

Spring Technical Meeting
of the Central States Section of the Combustion Institute
March 16-18, 2014.

A numerical investigation of the effect of moisture content on pyrolysis and combustion of live fuels

*B. L. Yashwanth*¹ *B. Shotorban*^{1*} *S. Mahalingam*¹ *D. R. Weise*²

¹*Department of Mechanical and Aerospace Engineering,
The University of Alabama in Huntsville, Huntsville, AL 35899, USA*

²*Pacific Southwest Research Station,
USDA Forest Service, Riverside, CA 92507, USA*

The effect of moisture content on the pyrolysis and gas-phase ignition of live fuels is investigated. Live fuels contain moisture content (dry basis) in the range of 30-200%. Here the fuel is modeled as a thin cellulosic material that is subjected to radiative heating on one side. The solid fuel has a dimensions of a typical Manzanita leaf. The coupled Gpyro3D/FDS model (Lautenberger, 2014) that simulates both solid phase thermal degradation and gas phase combustion was used. In addition, a five-step extended Broido-Shafizadeh reaction model that accounts for thermal degradation, moisture evaporation, and pyrolysis of cellulose was incorporated in Gpyro3D. The solid-phase model was initially validated against Blasi (1994) and a thermo-gravimetric analysis experiment (Reed and Posey, 1980). Subsequently, the coupled Gpyro3D/FDS model was utilized to study the ignition of cellulosic fuel with an initial, uniformly distributed moisture content of 40% and 80%. The case with lower moisture content underwent pyrolysis and ignition earlier in time, resulting in higher solid and gas phase temperatures. Furthermore, a local moisture evaporation and temperature rise were observed in both cases and a significant amount of moisture remained in the sample during ignition. The numerical results suggested that moisture content not only affected the gas phase combustion and ignition time of the fuel, but also influenced the pyrolysis process.

1 Introduction

Wildland fires can threaten life, property, and natural resources, yet they can perform necessary ecological functions throughout the world. A large number of fires occur in live fuels that contain significant moisture. Fires that burn through large areas of live vegetation often consists of smaller fuel elements such as leaves, twigs and branches. The ability to predict the spread of these wildland fires in live fuels is paramount in protecting both property and ecology.

When a solid fuel is heated to a sufficiently high temperature, it undergoes thermal degradation [1]. Thermal degradation occurs in two sequential steps. The first step is pyrolysis, which is usually an endothermic process that breaks down the forest matter into low molecular mass gases

*To whom correspondence should be addressed: babak.shotorban@uah.edu

(volatiles), tars, carbonaceous char and mineral ash. The second process is burning, which is an exothermic process known as combustion. Ignition is a transition process between the first and second step. In flaming combustion, it is these gaseous products of pyrolysis that ignite and burn as a diffusion flame over the surface.

All plant matter consists of different polymers present in the organic fraction of the fuel. They are generally divided into cellulose, hemicellulose, lignin, moisture, mineral matter and a few other organic compounds [2]. Hemicellulose, cellulose and lignin are the three main components of biomass and their proportions are 20–40, 40–60, and 10–25%, respectively [3]. Cellulose is the main component among all the constituents of plant matter. Therefore, a better understanding of various physical and chemical processes during its thermal degradation is a first step towards the development of pyrolysis models of complex solid fuels.

Chemical reactions of cellulosic materials exposed to high temperature sources can be roughly classified as primary and secondary reactions. Primary reactions are concerned with the degradation of the cellulosic fuel into char and numerous volatile products whereas secondary reactions are those undergone by primary volatile products [4]. The first kinetic models were proposed in the 1960s by Kilzer and Broido [5], Chatterjee and Conrad [6] and Shafizadeh [7], and are the basis of more recent kinetic models. Cellulose is assumed to decompose through two parallel or competitive reactions [5, 7]. Results obtained by Broido [5] and other investigators [6, 7] indicated that lower heating rate yields more char. Below approximately 280°C, the formation of char is assumed favored while above this temperature, formation of tar is assumed favored. The reason for this assumption could be due to the predominant depolymerisation reactions associated to the breakage of glycosidic bonds [8]. For high heating rates, Lewellen et al. [9] suggested that there is no char formation as the case in flash pyrolysis processes, aimed to produce liquid tar with a maximum yield. Several investigators have developed multi-step kinetic models more or less derived from the original mechanism of Kilzer and Broido [5]. Bradbury et al. [10] reformulated Broido's reaction model by introducing active cellulose, as an intermediate species between native cellulose and reaction products and this reaction model is called as 'Broido–Shafizadeh model (BS)'. Blasi [4] in her numerical work used the BS model of cellulose pyrolysis and extended it to include secondary reactions concerning the tar cracking. This has been referred as extended Broido–Shafizadeh model by [11].

Fuel moisture content (FMC) present in the plant matter is an important factor that influences the burning behaviour of live fuels [12]. Water affects ignition processes involving both solid and gas phases. According to [13], if all of the water within the fuel does not evaporate prior to ignition, then the water vapor will dilute the gaseous pyrolyzates, making it more difficult to generate a flammable mixture [14]. Ignition temperature increased by about 2°C for each percent increase in moisture [15]. Water has three effects on the solid according to [16]: it changes the thermal properties of the material (density, thermal conductivity, and specific heat), it transfers heat by molecular diffusion, and its evaporation is strongly endothermic. Some disagreement was found in the literature about whether FMC has a stronger effect on the solid phase or the gas phase. Babrauskas [13] claims the gas phase effect to be minor in comparison to the solid phase effects. Moreover, temperature profiles and pyrolysis rates at different points are modified by the FMC. However, Abu-Zaid [17] claims that the increase in ignition temperature with FMC is more important than the impact on solid pyrolysis. According to Pickett et al. [18], who investigated

the burning of various live leaf samples in detail, ignition does not occur at the end of global evaporation, as predicted by conventional models, but possibly at the end of local evaporation. They also found that a significant amount of moisture (30–60%) remains in the sample for most species at the time of ignition. Their experiments did not focus on pyrolysis and other physical processes inside the fuel while it pyrolyses. Experiments conducted by McAllister et al. [19] also reveal that there exists considerable amount of temperature and moisture gradients inside the solid during pyrolysis of moist fuels which are assumed to be thermally thin.

Ignition criteria are primarily defined based on whether the investigation involved are only a solid phase or combined solid and gas phase. There exist a wide range of these criteria due to various reason such as design of the test apparatus, the experimental operating conditions, incident heat flux, air flow and other factors. Key ignition criteria defined for solid phase involving cellulosic materials are based on surface ignition temperature, critical mass flux of volatiles, time to ignition and critical heat flux [20]. In case of gas phase, critical mass flux and heat release rate (HRR) are the two criteria discussed by [21] and [22]. According to [21], flaming combustion occurs when the maximum gas reaction rate exceeds a critical value of 0.2 kg/m^3 . A single value of heat release rate, as a reasonable criterion for ignition, is proposed by Kokkala and Baroudi [22]. In the current study, the time at which the HRR becomes positive in the gas phase over the surface of cellulose element, is considered as the ignition time.

The main aim of the present work is to better understand the effects of moisture content on pyrolysis and gas phase combustion in solid fuel composed of cellulose by taking into account multi-step thermo-physical processes occurring in the solid fuel and the associated combustion of the released gases using a three-dimensional solid-gas model. The solid model uses Gpyro3D [23] for pyrolysis and the gas phase fluid dynamics and combustion is solved using Fire dynamic simulator (FDS) [24].

2 Physical configuration

In a spreading wildland fire, unburnt vegetation that lies ahead of burning vegetation is exposed to varying combinations of convective and radiative heating. The heat fluxes associated with radiation are as high as 200 kW/m^2 [18, 19]. The focus of the present work is on an analysis of the effect of FMC during ignition achieved via radiation heating of a thin, rectangular cellulose material. The fuel element we choose is a three-dimensional piece ($0.04 \times 0.04 \times 0.002 \text{ m}$, $L \times W \times T$) of cellulose material with fixed thickness. The choice of this configuration is motivated by its similarity to experimental configurations studied by Pickett et al. [18]. A schematic of the physical domain along with the boundary conditions is shown in figure 1. The computational domain used for the gas-phase solver FDS, is a rectangular cube of size $x = 0.18 \text{ m}$, $y = 0.18 \text{ m}$ and $z = 0.16 \text{ m}$. The grid resolution used in x , y and z directions is $168 \times 168 \times 112$, respectively. The solid fuel particle is centered in the gas-phase domain and located at $z = 0.03 \text{ m}$ in the computational domain. The initial temperature, moisture content, pressure, gaseous species mass fractions, and condensed phase species were set uniform throughout the solid. Fuel element is simulated as a separate region modeled by Gpyro3D with a grid spacing of 0.0019 m in the x and y directions and 0.0005 m along the depth. Here, 1936 grid cells are used for Gpyro3D. The fuel element is exposed to a radiant surface located at $x = -0.09 \text{ m}$. The surface is maintained at 1500K through

the entire simulation. Effects of wind are not considered here.

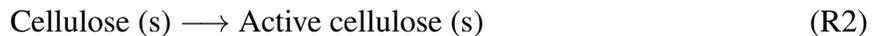
All the computations were performed using message passing interface (MPI) protocol using 18 processors of Dense Memory Cluster (DMC) located at Alabama Supercomputer Authority. A typical simulation of 30 seconds required a wall time of 72 hours and 64 GB of memory.

3 Reaction mechanism and computational models

A considerable amount of temperature and moisture variation was observed along the surface of fuel by Pickett et al. [18] and according to McAllister et al. [19] these gradients were observed along the depth of the fuel, indicating a three-dimensional nature of pyrolysis. CFD models such as FDS and FireFOAM resolve heat transfer only in the direction normal to the surface but not laterally in the directions parallel to the surface [23], which is important in the present context. Therefore, to investigate the three-dimensional effects during fire initiation and propagation on fuel elements where multidimensional heat and mass transfer effects are significant, a fully coupled Gpyro3D-FDS model is used. The model uses Gpyro3D for the solid phase degradation and FDS for gas phase combustion. Detailed descriptions of mathematical models with main assumptions and governing equations used in Gpyro3D and FDS are given in [23] and [24], respectively.

Here, only the essential features concerning the pyrolysis model of cellulose is highlighted: The governing equations involving the four condensed phase and four gas phase species consist of mass conservation of species expressed in terms of their mass fractions (four in the condensed phase and four in the gas phase), an overall mass conservation equation in terms of mass averaged density for the solid and overall gas density in the gas phase, and a single conservation of energy. The condensed and gas phases are considered to be in thermal equilibrium, and thus a single conservation of energy equation for the solid phase suffices. The gas phase mass conservation equation is formulated using Darcy’s law for the overall mass flux. Initially, the condensed-phase domain consists of moisture and cellulose and the gas phase domain consists of air (nitrogen and oxygen). Their respective initial mass fractions are given in Table 1. The initial mass fractions of other species were considered negligible. The initial temperature was 300K. Gpyro3D is coupled to FDS by obtaining the radiation and convective heat flux from FDS, which are applied as boundary conditions to the condensed phase. The solution is advanced in time for Gpyro3D. The obtained surface temperature is then passed from Gpyro3D to FDS. An analogous procedure is followed for gas-phase species, with the calculated mass flux of each species passed from Gpyro3D to FDS.

The chemical reactions used in the current study are as follow:



Reactions R2-R4, known as Broido-Shafizadeh reaction model [10], are primary reactions and R5

is a secondary reaction included by Blasi [4] for pyrolysis of cellulose. The primary reaction are concerned with the breakdown of cellulose to lower molecular weight gases while the secondary reaction, which is an oxidation reaction, is concerned with the tar breakdown to low molecular weight gases. In the current study, reaction R1 is included to take into account the evaporation of the moisture [25]. The reaction kinetics and thermo-physical properties for reaction R1 is adopted from [25] and for reactions R2-R5, are adopted from [4].

As discussed earlier, FMC also affects the thermal properties of the material, it is therefore necessary to account for the material functionality in terms of FMC. When the FMC is more than the fiber saturation point (FSP) of that material, all the water is present in the lumen as free water since the cell walls are now saturated with bound water [26]. Also both the density and volume increase up to the FSP whereas above this point, only the density increases. The FSP is usually considered to be around 30% (dry basis). In the current study, only density was considered moisture dependent through the correlation of [26]. On the other hand, thermal conductivity and specific heat capacities were considered only temperature dependent, following the correlations given by Yu et al. [27] and Reed and Posey [28], respectively. Here, since no equations that correlates the thermo-physical properties of cellulose with temperature were found, such correlations which are available for wood were utilized for cellulose:

$$\rho_{\text{cellulose}} = 1000 G_m \left(1 + \frac{M}{100} \right) \quad (\text{kg m}^{-3}), \quad (1)$$

$$k_{\text{cellulose}} = 0.08124 + 0.003695T \quad (\text{W m}^{-1} \text{K}^{-1}), \quad (2)$$

$$c_{\text{cellulose}} = 0.1031 + 0.00386T \quad (\text{kJ kg}^{-1} \text{K}^{-1}), \quad (3)$$

$$c_{\text{char}} = 1.39 + 0.00036T \quad (\text{kJ kg}^{-1} \text{K}^{-1}), \quad (4)$$

where ρ , G_m , M , k , T and c represent density, specific gravity, FMC, thermal conductivity, temperature and specific heat, respectively. The specific gravity used here is based on softwood species [26]. The properties for the remaining species were considered constant.

4 Results and Discussions

In order to validate the model, the simulations were first performed with only Gpyro, a one-dimensional version of Gpyro3D, for a configuration numerically studied by Blasi [4]. The configuration consist of a one dimensional slab with thickness of 0.025 m exposed to combined radiative and convective heating on one side and insulated on the other. The radiative and convective temperatures were increased from 450 K to 1100 K by using a heating rate of 15 K/s, following Ref. [4]. Since the model [4] did not account for moisture, the reaction R1 was not included for this validation. Figures 2(a), (b) and (c) illustrate the comparison between temperature, mass concentration of active cellulose and gas phase species velocity along the thickness of the slab at different times. The results of the current study are in reasonably good agreement with Blasi's

results [4]. It is seen that the greatest discrepancy between our model and Blasi's is in the gas phase velocity. The difference between the results of Blasi [4] and the current study can be mainly attributed to our assumption of temperature-dependent thermo-physical properties are considered temperature dependent which are assumed constant by Blasi [4]. Our explanation for a sudden increase and decrease of the concentration of active cellulose, as seen in fig. 2(b), is that active cellulose is formed initially as a result of depolymerization of cellulose; however, due to pyrolysis, it further undergoes destruction to char and gas species. It is also noted that the gas phase species velocity, seen in fig. 2(c), is a result of pressure gradients inside the specimen.

Further validation of the model was performed via the comparison of the modeling results against the experimental data of Reed and Posey [29]. They heated 6 mg of cellulose with a rate of $40\text{ }^{\circ}\text{C min}^{-1}$ to generate experimental thermogravimetric analysis (TGA) data. In the current study, a zero-dimensional model of Gypro was used to predict this experimental data. As seen in fig. 3, the remaining weight predicted by the model for this setup is in good agreement with that obtained experimentally [29]. The first reaction R1 was neglected in the modeling for this validation as well since experiments did not consider a moist specimen.

The classical combustion model assumes that all moisture will first evolve from the sample at a temperature near the boiling point of water. Ignition (according to the classical model) occurs when a combustible mixture of pyrolysis gases is obtained and follows shortly after moisture evaporation is complete [18]. In order to investigate this claim, for the main configuration considered in this work (Fig. 1), time history of temperature and mass fraction of moisture are plotted for a fixed point in figure 4. The point is noted as point A in fig. 1 which is located in the solid phase and is in proximity to the heat source. Figure 4(a) shows that the temperature slowly responds for the case involving higher FMC. This behavior could be attributed to the higher thermal conductivity of water compared to cellulose. The decay of mass fraction of moisture is illustrated in fig. 4(b), and it is observed that the evaporation rate is low for the case with high FMC. In order to analyze the temperature and FMC in the solid fuel at a region away from the heat source, temperature and mass fraction of moisture have been plotted at time 5 s.

Figures 5(a) and 5(b) display the variation of the temperature and moisture mass fraction variation, respectively, along the domain of the solid in x direction at $y = 0$ and $z = 0.0315$ m. It is seen in these two figures that temperature and evaporation of moisture locally rise at a region closer to the heat source. The temperature is higher all along the length for the case with lower FMC and a significant amount of moisture remained in the sample at the time of ignition. Two-dimensional contours of temperature and mass fraction of moisture are plotted along a xz slice located at $y = 0$ for an FMC of 80% in the solid phase and is as shown in figs 6(a) and (b). High temperature and moisture gradients are present along the x and z direction indicating that different points in the domain pyrolyze at different instants and rates. These observations agree well with the experiments [18] and are in contrast with the classical combustion model.

As a result of pyrolysis, pyrolysate or fuel vapors are released into the gas phase. The reaction of fuel vapors with air leads to flaming combustion. The fuel vapors are modeled as propane and is assumed to mix with air. The ignition time observed was 3.6 and 4.5 s for the two cases with an FMC of 40% and 80%, respectively. The two-dimensional contours of temperature and volume fraction of moisture are plotted along an xz slice located at $y = 0$ are shown in figs 7(a) and (b) for an FMC of 80% in the gas phase. Although ignition time was at 4.5 s for this case, flaming

combustion was observed at time 8 s, with peak gas phase temperatures at 900 °C. This flaming combustion zone was initially observed at a region close to the radiative heat source. As seen from fig. 7(b), the vapor (water) is predominant in the region away from the combustion zone, clearly manifesting the point that evaporation and combustion occur together. A three-dimensional view of instantaneous HRR are shown in fig. 8(a). The observed values are in the range of 30–50W. These low values of HRR could be attributed to the smaller dimensions of the cellulose particle, which result in low yields of fuel vapors.

5 Conclusions and Future Work

The effect of moisture content on pyrolysis and combustion of a thin cellulose particle subject to heating by radiation has been investigated numerically. The thermal degradation reaction mechanism used for cellulose breakdown was initially validated with other simulation and TGA experiments. An FMC of 40% and 80% was considered during the study. The temperature response and thermal degradation rate was higher for the case with 40% FMC and ignition occurred prior to the 80% FMC case. In the solid phase local evaporation of moisture and temperature rise at a point closer to the heat source was observed, also a significant amount of moisture remained in the sample at the time of ignition indicating that different points in the domain pyrolyze at different times. In the gas phase, high volume fraction of water vapor was observed in the region away from the combustion zone clearly manifesting the point that evaporation and combustion can occur together. The effect of heat source involving convection and combined radiation and convection on fluid dynamics, moisture content, pyrolysis and combustion of live fuels involving single and multiple fuel configurations will be the focus of our future work.

Acknowledgments

The authors gratefully acknowledge the financial support from the USDA Forest Service PSW Research Station through cooperative agreement 10-JV-11272166-091 with The University of Alabama in Huntsville. The authors thank Christopher W. Lautenberger for providing assistance on configuring and using Gpyro3D coupled with FDS.

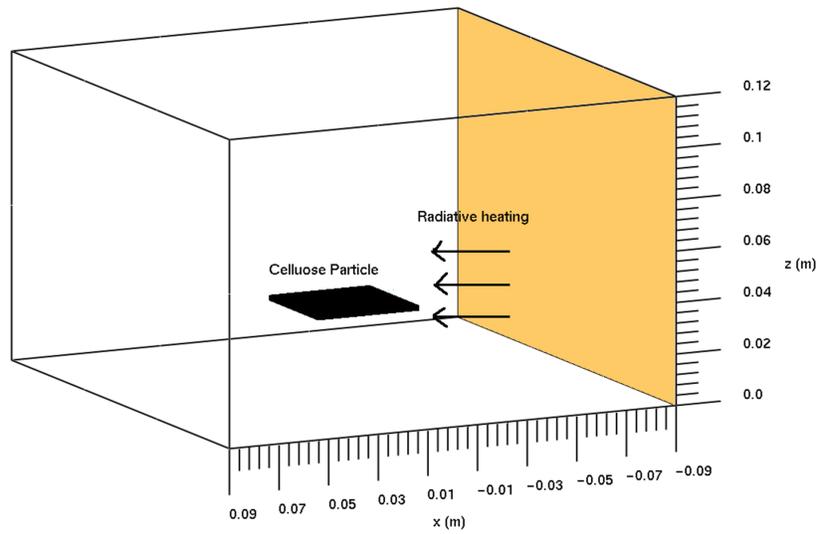
References

- [1] F. Shafizadeh. The chemistry of pyrolysis and combustion. In R. Rowell, editor, *Chemistry of Solid Wood*, Vol. 207, pages 489–529. ACS Publications, 1984.
- [2] M. W. van de Weerdhof. Modeling the pyrolysis process of biomass particles. MS Thesis, Eindhoven University of Technology, Eindhoven, The Netherlands, March 2010.
- [3] H. Yang, R. Yan, H. Chen, D. H. Lee, and C. Zheng. *Fuel*, 86 (2007) 1781 – 1788.
- [4] C. D. Blasi. *Biomass and Bioenergy*, 7(1-6) (1994) 87 – 98.
- [5] F. J. Kilzer and A. Broido. *Pyrodynamics*, 2 (1965) 151 – 163.
- [6] P.K. Chatterjee and C.M. Conrad. *Textile Research Journal*, 36 (1966) 487.
- [7] F. Shafizadeh. Pyrolytic reactions and products of biomass. In R. P. Overend, T. A. Milne, and L. K. Mudge, editors, *Fundamentals of Thermo-Chemical Biomass Conversion*, pages 183 – 217. 1985.

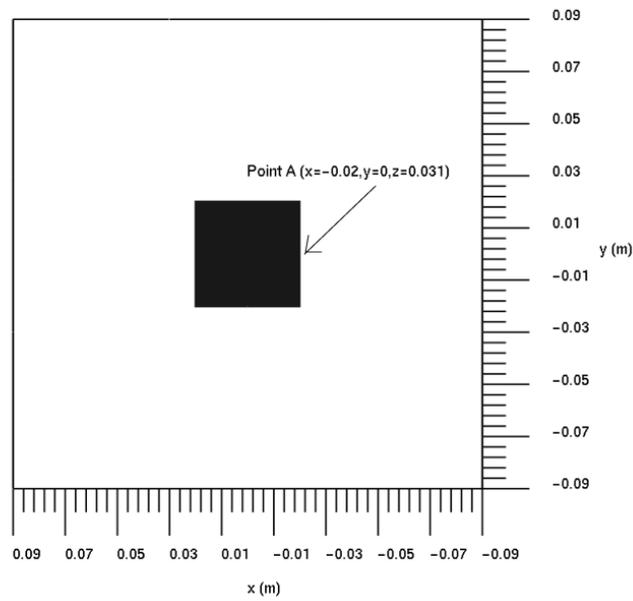
- [8] R. Capart, L. Khezami, and A. K. Burnham. *Thermochimica Acta*, 417 (2004) 79 – 89.
- [9] P. C. Lewellen, W. A. Peters, and J. B. Howard. Cellulose pyrolysis kinetics and char formation mechanism. In *International Symposium on Combustion*, Vol. 16, pages 1471–1480, 1977.
- [10] A. G. W. Bradbury, Y. Sakai, and F. Shafizadeh. *Journal of Applied Polymer Science*, 23 (1979) 3271–3280.
- [11] N. Bechand, M. B. Larsen, P. A. Jensen, and K. D. Johansen. *Biomass and Bioenergy*, 33 (2009) 999 – 1011.
- [12] C. M. Countryman. *Fire Management Notes*, 35 (1974) 10–14.
- [13] V. Babrauskas. *Ignition Handbook*. Fire Science Publishers, Issaquah, WA.
- [14] S. C. Ferguson, A. Dahale, B. Shotorban, S. Mahalingam, and D. R. Weise. *Combustion Science and Technology*, 185 (2013) 435 – 453.
- [15] M. Janssens. *Fire Materials*, 15(4) (1991) 151 – 167.
- [16] D. L. Simms and M. Law. *Combustion and Flame*, 11(5) (1967) 377 – 388.
- [17] M. Abu-Zaid. *Effect of Water on Ignition of Cellulosic Materials*. PhD Thesis, Michigan State University, East Lansing, MI, March 1988.
- [18] B. M. Pickett, C. Isackson, R. Wunder, T. H. Fletcher, B. W. Butler, and D. R. Weise. *International Journal of Wildland Fire*, 19 (2010) 153 – 162.
- [19] S. McAllister, I. Grenfell, A. Hadlow, W.M. Jolly, M. Finney, and J. Cohen. *Fire Safety Journal*, 51 (2012) 133 – 142.
- [20] D. K. Shen and M. X. Fang. *International Journal on Engineering Performance-Based Fire Codes*, 8(2) (2006) 69 – 83.
- [21] N. Boonmee and J. G. Quintiere. *Fire Safety Science—Proceedings of the 8th International Symposium*, (2005) 139 – 150.
- [22] M. Kokkala and D. Baroudi. A thermal model for upward flame spread on a combustible wall. In *Raportti A.2*, Espoo, Finland, 1993. Valtion Teknillinen Tutkimuskeskus.
- [23] C. W. Lautenberger. *Fire Safety Science (IAFSS Symposium)*, (2014) .
- [24] K. McGrattan, S. Hostikka, J. Floyd, H. Baum, and R. Rehm. Fire Dynamics Simulator, Version 5. Technical Reference Guide, NIST, 2007.
- [25] K. M. Bryden, K. W. Ragland, and C. J. Rutland. *Biomass and Bioenergy*, 22 (2002) 41 – 53.
- [26] Wood handbook. General Technical Report FPLGTR190, Forest Products Laboratory, United States Department of Agriculture Forest Service, 2010.
- [27] Z. T. Yu, X. Xu, L. W. Fan, Y. C. Hu, and K. F. Chen. *Forest Products Journal*, 6(2) (2011) 130 – 135.
- [28] K. W. Ragland and D. J. Aerts. *Bioresource Technology*, 37 (1991) 161 – 168.
- [29] T. B. Reed and F. Posey. Golden, CO, USA, 1980. Unpublished data at SERI.

Table 1: Initial mass fractions

FMC	Moisture	Cellulose	N ₂	O ₂
80%	0.46	0.56	0.77	0.23
40%	0.22	0.78	0.77	0.23



(a)



(b)

Figure 1: (a) Isometric view of computational domain showing thin cellulose particle subjected to radiative heating from surface at $x = -0.09$ m, (b) two-dimensional view of computational domain along the xy -slice at $z = 0.031$ m. Point A located at $x = -0.02$ m, $y = 0$ m, $z = 0.0315$ m is considered for analysis.

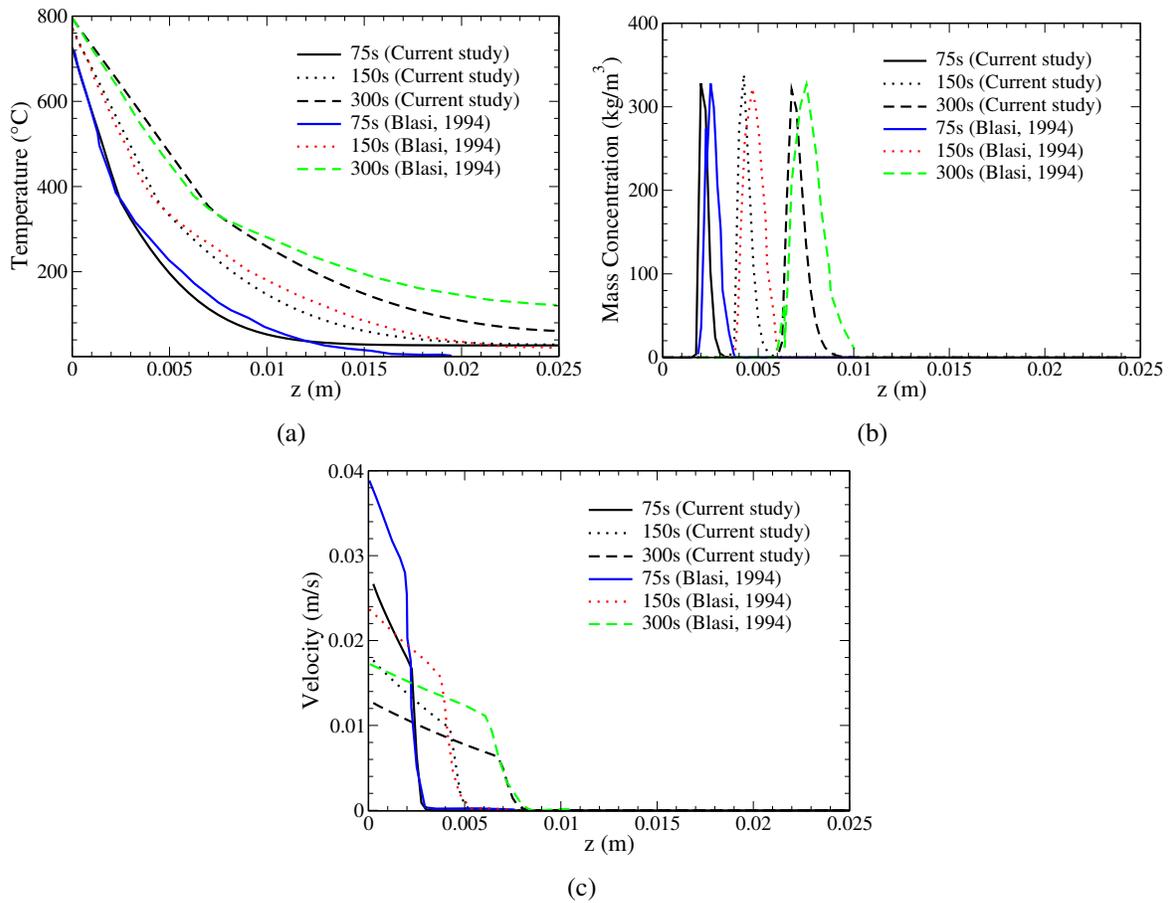


Figure 2: Comparison between the results obtained in the current study (black) and simulations of Blasi [4] (color) along the length of the specimen at different times; (a) Temperature (b) Mass concentration of active cellulose (c) Velocity of gas species.

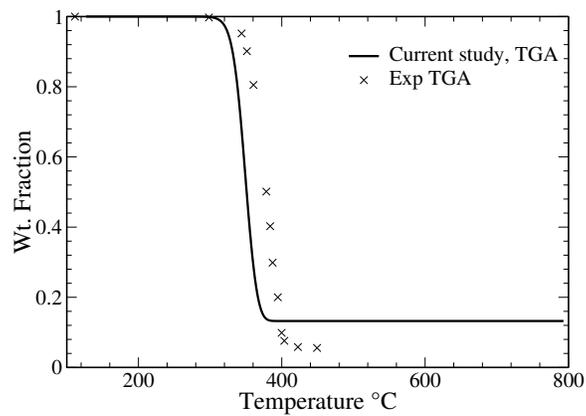


Figure 3: Comparison between the current study of TGA setup (solid line) and TGA experimental data of Reed and Posey [29] (crossmarks).

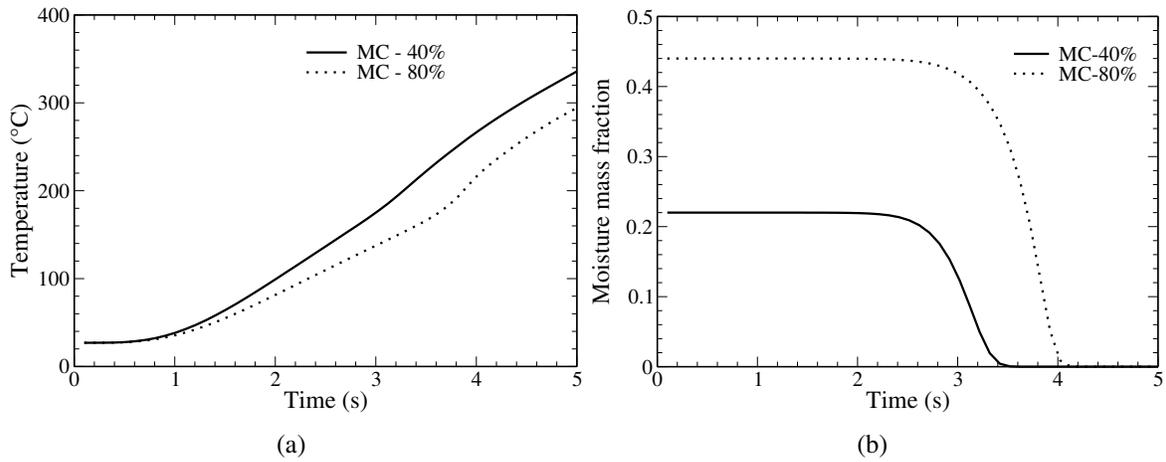


Figure 4: Time history of temperature (a), and mass fraction of moisture (b) at point A (see fig. 1) for two cases with an initial FMC of 40% and 80%.

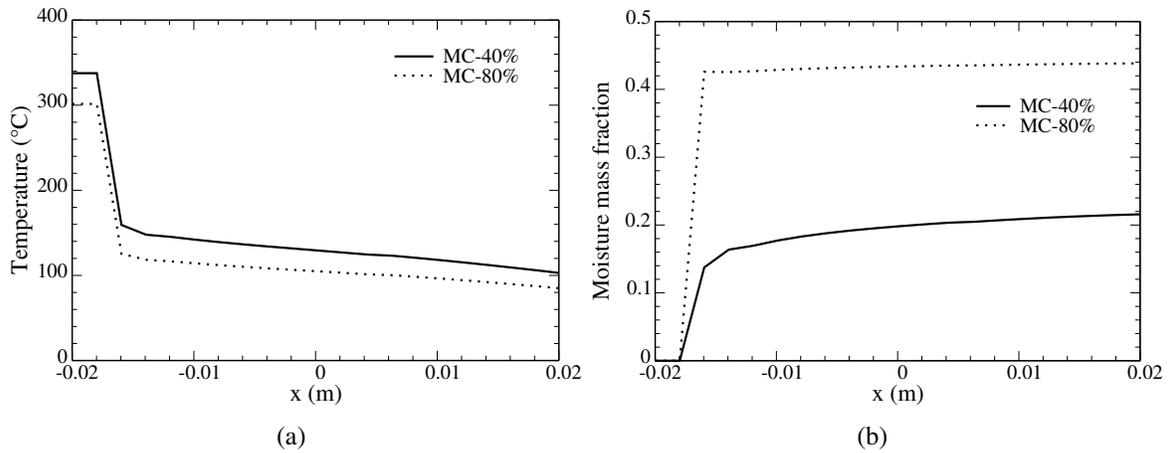
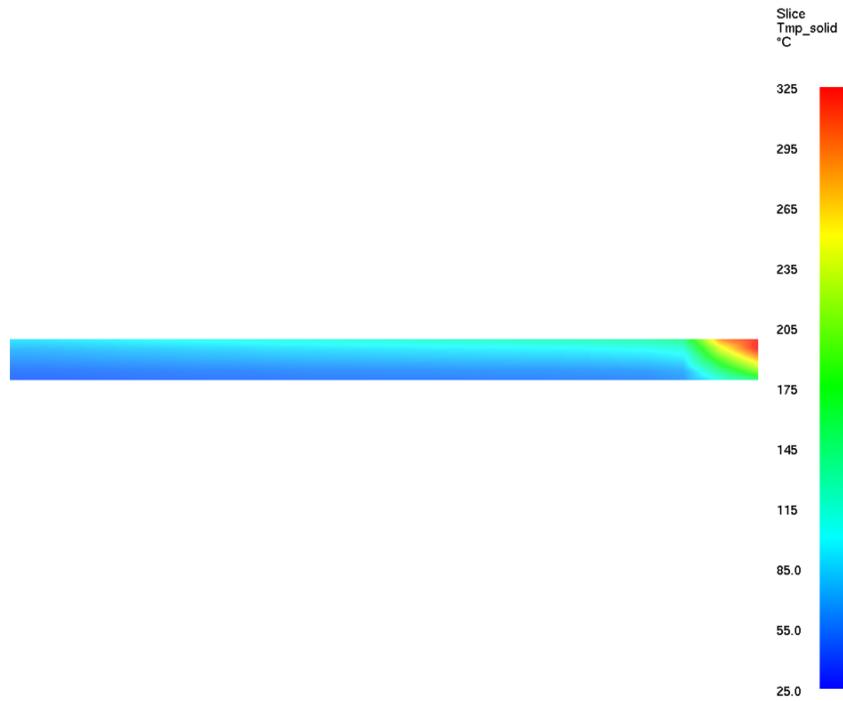
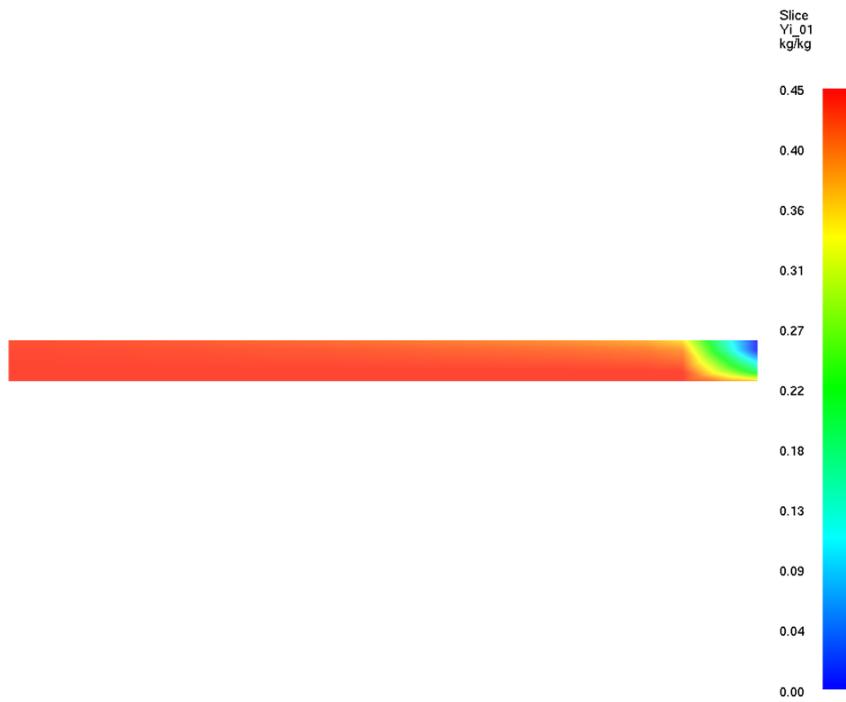


Figure 5: Variation of (a) Temperature, (b) Mass fraction of moisture along x at $y=0$ and $z=0.0315$ m at time 5s for two cases with an initial FMC of 40% and 80%.

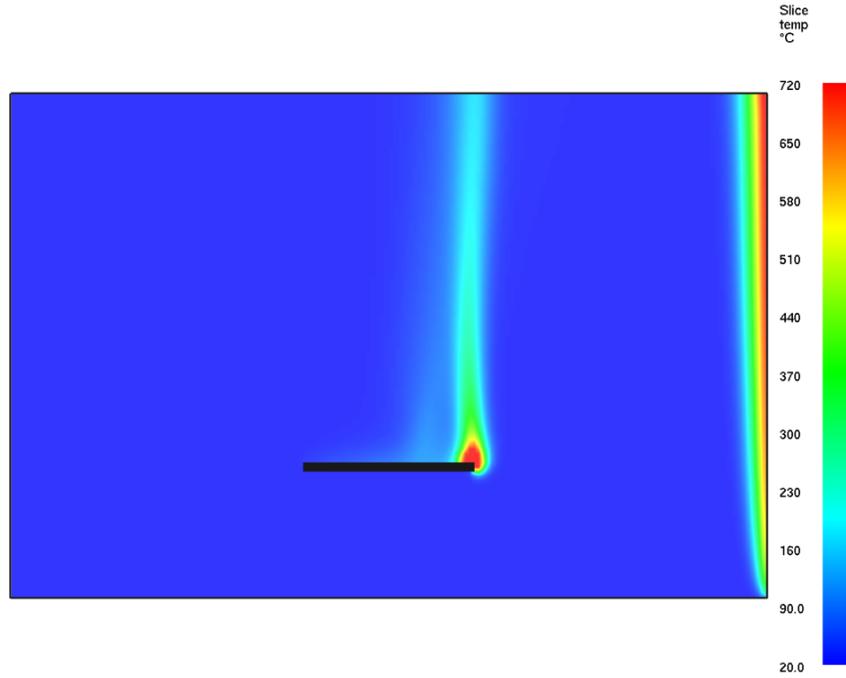


(a)

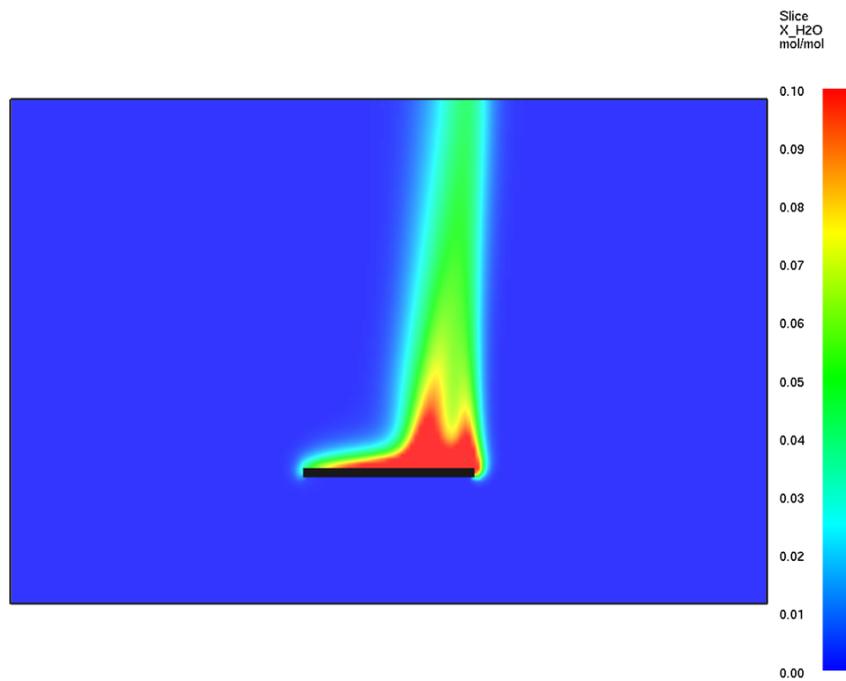


(b)

Figure 6: Color contours of temperature (a), and mass fraction of moisture (b) at $t = 8$ s on an xz -slice located at $y = 0$ in the solid phase for a case with an initial FMC of 80%.



(a)



(b)

Figure 7: Color contours of temperature (a), and volume fraction of moisture (b) at $t = 8$ s on an xz -slice located at $y = 0$ in the gas phase for a case with an initial FMC of 80%.

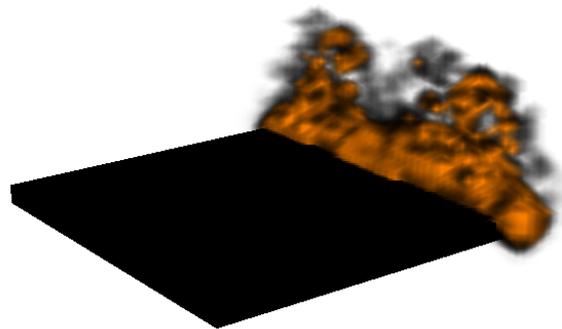


Figure 8: Three dimensional view of heat release rate (HRR) values in the gas phase at time 8 s for a case with an initial FMC of 80% (colored values indicate HRR = 30W).