large eddy simulation of turbulent vertical wall fires, in: Proc. 7th International Seminar on Fire and Explosion Hazards, 2013.
[37] M. Kim, J. Lim, S. Kim, S. Jee, D. Park, Assessment of the wall-adapting local eddy-viscosity model in transitional boundary layer, Comput. Methods Appl. Mech. Eng. 371 (2020) 113287.
[38] S.C. Mishra, H.K. Roy, Solving transient conduction and radiation heat transfer problems using the lattice Boltzmann method and the finite volume method, J. Comput. Phys. 223 (1) (2007) 89–107.
[39] J. Chai, P. Rath, Discrete-Ordinates and Finite-Volume Methods for Radiation Heat Transfer, 2006.
[40] Y.P. Almeida, P.L. Lage, L.F.L. Silva, Large eddy simulation of a turbulent diffusion flame including thermal radiation heat transfer, Appl. Therm. Eng. 81 (2015) 412–425.
[41] P. Rahimi Borujerdi, B. Shotorban, Pyrolysis and combustion characteristics of leaf-like fuel under convection and radiation heating, Combust. Sci. Technol. 194 (12) (2022) 2558–2579.
[42] I. Mahle, J. Mellado, J. Sesterhenn, R. Friedrich, S. de Ingenieros, LES of reacting turbulent shear layers using infinitely fast chemistry, in: Contribution to: Turbulence and Interaction, 2006.
[43] A. Favre, Turbulence: space-time statistical properties and behavior in supersonic flows, Phys. Fluids 26 (10) (1983) 2851–2863.
[44] E. Amini, M.-S. Safdari, N. Johnson, D.R. Weise, T.H. Fletcher, Pyrolysis kinetics of wildland vegetation using model-fitting methods, J. Anal. Appl. Pyrolysis 157 (2021) 105167.
[45] Q. Xue, D. Dalluge, T. Heindel, R. Fox, R. Brown, Experimental validation and CFD modeling study of biomass fast pyrolysis in fluidized-bed reactors, Fuel 97 (2012) 757–769.
[46] W.-C.R. Chan, M. Kelbon, B.B. Krieger, Modelling and experimental verification of physical and chemical processes during pyrolysis of a large biomass particle, Fuel 64 (11) (1985) 1505–1513.
[47] J. Sodagar-Abardeh, P. Nasery, A. Arabkoohsar, M. Farzaneh-Gord, Numerical study of magnetic field influence on three-dimensional flow regime and combined-convection heat exchange within concentric and eccentric rotating cylinders, J. Energy Resour. Technol. 142 (11) (2020) 112115.
[48] A. Edalati-nejad, S.A. Fanaee, M. Ghodrat, J. Khadem, Investigation of unsteady premixed micro/macro counterflow flames for lean to rich methane/air mixture, J. Energy Resour. Technol. 143 (5) (2021) 052302.
[49] A. Edalati-nejad, M. Ghodrat, J.J. Sharples, Modelling the moisture effect on the rate of spread of fire in a leaf-like fuel element, in: Proc. 23rd Australian Fluid Mechanic Conference-23, AFMC, Sydney, Australia, 2022, p. 242.
[50] F.J. Matt, M.A. Dietenberger, D.R. Weise, Summative and ultimate analysis of live leaves from southern US forest plants for use in fire modeling, Energy Fuel 34 (4) (2020) 4703–4720.
[51] H. Zhang, X. Cao, X. Yuan, F. Wu, J. Wang, Y. Zhang, Q. Li, H. Liu, Z. Huang, Study on thermal radiation characteristics and the multi-point source model of hydrogen jet fire, Appl. Sci. 14 (16) (2024) 7098.
[52] Y. Zhu, S. Luo, Y. Zhao, Y. Zeng, G. Wu, R. Wei, S. Sun, Numerical simulation of downward flame propagation in discontinuous region of solid fuel, Fire 6 (5) (2023) 207.
[53] D. Cirrone, D. Makarov, M. Kuznetsov, A. Friedrich, V. Molkov, Effect of heat transfer through the release pipe on simulations of cryogenic hydrogen jet fires and hazard distances, Int. J. Hydrog. Energy 47 (50) (2022) 21596–21611.
[54] K.E. Gibos, Effect of Slope and Aspect on Litter Layer Moisture Content of Lodgepole Pine Stands in the Eastern Slopes of the Rocky Mountains of Alberta, 2010.
[55] M.M. Masinda, L. Sun, G. Wang, T. Hu, Moisture content thresholds for ignition and rate of fire spread for various dead fuels in northeast forest ecosystems of China, J. For. Res. 32 (2021) 1147–1155.
[56] A. Fukutome, H. Kawamoto, S. Saka, Gas-phase pyrolysis of methyl glucosides and levoglucosan, J. Wood Sci. 63 (2017) 295–306.
[57] D. Shen, M. Fang, W. Chow, A review on ignition of cellulose materials under external heat flux, Int. J. Eng. Perform. Based Fire Codes 8 (2006) 28–42.
[58] A.L. Sullivan, R. Ball, Thermal decomposition and combustion chemistry of cellulosic biomass, Atmos. Environ. 47 (2012) 133–141.
[59] Y. Chen, A. Frendi, S. Tewari, M. Sibulkin, Combustion properties of pure and fire-retarded cellulose, Combust. Flame 84 (1–2) (1991) 121–140.
[60] M. Ge, G. Chen, W. Liu, C. Liu, Study of heat and mass transfer during drying process of maize grain pile based on computed tomography, Biosyst. Eng. 248 (2024) 82–96.
[61] D.E. Maier, F.W. Bakker-Arkema. Grain drying systemsProceedings of the Facility Design Conference of the Grain Elevator & Processing Society, St. Charles, Illinois, USA, July, 2002, pp. 28–31.
[62] M. Anwarullah, V.V. Rao, K. Sharma, Effect of nozzle spacing on heat transfer and fluid flow characteristics of an impinging circular jet in cooling of electronic components, Int. J. Therm. Environ. Eng. 4 (1) (2012) 7–12.
[63] A.K. Hassan, M.M. Aldabbagh, K.S. Mohammed, M.A. Eleiwi, H.S. Majdi, Effect of tube arrangements on water heat transfer in a rectangular channel: a computational fluid dynamics study, Int. J. Heat Technol. 43 (2) (2025).