Effective heat of combustion for flaming combustion of conifers

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Abstract: The heat of combustion of burning trees is often used in forest-fire hazard modeling to relate mass-loss results to the heat produced; therefore reliable values are needed. Experimental results for the effective heat of combustion of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees are presented as a function of moisture content. It is also shown that during a forest fire, the effective heat of combustion does not correspond to the oxygen-bomb-test value. Instead, the value will always be lower, since the heat of combustion of char is higher than that of the pyrolysate vapors, and char mostly remains unburned during a forest fire. These are the first and only experimental results obtained from testing of actual trees. But results from benchmark testing and studies on wood products by other investigators are broadly consistent with our findings. It is further shown that moisture content has a major effect on the effective heat of combustion. A quantitative expression for the effective heat of combustion, as a function of moisture content, is obtained. Benchmark testing by earlier researchers established that generally there is only a slight species effect on the heat of combustion; therefore the present Douglas-fir results can be applied in more general forest-fire modeling.

Résumé : La chaleur de combustion des arbres en flammes est souvent utilisée pour modéliser le risque d'incendie de forêt dans le but de relier la perte de masse qui en résulte à la chaleur produite. Il faut par conséquent avoir des valeurs fiables. Des résultats expérimentaux pour la chaleur de combustion réelle de tiges de douglas (*Pseudotsuga menziesii* (Mirb.) Franco) sont présentés en fonction du contenu en humidité. Il est également démontré que, durant un feu de forêt, la chaleur de combustion réelle ne correspond pas à la valeur obtenue avec la bombe calorimétrique à oxygène. Au contraire, la valeur sera toujours plus faible étant donné que la chaleur de combustion du bois carbonisé est plus élevée que celle des vapeurs produites par la pyrolyse et que le bois carbonisé ne brûle pratiquement pas durant un feu de forêt. Il s'agit des premiers et seuls résultats expérimentaux obtenus après avoir testé de vrais arbres. Mais les résultats des tests et expériences en laboratoire sur des produits du bois obtenus par d'autres chercheurs sont généralement consistants avec nos résultats. Il est de plus démontré que le contenu en humidité a un effet important sur la chaleur de combustion réelle. Nous avons obtenu une expression quantitative de la chaleur de combustion réelle en fonction du contenu en humidité. Les tests en laboratoire effectués précédemment par d'autres chercheurs ont établis que, généralement, l'espèce d'arbre a seulement un léger effet sur la chaleur de combustion. Les résultats actuels obtenus pour le douglas peuvent donc être appliqués dans les modèles plus généraux d'incendie de forêt.

[Traduit par la Rédaction]

Introduction

The quantification of the frontal fire intensity of crown fires, expressed as heat-release rate per unit length ($kW \cdot m^{-1}$), is an important factor in evaluating or estimating forest-fire hazard (e.g., Wilson 1984). Since instrumental techniques are not available to measure this variable directly, it is usually estimated from the mass-loss rate:

$$[1] \qquad I = Hwr$$

where I is frontal fire intensity ($kW \cdot m^{-1}$), H is heat of combustion ($kJ \cdot kg^{-1}$), w is fuel consumption on an area basis ($kg \cdot m^{-2}$), and r is fire spread rate ($m \cdot s^{-1}$). For this simple calculation to be accurate, the value of H used must be correct. In reducing the data from the recently completed International Crown Fire Modeling Experiment (ICFME), Stocks et al. (2004) assumed that the value of H was the handbook value of the net heat of combustion, which they postulated to be 18.0 $MJ \cdot kg^{-1}$. This has been a common strategy, but it leads to substantial error. The purpose of this paper is to examine the factors that determine the actual heat of combustion that is developed during the fire and to offer a suitable recommendation.

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Oxygen-bomb measurements of the heat of combustion

Handbook values of heat of combustion are normally determined from measurements in an oxygen bomb (ASTM 2002). This is a hyperbaric environment with a 100% oxygen atmosphere, which ensures the complete combustion of the specimen. However, it does not represent conditions that are similar to fires burning in the open atmosphere. Handbook values of the heat of combustion for conifers are typically 19.2–21.8 $MJ \cdot kg^{-1}$ for the gross value and 17.8–20.4 $MJ \cdot kg^{-1}$ for the net value (Babrauskas 2003). The gross value ($\Delta h_{c,gross}$) is the value that is directly obtained from the oxygen-bomb test. The net value ($\Delta h_{c,net}$) is a calculated adjustment that accounts for the fact that the water in the combustion product is vapor, rather than liquid:

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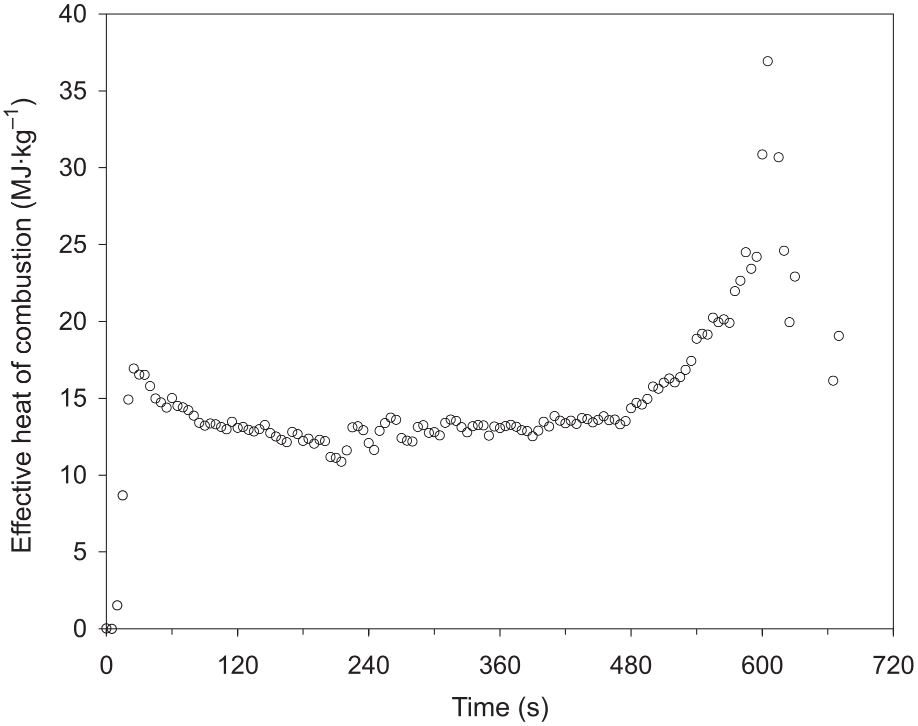
Fig. 1. Effective heat of combustion for a 17 mm thick western redcedar (*Thuja plicata*) (moisture content = 6.9%).



$$\Delta h_{c,\text{net}} = \Delta h_{c,\text{gross}} - 0.2183\,[\%H] \quad [2]$$

where $[\%H]$ is the percentage of hydrogen in fuel, by mass.

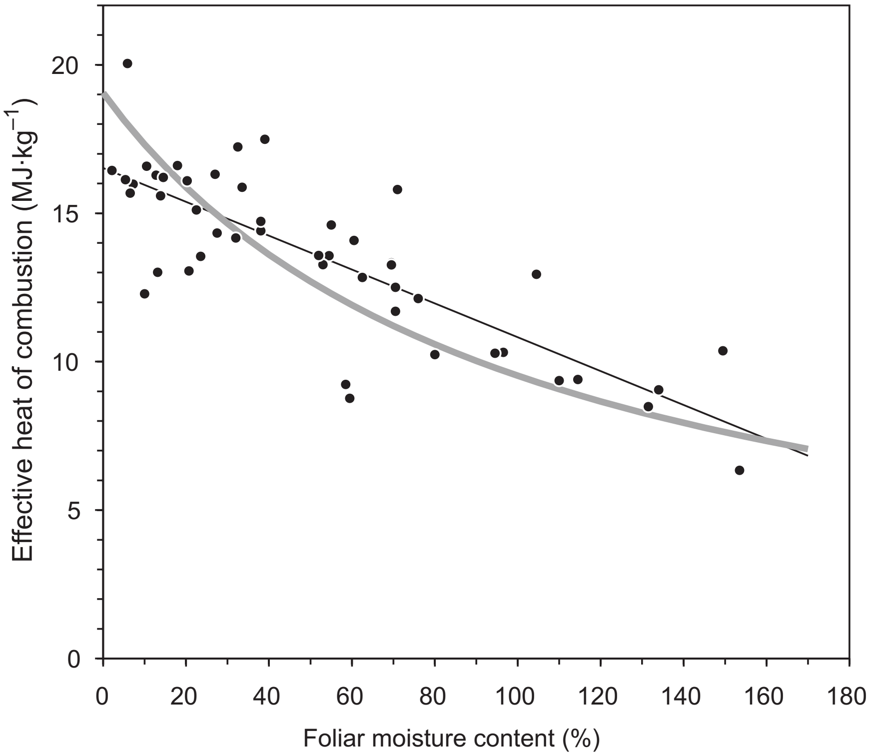
Thermal decomposition of wood

A single value of heat of combustion is often used to characterize burning materials; however, this is only appropriate if the chemistry of the thermal decomposition for the substance is such that there is only a single chemical reaction that needs to be taken into account. Unfortunately, wood is not a material with a single path of decomposition. The actual response of wood to heating is complicated, but the simplest viable representation (Lipska and Parker 1966; Shafizadeh 1968) involves two paths: (1) the early heating is a pyrolysis process whereby flammable vapors are emitted and burned in the gas phase; (2) later heating involves a surface-oxidation reaction and manifests as a glowing combustion of the char. The effective heats of combustion during the two processes are quite different. They have been measured in the laboratory on various wood specimens and a typical result is shown in Fig. 1. These results were obtained using the Cone Calorimeter (ASTM 2004) and the procedures described by Janssens (1991); a heat flux of 65 kW·m^{-2} was used, and the specimen was tested in the vertical orientation. During the flaming combustion period the effective heat of combustion is 12–15 MJ·kg^{-1}, while during the later glowing combustion the value rises substantially and averages roughly 30 MJ·kg^{-1}. When the wood is in the glowing stage, most of its hydrogen has been driven off and the residue is highly carbonaceous. Thus, the 30 MJ·kg^{-1} value is comparable to the heat of combustion of pure carbon, which is 32.8 MJ·kg^{-1} (Babrauskas 2003).

Materials and methods

A systematic study has been conducted on Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees, as reported by Babrauskas et al. (2001) and Babrauskas (2002). The trees were cut at a Christmas tree farm and were approximately 2.0 m tall, with the mass ranging from 6.5 to 22.4 kg and the foliar moisture content (MC) from 2% to 154%. To determine foliar MC, two small branches from each specimen were selected just prior to testing, one near the outer periphery and the other close to the trunk; the branches were then weighed, oven-dried, and reweighed, and the average MC of all samples was recorded as the foliar MC. As is customary, MC was expressed as a percentage of the dry mass of the specimen; thus MC values can be well above 100%. A total of 48 trees were tested. Testing was done in an indoor laboratory, using a large-scale heat-release-rate calorimeter, which allows continuous measurement of the heat released. Data on mass-loss rate were obtained by placing the specimens on a load cell and using these data to compute the instantaneous heat of combustion. A small error is introduced, since some water is released from the portions that do not burn (i.e., the trunk). However, this error is minimal because of the short time that it takes for the fire to consume the foliage, typically 1–3 min, longer only in the case of very wet trees. Furthermore, if the results are applied to burning of trees in the forest (as opposed to burning of foliage removed from trees), no error is introduced into the calculation, since the same effect of slight desiccation of the outermost layer of the trunk will occur in actual fire. The heat-release-rate calorimeter procedures generally followed the recommendations of the American Society for Testing Materials standard E 2067 (ASTM 2003). Instrumental data were corrected for the time lag associated with each instrument. The heat-release rate was measured using the oxygen-

Fig. 2. The dependence of the effective heat of combustion on foliar moisture content, as measured on cut Douglas-fir trees. The black line is the linear regression obtained with eq. 3; the gray line is the alternate hypothesis where moisture is assumed to act only as an inert diluent (eq. 5).



consumption principle (Babrauskas and Grayson 1992). The repeatability and reproducibility of the method have been documented by Janssens (2000).

Results from full-scale tree tests

The trees showed primarily only flaming combustion. For the less moist trees, combustion was rapid, and at the end of the period, only the trunk and some larger branches, which showed negligible glowing combustion, remained. For the more moist trees, the propagation of flames throughout the foliage took much longer, but the outcome was similar. This is because, unlike some other forms of vegetation (e.g., a pile of slash on the ground), upright Douglas-fir trees are not packed densely enough to produce the radiant feedback needed to support glowing combustion. The tree mass remaining was typically 30%–45% and averaged 37.7%. A test-average effective heat of combustion was determined for each test by dividing the total heat released by the total mass lost, as determined from the load cell. A linear regression fitting of the data is shown in Fig. 2 (black line):

$$[3]\qquad \Delta h_{\mathrm{c,eff}} = 16.52 - 0.057\mathrm{MC}$$

where $\Delta h_{\mathrm{c,eff}}$ is effective heat of combustion (MJ·kg^{-1}), and MC is the average foliar moisture content (%). Despite some scatter ($r^2 = 0.65$; $p < 0.01$), the regression correctly express the data trend, and no nonlinearity is exhibited (see Fig. 2). For comparative reference, we note that the gross heat of combustion of Douglas-fir (Parker and LeVan 1989), as measured in the oxygen bomb, is 19.7 MJ·kg^{-1}, and the net heat of combustion is 18.3 MJ·kg^{-1}.

It is useful to examine to what extent the presence of moisture alters the burning process as opposed to acting simply as an inert diluent. In oxygen-bomb testing, the moisture cannot influence the combustion process and has to simply act as an inert component. Thus, for the oxygen bomb:

$$[4]\qquad \Delta h_{\mathrm{c(wet)}} = \Delta h_{\mathrm{c(dry)}}\left(\frac{100}{100+\mathrm{MC}}\right)$$

Our experimental data can alternatively be fitted to a relation of this sort, giving the curve shown in Fig. 2 (gray line):

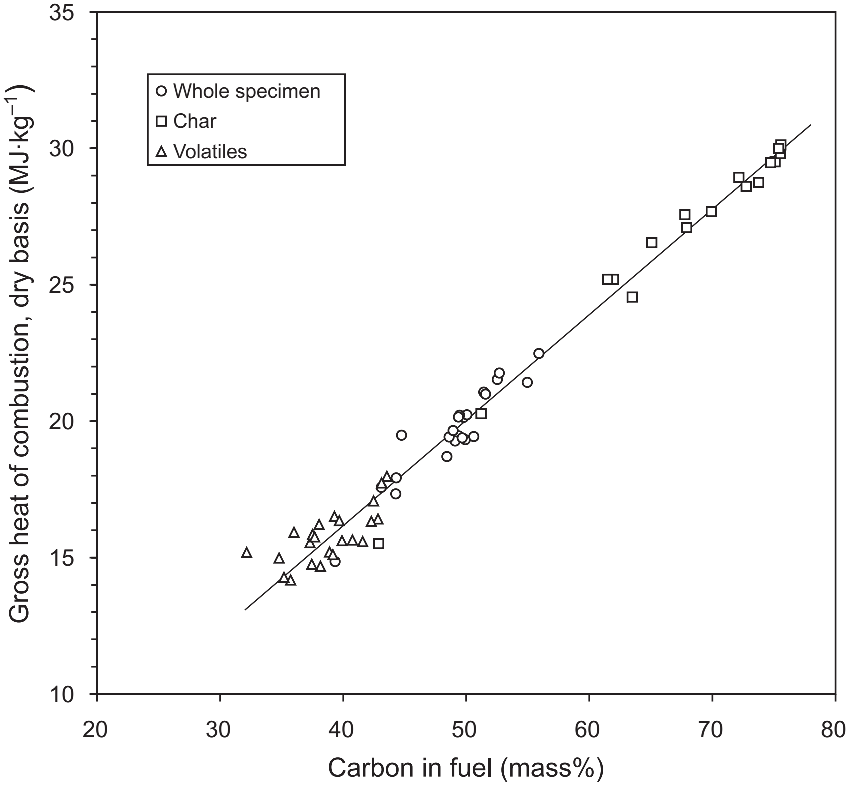
$$[5]\qquad \Delta h_{\mathrm{c(wet)}} = 19.05\left(\frac{100}{100+\mathrm{MC}}\right)$$

However, the curved line obtained with eq. 5 does not represent the data as well as the linear relation obtained with eq. 2 (see Fig. 2). Thus, it may be concluded that moisture alters the combustion process and therefore does not simply act as an inert diluent.

Related research

While this is the first study where whole trees were burned to determine the effective heat of combustion, a number of researchers have investigated the effective heat of combustion of wood in benchmark tests on small samples. Thus, it is of interest to examine how close such benchmark tests come to capturing the performance of real trees. Roberts (1964*a*) was perhaps the earliest researcher to examine the dependence of wood's heat of combustion on the stage of burning. He tested samples of European beech (*Fagus*

Fig. 3. Relation between carbon content and gross heat of combustion, as determined by Sussott et al. (1975).



sylvatica L.) and found that the gross heat of combustion of the whole wood, as tested in an oxygen bomb, was 19.50 $MJ \cdot kg^{-1}$, the flammable pyrolysates had a gross heat of combustion of 16.57 $MJ \cdot kg^{-1}$, while for glowing combustion of the charcoal the value was 34.31 $MJ \cdot kg^{-1}$. The net values (Roberts 1964*b*) were 18.19, 15.06, and 33.98 $MJ \cdot kg^{-1}$, respectively.

Baileys and Blankenhorn (1982) later demonstrated that a similar situation holds for softwoods as well as hardwoods, but they only studied partly charred woods and did not derive values for the initial pyrolysates. Howard (1973) tested various portions of southern pines in an oxygen bomb and found only slight differences in the gross heat of combustion of needles, bark, and stemwood. Cones, however, showed a heat of combustion about 7% lower than that of the other components of the tree.

Sussott et al. (1975) measured the oxygen-bomb heat of combustion[1] for a variety of conifers, deciduous trees, and shrubs. In addition to determining a value for whole specimens, they separately measured the heat of combustion of the volatiles and of the char. Figure 3 shows that all of these results can be expressed by a single predictive equation:

$$[6] \qquad \Delta h_{c,\text{gross}} = 0.3866C + 0.71$$

where $\Delta h_{c,\text{ gross}}$ is gross heat of combustion ($MJ \cdot kg^{-1}$) for a dry specimen, and C is percentage of carbon in the specimen (%). It is striking that percent carbon is the only variable necessary to predict the heat of combustion of vegetation, and that this relation is the same for both coniferous and deciduous specimens and covers not only whole specimens but also volatiles and char.

Parker and LeVan (1989) measured the heat of combustion of the volatiles produced by Douglas-fir (0% MC) as it was pyrolyzed in a specially built apparatus. The heat of combustion of the volatiles progressively increased as the mass was being consumed, going from 10.6 $MJ \cdot kg^{-1}$ at the start to 15.5 $MJ \cdot kg^{-1}$ at the end, with an average of 13.8 $MJ \cdot kg^{-1}$.

Finally, it can be noted that the fire research group at Factory Mutual (Heskestad and Delichatsios 1989) reached the same conclusions as this study. The fire research group extensively used sugar pine (*Pinus lambertiana* Dougl.) "cribs" (rectangular arrays of sticks) and pallets for fire-testing purposes and assumed that the heat of combustion was the oxygen-bomb value of 20.9 $MJ \cdot kg^{-1}$. Upon review, they found a systematic error in this procedure and concluded that the correct value to be used for these lumber specimens (MC = 6%) was 12.5 $MJ \cdot kg^{-1}$. While the MC value was low for these specimens, the analysis encompassed only the active-flaming period; thus effective heat of combustion reflects only the contribution to combustion of the pyrolysates and not the later char oxidation.

Conclusions

During a rapid flaming fire, the heat released from vegetation does not correspond to the oxygen-bomb heat of combustion. The heat of combustion of volatiles (pyrolysates) is

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[1] Sussott et al. (1975) reported their results using a nonstandard definition for heat of combustion, but here we made the appropriate corrections so that the data presented in eq. 6 conform to the standard definition used in thermochemistry.

less than half that of the char. Since significant combustion of the char does not take place during a rapid flaming fire, the effective heat of combustion is close to the heat of combustion of the volatiles alone. Furthermore, the effective heat of combustion of all vegetation is strongly dependent on the MC. The experimental results obtained on the effective heat of combustion of Douglas-fir, as a function of MC, can be applied to a variety of other common North American trees, since interspecies differences in heat of combustion are small.

Stocks et al. (2004) reported the MC of their test fires segregated by tree species and fuel fineness, without estimating an average MC for the fuel actually contributing to the crown fire peak burning period. On the assumption that this burning is mostly dominated by the needles of the canopy, a rough estimate of MC ~70% can be made. According to eq. 3 then, it can be estimated that the true effective heat of combustion was approximately 12.53 $\mathrm{MJ \cdot kg^{-1}}$. This is 30% lower than their assumed value of 18.0 $\mathrm{MJ \cdot kg^{-1}}$; thus the correction needed is significant.

A review of other studies on this topic indicates that our results are consistent with those of other investigators, who have inevitably found the effective heat of combustion during the active-flaming period to be significantly lower than the oxygen-bomb value for wood burned completely.

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