USING MODIFIED CONE CALORIMETER TO DETERMINE HEAT/MOISTURE TRANSPORT PROPERTIES AND PYROLYSIS/COMBUSTION PROPERTIES OF WOOD-BASED MATERIALS FOR USE IN CFD MODELS

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ABSTRACT

The trend towards performance-based codes for achieving acceptable fire safety creates a significant demand for improved material properties and computer fire models. The performance-based engineering analysis is very difficult to achieve for wood-based materials because of their complex physical processes for pyrolysis and combustion. To address this need the cone calorimeter (ASTM E1354) was modified to be the primary test method for deriving properties of (1) heat/moisture transport, (2) mechanistic kinetics of pyrolysis, (3) surface ignition and creeping flame spread, and (4) combustion emission characteristics for the tested material. Each of these four major properties required a unique sample holder for revealing the targeted properties, with a corresponding mathematical analysis. With these four separate tests, using samples cut out from the same block of wood, the algorithms for drying, ignition, flame spread, pyrolysis and combustion can be incorporated into Computational Fluid Dynamics codes (CFDs) to predict larger scale behavior for the particular material.

INTRODUCTION

For certain material properties certain test methods are popular. For thermal properties, heat capacities are typically obtained with differential scanning calorimeter (DSC), orthotropic thermal conductivities are derived with a one-dimensional steady-state heat guarded apparatus, or with a heat impulse device such as Lasercomp K-tester 637, moisture diffusivity is obtained with a dual-chamber with the test membrane that transports moisture, and heats of evaporation and chemical reactions are obtain with a DSC. For fire properties, gross heat of combustion is usually measured with oxygen bomb calorimetry, ignition characteristics are obtained with an apparatus with a calibrated heat source, pyrolysis kinetics are derived with a thermal gravimetric analysis (TGA) coupled with a DSC using ground up samples, effective heat of combustion is measured with oxygen consumption calorimetry such as the cone calorimeter (ASTM E1354), creeping flame spreading characteristics with the LIFT apparatus (ASTM E1321), and combustion products composition are typically evaluated with gas analyzers, FTIR, and extraction methods including GC/MS. The process of obtaining all of these properties for fire performance engineering can end up being quite tedious with multiple instruments and various material preparations. We report here modeling and hardware advancements that allow us to modify the cone calorimeter testing methods to measure the material properties identified for computational fire modeling. The usual cone test method of imposing a heat flux of 50 kW/m^2 on a test specimen and measuring the

heat release rate as a function of time may reflect the real world conditions, but will generally fail to provide the complex thermal, moisture, and fire properties needed for a detailed computational model.

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Rather, the usual test method provides data to verify complex model predictions[1]. Therefore, special test holder and after-burner furnace configurations using the cone calorimeter instrument with enhanced gas and volatiles analysis in a modified protocol were developed and the data used to derive the needed material properties. Particular test holders are described as 1) standard holder at high flux on realistic test specimen with a backing material and heating volatiles in a ventilated-controlled furnace, 2) screen-like holder for medium heat flux heating of thermally thin solid samples and combusting all volatiles with an afterburner furnace, 3) styrofoam holder for very low heat flux to heat and dry a thick uniform sample via its exposed surfaces with thermocouples at differing depths, and 4) a vertical holder for creeping flame spreading in the lateral direction.

METHOD OF REALISTIC SAMPLE WITH BACKINGS AND COMBUSTION EMISSIONS

The first test description (Figure1) involves minimal variation from the standard test description in ASTM E1354 in which greater focus is on determining realistic combustion emission characteristics. The standard test usually involves relative flammability performances (time to ignition, peak heat release rate, total heat release rate, and smoke production) of building products to indicate improvements as a result of adding fire retardants, or of intrinsic construction changes. It is then sufficient to test materials at common thickness over a common insulation under a common irradiance. It is when attention is turned to obtaining material properties that the test method must be considered more carefully.

Figure 1. Peak flaming on realistic sample with backing material in cone calorimeter test at Forest Products Laboratory

On the subject of combustion emissions, there are concerns about the over-ventilation conditions of the cone calorimeter as compared to realistic large fires. Thus getting back to the basics, the wood and much of biomass on the average has the empirical formula $C_6H_9O_4$ (ash free and moisture free basis)[2], which will require proper accounting of carbon, hydrogen, and oxygen emitted from the sample as function of time if combustion emissions must be characterized. For example it was found in a comparison between room burn tests (ISO9705) and the cone calorimeter tests the combustion emissions are most similar

between the two tests if the same material with the same backing material is used in both tests. The comparison was effective on the basis of ratio of fuel or gaseous yield to oxygen depletion yield (yields from propane of ignition burner was subtracted out), $\beta_l = Y_l / Y_{O2}$, as shown in Table 1 which was derived from our test data of room lining materials. Various averaged betas computed from global cone calorimeter test results are given as, $\beta_f = 1/r_{o,cone} = 13.1/EHC$, $\beta_{CO2} = Y_{CO2}\beta_f$, $\beta_{CO} = Y_{CO}\beta_f$, $\beta_{O2} \equiv 1$, and $\beta_s = (SEA/8300)\beta_f$. In a comparison study of smoke emissions between room burn tests and the cone calorimeter tests[3] it was found that peak values of smoke production at the cone irradiances at or greater than 35 kWm^{-2} had the best correlation with the room burn smoke production rates for various wood products. Since plastics and liquid fuels have been found to be not affected by these factors between bench scale tests and full scale tests in early developments of the cone calorimeter, there was no need to modify the standard cone tests for these materials.

Table 1. Comparison of Betas from standard cone calorimeter tests to Room corner tests

Material	Test #	β_f	β_{Soot}	$\beta_{Soot,room}$ (r^2=0.90)	β_{CO}	$\beta_{CO,room}$ (r^2=0.95)	β_{CO2}	$\beta_{CO2,room}$ (r^2=0.99)
Gypsum board, Type X	1,7,15	29.11	0.0500	0.0033	0.1488	0.03	1.035	1.351
FRT Douglas-fir plywood	2	2.835	9.57E-05	0.00319	0.2365	0.2139	1.393	1.364
Oak veneer plywood	3	1.358	0.0062	0.00394	0.0682	0.1411	1.205	1.356
FRT plywood (Forintek)	4	---	---	0.00440	---	0.1747	---	1.36
Douglas-fir plywood (ASTM)	5	1.264	0.00161	0.00088	0.0671	0.1086	1.320	1.307
FRT Polyurethane foam	6	1.747	0.0968	0.04507	0.1301	0.1809	1.074	1.047
FRT South pine plywood	8	1.810	0.00596	0.00424	0.0880	0.2056	1.119	1.265
Douglas-fir plywood (MB)	9	1.080	0.00386	0.00135	0.0373	0.0901	1.279	1.106
Southern pine plywood	10	1.051	0.00868	0.00791	0.0210	0.1555	1.290	1.186
Particleboard	11	1.081	0.00933	0.01	0.00376	0.1429	1.208	1.251
Oriented strand board	12	1.060	0.00659	0.00592	0.0628	0.1228	1.347	1.27
Hardboard	13	0.999	0.00784	0.0105	0.0602	0.2215	1.292	1.186
Redwood lumber	14	0.922	0.00668	0.00318	0.00193	0.0782	1.218	1.188
White spruce lumber	16	1.189	0.00098	0.00292	0.00774	0.0459	1.516	1.309
Southern pine boards	17	0.981	0.00620	0.00694	0.00328	0.2307	1.244	1.138
Waferboard	18	0.973	0.00755	0.0103	0.00297	0.1769	1.195	1.139

The wood and biomass on the other hand has complex degradation behavior that includes major components of extractives, holocellulose, and lignin that degrade at different temperatures and the nature of their charring also changes with temperature and rise rate of temperature[4]. This degradation will also result in changing volatile composition as a function of time, and of such variations, such that their further degradation of heavy tars at high temperature into light tars, and simple molecules such as H_2O, CO, CH_x and CO_2 can develop without experiencing combustion[5]. Therefore the popular approach of correlating VOCs and PAHs with CO production that is successful with plastic and liquid fuel can become problematic or very different with wood materials[6] because of the way CO and other simple molecules are produced during under-ventilation conditions. The importance of under-ventilation for room tests is shown from results[5] on bench-scale thermal cracking of volatiles at 800°C for sweet gum hardwood charred at 450 °C (char fraction = 0.18) giving mass fraction emissions as: $f_{CO2} = 0.16$, $f_{CO} = 0.43$, $f_{H2O} = 0.18$, $f_{THC} = 0.16$, and $f_{soot} = 0.07$. As an excess fuel, it has threatening high CO concentrations (up to half of fuel's carbon converted to CO) if it is not combusted after leaving the

doorway in a room test. Therefore the results of room burns (as measured in the flue exhaust duct) only apply to over-ventilated combustion, while data is needed for under-ventilated combustion. Since excess fuel portion at "combustion" temperature is basically thermally cracked into simpler gas components, including THC's, given as mass fractions of excess fuel, $f_l = \dot{m}_{l,ex} / \dot{m}_{f,ex}$, we propose a new correlation in which gaseous emission yield has a simple function with global equivalent ratio (GER) as,

$$Y_l = \frac{(\beta_l / \beta_f)\dot{m}_{f,ox} + f_l \dot{m}_{f,ex}}{\dot{m}_{f,ox} + \dot{m}_{f,ex}} = \frac{\beta_l}{\beta_f}\frac{1}{\Phi} + f_l\left(1 - \frac{1}{\Phi}\right) \qquad [1]$$

$$\Phi = 1 + (GER - 1)H(GER - 1) \qquad [2]$$

The parameter, H, is the Heaviside function. We note by definition that oxygen depletion mass ratio to itself, $\beta_{O2} = 1$ and, so also that with $f_{O2} = 0$ the "oxygen depletion" yield is equal to $1/\beta_f$ for GER<1 and inversely proportional to GER for GER>1, even under the conditions of incomplete combustion. With specially designed compartment fires[7] they obtained a very good agreement of this oxygen yield prediction with the data for the fuel sources: Hexane, polymethyl-methacrylate (PMMA), Spruce, and Polyurethane. This and other references have reported data in which we could confirmed the use of Equation 1 for correlating fairly well the carbon oxides, water vapor, hydrogen gas, hydrocarbons, and soot as functions of GER. Therefore the gaseous emission yields as divided by the oxygen depletion yield has an expression proportional to GER, and to beta factors for the gas component *l* and the fuel *f*, as,

$$\frac{Y_l}{Y_{O2}} = \beta_l + f_l \beta_f (\Phi - 1) \qquad [3]$$

Expecting this relationship to be independent of scale for a particular fuel, even during incomplete combustion, we will take advantage of recent hardware advancements to the cone calorimeter. Our cone calorimeter came installed with the gravimetric smoke measurement not commonly available. Indeed, the black smoke is readily measured with the laser obscuration system, such that for many years we had no need for gravimetric smoke measurements. Now instead of trapping smoke on a collection filter, we modified it by replacing it with dry-iced cold trap for the white smoke constituents, and then analyze the deposited residue with a special solvent and a modern GC/MS. We also have the ability to reduce cone's over-ventilation through the use of the smaller orifice plate in the exhaust pipe. To achieve a further reduction of over-ventilation, and also obtain better control of the tar degradation temperature, we have built a temperature controlled furnace tube situated above the cone radiant heater in which the white smoke must travel through. A stainless steel screen surrounding the sample holder can slow down the air flow to where under-ventilation might be achievable in the combustion zone. Ultimately, we can provide for any degree of under-ventilation by utilizing an external natural gas burner whose output is such that its flue is at fixed oxygen levels and its flue as cooled to targeted temperatures can then be blown into the cone's test chamber at a slight pressure elevation.

To some degree, this modification to the standard test can be thought of as a variation to a French bench test for determining emissions during the high temperature (800–1077°C) incineration of wood waste furnitures[6], although ground up samples were used in that test, and over-ventilation was typical. With the availability of Equation 3 and along with the measurements of oxygen depletion yield and global equivalent ratio, it should provide an alternative, more rational approach to correlating the PAHs and VOCs with incomplete combustion conditions rather than just merely with the CO production. If

Equation 3 can be verified for a wide variety of combustion situations, particularly for forest fires simulations with CFDs, it can substitute for the time consuming gaseous kinetics analysis.

METHOD OF PYROLYTIC METAL SCREEN FOR THIN SAMPLE WITH AFTERBURNING

When we began to test thin materials with a lighter sample holder (shown in Figure 4), the standard cone testing protocol began to be problematic. For example, if the higher irradiances are used, quite short ignition times are achieved such that the time shifting of the oxygen signal goes so far that the oxygen baseline is no longer at ambient levels, thus creating severe errors in the heat release rate (HRR). With about 9 seconds for the time response constant of the older oxygen analyzer (1990s technology) the true narrow sharp HRR peak associated with thin wood materials is greatly diminished and flattened by slow time response of oxygen analyzer. The instantaneous measured quantities of HRR, oxygen depletion, and smoke show the effects of slow time responses as compared to the relatively rapid weigh changes. However, the CO_2 and CO analyzers demonstrated rapid response within 2 seconds and were time shifted properly to the spark ignition event. Even if the baseline oxygen is corrected for, the only reliable quantity is the overall effective heat of combustion (EHC) calculated as total heat release by the total mass loss. Therefore we closely evaluated the measurements to improve information for the thin materials.

Since wood contains oxygen in its structure, water vapor fraction value became a requirement to close the mass balance of incomplete, but over-ventilated, combustion (H_2O, CO_2 , CO, and soot) and compare it to load cell weight loss as function of time. A relatively fast response RH and temperature sensor was installed in the gas sample line after the filters, but prior to the cold trap. Heat wraps were placed around the gas lines to prevent moisture condensations prior to the RH sensor. We note that for any incomplete hot combustion the dynamic mass flow rate of a fuel mixture with empirical formula $C_XH_YO_ZN_US_V$ has six equivalent calculations as,

$$\begin{aligned}
\dot{m}_{fuel} &= \left(\frac{12X+Y+16Z+14U+38V}{32(X+V)+8Y-16Z}\right)\left(\Delta\dot{m}_{O2}+\frac{32\dot{m}_s}{12}+\frac{16\dot{m}_{CO}}{28}+\frac{(32+8W)\dot{m}_{CHw}}{12+W}\right) \\
&= \left(\frac{12X+Y+16Z+14U+38V}{44X}\right)\left(\dot{m}_{CO2}+\frac{44\dot{m}_s}{12}+\frac{44\dot{m}_{CO}}{28}+\frac{44\dot{m}_{CHw}}{12+W}\right) \\
&= \frac{12X+Y+16Z+14U+38V}{9Y}\left(\Delta\dot{m}_{H2O}+\frac{9W\dot{m}_{CHw}}{12+W}\right) \qquad [4] \\
&= \frac{12X+Y+16Z+14U+38V}{14U}\Delta\dot{m}_{N2} = \frac{12X+Y+16Z+14U+38V}{70V}\dot{m}_{SO2} \\
&= \dot{m}_{CO2}+\dot{m}_s+\dot{m}_{CO}+\Delta\dot{m}_{H2O}+\dot{m}_{CHw}+\Delta\dot{m}_{N2}+\dot{m}_{SO2}-\Delta\dot{m}_{O2}
\end{aligned}$$

This mass balance for incomplete combustion assumes all of (1) fuel's carbon is accounted for in the carbon dioxide, carbon monoxide, soot, and THC measurements, (2) fuel's hydrogen is accounted for in water vapor and THC measurements, and (3) fuel's oxygen is converted to become part of carbon dioxide, carbon monoxide, water vapor, and sulfur dioxide. The THCs and sulfur dioxide can be ignored for our wood samples, and the emissions of the alkalis compounds are also negligible and retained in the ashes. It is seen that with a known fuel any one of the six calculations can be used. The wood volatiles as a fuel have an unknown composition, and only the last form of Equation 4 can be compared with the load cell mass loss rate.

This requires that each mass rate term to be both properly calibrated and synchronized in their time responses. For the proper calibration we used a methane afterburner above the cone heater to provide the known fuel composition and used the full gas analysis described in the Annex of ASTM E1354 standard to calculate mass flow rates of O_2, H_2O, CO_2, CO, and soot. It was found that to achieve agreement among all forms of Equation 4 for the steady combustion of methane fuel, reasonable adjustments were needed to the oxygen sensor output and the relative humidity output. It appears that the presence of carbon dioxide caused a deviation in oxygen measurement in that their scrubbing generated some water vapor that resulted in over-prediction of true oxygen concentrations. A linear relationship with carbon dioxide value was used to correct oxygen concentrations for varying levels of methane combustion. It was found simple minor corrections were needed to RH sensor, such that we used Equation 4 as the basis to calibrate RH sensor for each test (while burning methane at different levels).

The step changes in the methane afterburner output were used to synchronize the various measurement signals. A numerical deconvolution procedure was applied to the oxygen sensor signal in four simple stages to create a faster, but somewhat noisier and truer oxygen signal, for matching with time responses of the carbon oxides signal during step changes of methane output. Likewise, a single stage numerical deconvolution along with a time shift was applied to the RH sensor to match time responses of the carbon oxides signal. Results for step changes in methane burning using four forms of Equation 4 are shown in Figure 2. Evaluation of the last form of Equation 4 provides the noisiest levels as expected. Also shown in Figure 2 is the pyrolysis of thin redwood beginning at around 480 seconds. It shows the good agreement of Equation 4 with the load cell measured mass loss rate. The methane was left burning during wood pyrolysis to ensure that all wood volatiles are being combusted, and not have to wait for the piloted ignition to occur to measure combustion products. It is noteworthy that the improved gas analysis is able to preserve the sharpness of the thin wood pyrolysis as exposed to 35 kWm^{-2}. Newer gas analysis equipment should further improve these results during our current upgrades.

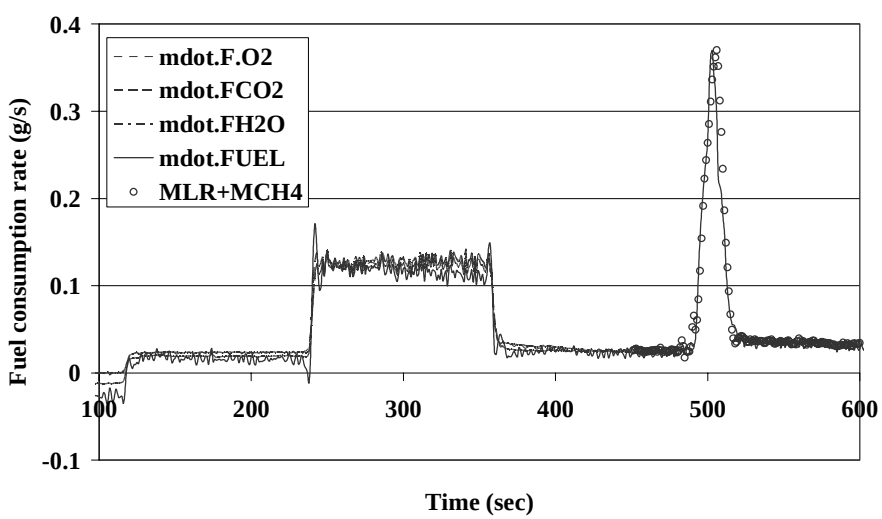

Figure 2. Comparison of fuel mass rates calculations.

We can also calculate the dynamic mass flow rates of carbon, hydrogen, and oxygen contained within the wood volatiles using the mass balance equation for methane and wood as in,

$$\begin{aligned} \dot{m}_{C,wood} + \dot{m}_{C,methane} &= \dot{m}_{SOOT} + (12/28)\dot{m}_{CO} + (12/44)\dot{m}_{CO2} \\ \dot{m}_{H,wood} + \dot{m}_{H,methane} &= (2/18)\Delta\dot{m}_{H2O} \\ \dot{m}_{O,wood} + \dot{m}_{O,methane} &= (16/28)\dot{m}_{CO} + (32/44)\dot{m}_{CO2} + (16/18)\Delta\dot{m}_{H2O} - \Delta\dot{m}_{O2} \end{aligned} \qquad [5]$$

While only the methane is burning, we can determine its C, H, and O mass flow rates, and then fixate at those flow rates during the consequential wood combustion; so that the mass flow rate of C, H, and O in the wood volatiles can be derived during the dual combustion of methane and wood volatiles. This allows us to calculate other relevant quantities as a function of time (or of temperature using our thermocouple data) such as ratio of molar carbon content of the fuel mixture to its stoichiometric molar consumption of oxygen gas that helps identify the fuel (Hydration value C/O of unity is a carbohydrate), and the stoichiometric oxygen mass consumption to fuel mass ratio, $r_{o,st}$, that converts to stiochiometric heat of combustion by multiplying it by 13.23 kJ/g derived for wood volatiles[4].

The results plotted in Figure 3 shows the reasonableness of changes occurring in each temperature range. It is interesting that the peak mass loss rate occurs right around the measured piloted ignition temperature of 365 ^{o}C. Three thermocouples indicated temperature uniformity across the redwood thickness of 1.47 mm to within 15%. Therefore in low pyrolysis temperatures of 200 ^{o}C, the hydration level much less than unity and a $r_{o,st}$ nearing the value 2 indicate the presence of evaporating extractives. In the temperatures beginning around 230 ^{o}C up to 370 ^{o}C, results indicates the dominance of evaporating holocelluloses (hemi and alpha) according to the hydration value near unity, although the low $r_{o,st}$ values indicate a significant competing dehydration reaction that emits water vapor and forms the interlinking carbon char. In the temperature interval from 370 ^{o}C to 450 ^{o}C shows a slight dropping of hydration value and peaking of $r_{o,st}$ value consistent with some evaporation of the lignin component, whereas at temperatures above 450 ^{o}C the hydration value is above unity and $r_{o,st}$ below unity indicates CO mass losses for final diminishing of oxygen content of the residue. The remainder of mass losses is primarily oxidative gasification of carbonized char with the $r_{o,st}$ nearing carbon level and hydration level remaining at unity, also for carbon. This data is suggestive of pyrolysis kinetics derivation shown as predictive curves in Figure 3.

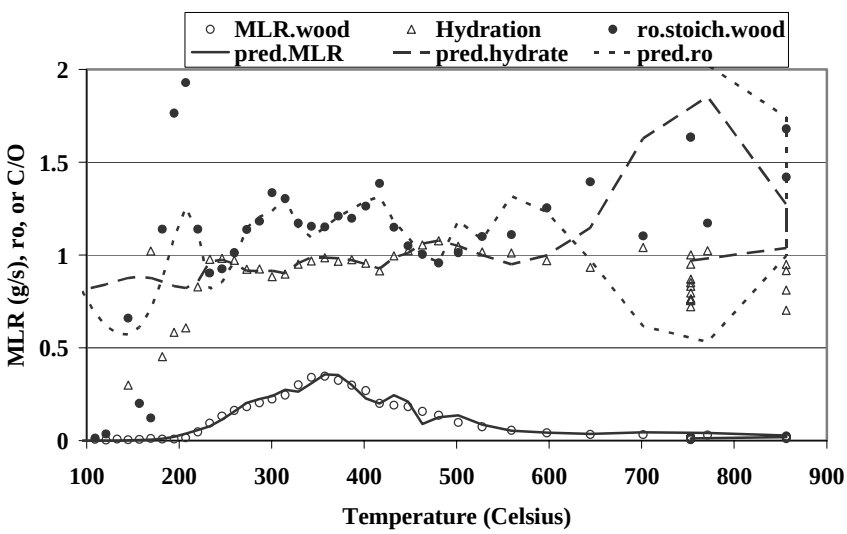

Figure 3. Trends of MLR, oxygen consumption ratio, and hydration level.

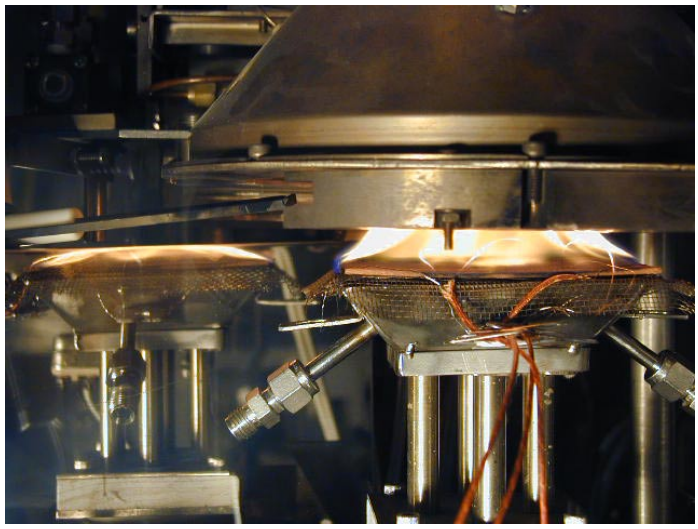

Figure 4. Thin wood held down by corner wires to allow 10% shrinkage at ignition.

METHOD OF STYROFOAM BOX WITH PARTLY SEALED SAMPLE DRYING

Since the moisture content of wood at near equilibrium conditions (ranging from 3% MC to fiber saturation of 24% MC) has a strong effect on wood ignitibility[8], some effect on creeping flame spread (next section), and direct effect on the effective heat of combustion, the CFDs for fire simulations would need the ability to vary the moisture content of targeted flammable materials during the daily environmental exposures. The moisture transports in wood is orthotropic and reversible and its moisture diffusivity value is about two orders of magnitude less than the thermal diffusivity value. The moisture evaporation from wood continues to be a subject for research, as it is difficult to distinguish between external and internal resistances to wood drying[9]. These properties and factors create a significant challenge to solve using the numerical approach, particularly if numerous thermal and moisture properties need to be determined.

To solve this problem with the cone calorimeter, we developed a rigorous analytical solution of Luikov's PDE equations[10] for reversible heat and moisture transport within the wood for varying environmental conditions[11]. Material thermal properties of thermal conductivity, heat capacity, and surface emissivity and moisture properties of moisture diffusivity, thermo-moisture gradient, and moisture vapor flow fraction need to be determined in a suitable test. The boundary conditions to the analytical Laplace solution implemented in an Excel spreadsheet consists of surface heat and mass fluxes changing with time on both sides of the sample. By sealing unexposed sides with BOSS wax sealant, the moisture surface mass flux only occurs on the exposed side to the imposed heat, which is decreasing with time due to the cooling effect of the rising surface temperature. The gradually increasing temperature on the unexposed surface will give rise to additional cooling flux at that position. The cone load cell measures the mass loss rate of the sample, which is converted to mass flux of water vapor exiting the unsealed surface during exposure to very low irradiance level, similar to the sun's exposure levels. Thus the holder includes seating the sealed sample in a 25 mm thick blue styofoam cavity as shown in Figure 5. Note the use of reflecting aluminum tape and several thermocouples. We also have a mass loss calorimeter, which is the same as the cone calorimeter, but without the gas analyzers, exhaust flow measurements and the laser obscuration system, that can be used to obtain the required data.

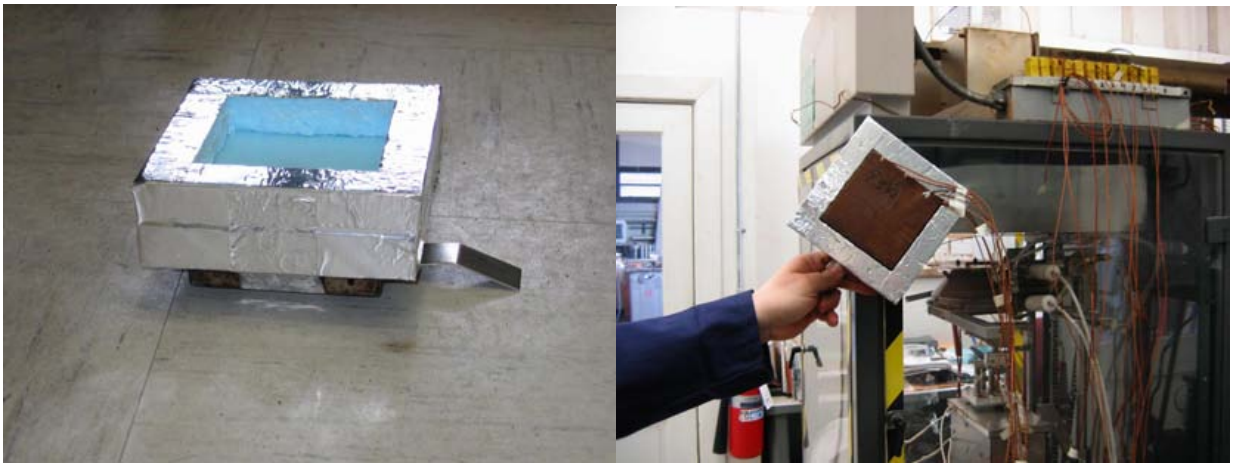

Figure 5. Sample in blue Styrofoam cavity exposed to very low irradiances for time dependent drying though exposed surface. BOSS wax coating seals unexposed surfaces.

The rapid rise of surface temperature will immediately give rise to high water vapor pressure within the exposed surface in local equilibrium with the moisture. That is, the moisture isotherm relationship can assume to be locally valid at the surface, particularly if only water vapor is emitting from the surface. The high surface vapor pressure will give rise to vapor transport inward to the wood, as well as evaporating into the environment, via vapor density gradients in both directions. This will result in a fairly rapid reduction of surface moisture content depending on the temperature rise rate and magnitude, which in turn will eventually create an opposing moisture gradient for moving the interior moisture towards the surface to gradually replenish moisture evaporating into the environment. This is a non-isothermal drying process intended to derive the Luikov's heat and moisture properties simultaneously through a process of curve fitting the surface temperatures and moisture loss data as a function of time using the spreadsheet least-squares solver. Preliminary results have been obtained for redwood.

METHOD OF PILOTED IGNITION AND CREEPING FLAME SPREAD ON SAMPLE

Piloted ignition and creeping flame spread presents a difficult process for the CFDs to simulate, primarily due to the small features of the flame foot responsible for the flame spreading and ignition. This problem can be overcome via analytical solutions of flame spreading that also requires the properties of the flame foot to be determined. Many situations involving creeping flame spread also involves preheated air, often coupled with under-ventilated conditions. The under-ventilation of the oxidizer will result in a decreasing flame spreading progression as would be reflected in a decrease of flame temperature and buoyancy velocity terms in the flame spreading formula[12]. The preheated air on the other hand increases the flame spreading progression by reducing heat losses in the vicinity of the flame foot. It is difficult to provide for under-ventilation and preheated air on the LIFT apparatus (ASTM E1321) which has a gas-fired pre-mixed burner panel for heating laterally, with a heating distribution, on 850 mm by 150 mm vertical sample in which to measure ignition and flame spread. This apparatus was refurbished with better controls and data acquisition. Numerous thermocouples were placed on the surface, and the analytical solutions based on the thermal portion of Luikov's PDEs was used to predict quite well the surface temperatures in response to irradiant preheating, exponentially rising heating by the flame foot, and then constant heating by the main flame[13]. The exponential rising heating by the flame foot can be linked with the analytical flame spreading formulas, particularly that of flame foot flux and length, or equivalently, the flame foot temperature and laterally buoyant flow speed.

Therefore, to overcome the various limitations with the LIFT apparatus, we built a smaller lateral ignition and flame spread holder for use in the cone calorimeter. The sample is 300mm by 100mm and is

mounted aside the vertically orientated cone heater, as shown in Figure 6 for flame spreading on redwood at 45 degree angle from the heater plane. Several surface thermocouples mounted at 25 mm intervals initially and at 50 mm intervals for last three positions, has temperature data that not only record flame spreading positions as a function of time, but also verify the heating progression as shown with our previous analysis with the refurbished LIFT apparatus. The flame foot heat flux as derivable from the cone's lateral flame spread can be compared with analytical formulation of flame spreading. This then can be incorporated into an analytical fire growth model[13] that predicts lateral flame travel and HRR as a function of time, and adjusts to changing environmental conditions, such as preheated air and air vitiation. We plan to provide for this environment in the test chamber as discussed in the combustion emissions section. As for normal air environments, preliminary results for fire growth prediction were obtained.

Figure 6. Light weight holder for lateral flame spread measurement contains the redwood sample backed by gypsum board with several thermocouples on surface.

CONCLUSION

This paper describes the progress made towards using the cone calorimeter for the determination of material properties for wood-based materials for use in computer fire models utilized in performance based codes. The motivation was to avoid use of multiple testing equipments and reduce the number of tests needed to effectively determine the material properties. For a number of years the standard cone calorimeter, and other calorimeters like it, was a candidate to provide for material properties. Some degree of success was achieved for well defined materials, such as plastics. However, the complex nature of wood degradation, combustion, and emissions documented over the years indicated that wood materials need to be tested in differing fire regimes and constructions, and thereby led to devising the four different test configurations.

The first case of cone test modification is reducing the over-ventilation effects and inserting the proper backing material for the sample in the efforts to reproduce emissions occurring at full scale. Since the wood volatiles has a tendency to crack into simpler molecules at higher temperatures without the presence of oxidation, we developed an emission formulation that applies also to under-ventilation conditions and devised hardware to reduce air flow or reduce oxygen concentrations into the combustion zone. The data collection is ongoing, and it would be useful if the CFDs can avoid solving detailed combustion kinetics for many situations.

The second case is the pyrolysis kinetics modeling (with corresponding material properties) that is achievable with a solid 1 mm thick sample on a light holder whose volatiles are effectively combusted with a methane afterburner, and in which gas analysis was more carefully recalibrated, deconvolved, and synchronized. We were able to capture the sharp peak in the mass loss rate profile, the changing stoichiometric heat of combustion, and the changing hydration level of the wood volatiles just from the combustion emission analysis. The enhanced information of separate mass flow rates of C, H, and O contents of the volatiles also allowed us to develop pyrolysis kinetics with fine details suitable for the complex wood materials. We are embarking on testing additional thin samples after just recently upgrading gas analyzers and data acquisition, and on updating Parker's pyrolysis model[14] for thick wood with the robust, flexible, and detailed pyrolysis kinetics derived in this work. It is expected to be much more efficient and reasonable than the current pyrolysis models being used in the CFDs.

The third case is the dynamic and non-isothermal heat and moisture transfer analysis for wood and woody biomass, which is of vital importance to the Forest Service. The rigorous analytical solution for changing environmental conditions for realistic duff material and building products can be incorporated into various CFD models to serve as efficient boundary conditions to their computational cells. The same analytical solution has been adapted to the sample in the cone calorimeter blue Styrofoam holder and exposed to low irradiance so that the material parameters of Luikov PDEs at low temperatures can be calibrated as best fit to surface temperatures and water vapor mass loss rate as a function of time. Preliminary values for material parameters for redwood have been obtained using the Excel spreadsheet implementation of Dietenberger's analytical solutions to Luikov's PDEs.

The fourth case is the ignition and flame spread analysis for wood and duff, which is of vital importance for building and construction, as well as for prescribed fires. Since fire growth is a short time event, we successfully utilized only the heat transfer portion of Luikov's PDEs to predict surface temperature responses on a flame spread sample to high irradiance preheat, the exponentially rising flame foot flux to ignition condition (or pyrolysis front), and constant flux from the main flame. The exponentially rising flame foot flux profile was linked with the analytical solutions of flame spreading theories, thus having the potential of relieving the CFDs of the burden of calculating fine details of flame spreading occurring within a computational cell adjacent to pyrolyzing surface.

With these four separate tests with the modified cone calorimeter and their analysis for material properties, using samples cut out from the same block of wood, the proposed algorithms for moisture content, ignition, flame spread, pyrolysis and combustion can be incorporated into CFDs to predict larger scale behavior for the particular material.

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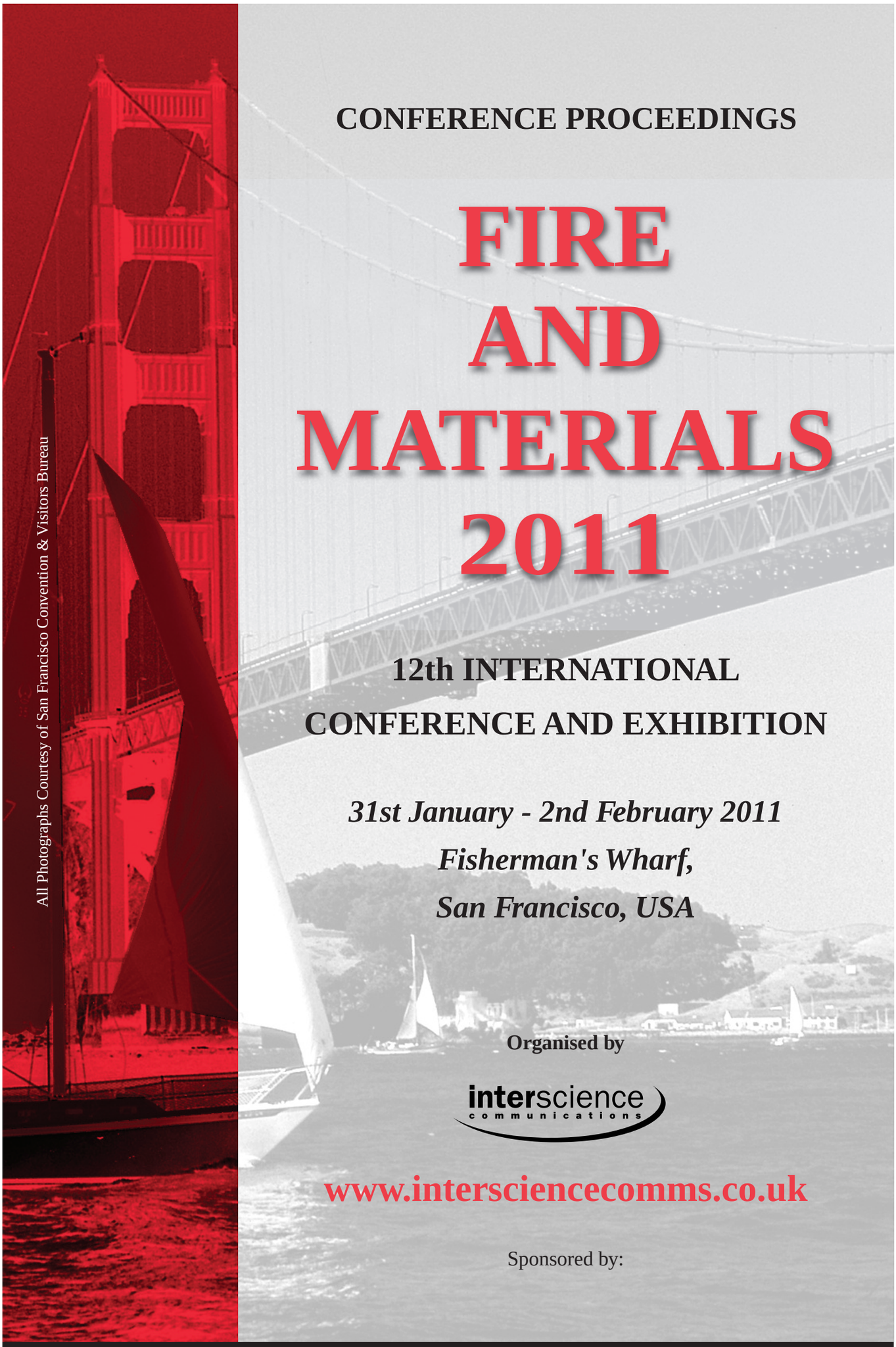

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