HEAT AND SMOKE RELEASE AT THE COMBUSTION OF THE DIFFERENT WOOD VARIETIES.

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ABSTRACT

The influence of wood species and the content of the main constituents of wood varieties, including classical hardwoods and softwoods, on heat and smoke release at the combustion has been studied. The tests cover 11 wood materials from coniferous and foliate trees of the middle Russia region and 5 wood varieties of tropical and subequatorial Viet-Nam region. The linear correlation between the lower values of heat combustion and summary content of lignin and extractives in wood samples has been established. Extremum dependence of smoke index for wood, D_m^{max}, on external radiant heat flux within the range from 10 to 35 kWm^{-2} without pilot ignitor has been found. Coniferous wood varieties show the biggest values of smoke index on the limit of smoldering combustion (853 –1066 m^2kg^{-1}). Smoke index decreases after self-ignition of wood samples at radiant heat flux above 20-25 kWm^{-2}.

NOMENCLATURE

B - a constant (in equation 5)
C_s - smoke aerosol concentration (kg/m^3)
D_m^{max} - maximum optical density of smoke normalized to mass of sample (m^2/kg)
L - optical path length (m)
m - mass of sample (kg)
Δm - mass loss of sample (kg)
q_e - external radiant heat flux (kW/m^2)
Q_{net} - net (lower) heat of combustion (kJ/kg)
T_o - light transmittance without smoke (%)
T_{min} - light transmittance in smoke (%)
V - enclosure volume (m^3)
W - moisture content (%)
X_l - mass fraction of lignin
X_{ext} - mass fraction of extractives

Greek letters:
μ - extinction coefficient (m^{-1})
μ_m - specific extinction coefficient of smoke (m^2/kg)
ρ - density (kg/m^3)
τ - time (s)
ψ - mass burning rate (kg/s)

INTRODUCTION

Wood is a natural vegetable material used widely in building construction and other technique fields. Wood is a complex composite material in which the fibers are the main structural elements. It is well known that macro- and microstructure, chemical composition, humidity, density, mechanical and thermal physical properties of wood materials depend on the species of trees, their age, the source of material, processing conditions and other factors [1].

Wood is combustible material. The heat release is a general cause for the appearance and the combustion process development. The regime and the intensity of this process depend on the ratio between the heat release rate and the heat loss rate from the combustion reaction zone of material. The heat and smoke production is the dominant hazard factors in fires. The smoke hazard arises as the result of its toxic, irritation effects and also the reducing the visibility into smoked surroundings and consequently the possibility for escaping the occupants. Thus, the risk to be exposed to lethal toxic gases (or heat) increases. The situation in fire is complicated at the same time due to the fact that the smoke gases are quickly spread in the space and penetrate into the enclosures removed from the place of fire.

The present work is focused on the determination of the heat and smoke release characteristics at the combustion of different wood varieties from a middle region of Russia and tropical ones of Viet-Nam. The objective of this research was to elucidate the main factors and distinctive signs of wood varieties, affecting heat and smoke release at the combustion. First of all, it was important to determine the chemical composition of specimens from hardwoods and softwoods. Secondly, to determine the values of net (lower) complete combustion heat for wood. And thirdly, to study the smoke formation ability of wood in depends on the intensity of external radiant heat flux.

The published data concerning to the aspects [1- 5] are hardly comparable because of the differences in the experimental methods, testing conditions, lack of detailed characteristics of samples and also limited number of studied wood varieties. It has been believed [6] that hardwoods and softwoods are distinguished by the behaviour in fire.

MATERIALS AND TEST METHODS

The tests cover 13 coniferous and foliate wood varieties from the middle region of Russia and 5 tropical wood ones from Viet-Nam. The tropical wood varieties consist of thongkaribe (pinus massoniana), vansham (picea koraiensis nakai), bachdan (eucalyptus camaldulensis), keo thy tion (acacia mangium), keo lay (acacia auriculiformis). Physical properties and chemical analyses for wood varieties, represented in Table 1, have been determined through the procedures reported in [1].

The values of net (lower) complete combustion heat, Q_{net}, for wood samples studied have been evaluated with an oxygen bomb calorimetry in according to Russian standard method of GOST 147-74. Besides, these ones have been calculated by D.Mendelejev equation on the basis of elementary composition of wood:

$$Q_{net} = 339.4\ C + 1257\ H - 108.9(O + N - S) - 25.1(9\ H + W), \qquad (1)$$

where C, H, O, N, S – element content into wood composition, %; W- moisture content in the specimens studied, %.

Automatic apparatus of Carlo Erba 1106 (Italy) has been used to determine the elementary composition of oven-dried wood samples. Moisture content in samples has been determined by means of Q-1500 derivatograph (Hungary) at heating rate of 10^{o}C/min. Sample weight was 50-100 mg.

The smoke release has been studied in the most hazard regime of thermal oxidative pyrolysis and smoldering combustion of wood by standard method of GOST 12.1.044-89, item 4.18, without pilot ignitor. The external radiant heat flux has been varied in the range 10-40 kW/m^2. The wood samples, having sizes of 40 x 40 x 5 mm, were tested under an angle of 45^{o} to the horizontal surface.

RESULTS AND DISCUSSION

Wood species are usually subdivided on two broad classes: hardwoods and softwoods [7]. However, by the opinion of Tran [3], these terms have little to do with the hardness of the wood. Botanically, the hardwoods are from trees with broad leaves and the softwoods are from conifers with needle-like or scale-like leaves.

The study of the static hardness of tropical wood varieties shown that really coniferous species of thongkaribe and vansham have the lower mean values of static hardness (37.4 and 43.7 MPa accordingly at moisture content of 12%) than foliate ones of bachdan, keo thy tion and keo lay (78.8; 74.8 and 65.5 MPa). When moisture content in the samples is increased up to 21%, static hardness of the foliate wood is decreased in 1.35-1.4 time, while that for the coniferous wood is decreased only in 1.1-1.2 time.

The density of classic softwood [4] is in the interval of 400-540 kg/m^3, while hardwood density is over 560 kg/m^3 (Table 1). Thus, birch and aspen can be considered as foliate softwoods. Keo thy tion is foliate softwood by density and foliate hardwood by static hardness. Larch amongst conifers must be attributed to hardwood.

NN	Specimen	ρ, kgm^{-3}	W, %	Q_{net} , kJg^{-1}	Holocellulose/ Hemicellulose, %	Lignin,%	Extractives, %
1	Spruce	430	9.5	18.90	62.7 /-	27.3	10.0
2	Pine	450	10	19.62	62.9 / -	28.0	9.1
3	Larch	660	9.6	18.61	-	-	-
4	Cedar	400	10	18.84	61.4 / -	30.8	7.8
5	Beech	600	9.2	18.26	74.1 / -	21.0	4.9
6	Ash-tree	740	-	18.40	-	-	-
7	Maple	610	8	18.04	71.9 / -	23.2	4.9
8	Oak	570	7.0	18.66	68.7 / -	23.6	7.7
9	Birch	540	6.5	18.08	73.3 / -	20.6	6.1
10	Hornbeam	595	-	18.42	-	-	-
11	Aspen	480	6.8	18.14	74.6 / -	21.5	3.9
12	Thongkaribe	430	4	18.62	65.5 / 10.5	27.0	7.93
13	Vansham	400	4	18.84	65.91 / 11.24	27.5	5.06
14	Bachdan	595	5	18.55	67.26 / 19.16	25.4	6.40
15	Keo thy tion	420	4	18.11	69.98 / 21.03	24.75	5.09
16	Keo lay	560	4	18.53	69.12 / 20.10	25.16	5.56

Table 1. The values of lower complete combustion heat and chemical composition for different wood varieties

Experimental results represented in Table 1 confirm that softwoods are characterized by higher lignin content as compared to hardwoods. The varieties of foliate tropical woods contain the higher proportion of hemicellulose (19.16 – 21.03%), in the main as lightly hydrolysable pentosanes. Total content of holocellulose in wood samples studied is changed from 61.4 % (for cedar) to 74.6% (for aspen).

Extractives are a complex mixture of low molecular weight sugars, inositols, simple fats, carboxylic acids, terpenes, phenolic and other substances [1]. The high content of extractives is found both in coniferous wood varieties and in some foliate ones. For instance, the samples of oak and birch by this index are approached to coniferous wood.

The relative proportions of the wood components affect pyrolysis dynamics, the yields of char and other products, heat and smoke release at the combustion of the different wood varieties.

Table 1 demonstrates that net (lower) values of heat of complete combustion with account of the latent heat of water vaporisation for all wood varieties studied are in the range of 18.04–19.62 kJg^{-1}. The near content of elements into the composition of different wood species (Table 2) is reflected in near values of the complete combustion heat of the samples.

NN	Specimen	C , %	H , %	O , %
1	Thongkaribe	50.43	6.14	43.43
2	Vansham	51.01	6.10	42.8
3	Bachdan	51.19	5.81	44.1
4	Keo thy tion	50.06	5.84	45.06.
5	Keo lay	50.34	6.11	43.55

Table 2. Elementary composition of tropical wood samples

Chemical composition of wood affects net (lower) heat of complete combustion. Fig.1 shows the graphic dependence of net combustion heat on summary content of lignin and extractives for different wood varieties. There is a linear correlation between these parameters. The equation of the linear regression for data presented in Fig.1 is estimated as follows:

$$Q_{net} = 15.45 + 0.1\,(X_l + X_{ext}),\quad \text{kJ g}^{-1} \qquad (2)$$

where X_l and X_{ext} - the content of lignin and extractives in oven-dry wood, %

Coefficient of the correlation for the regression equation obtained is R=0.86. The biggest scattering of the values of net complete combustion heat is found for coniferous wood varieties with a high content of extractives.

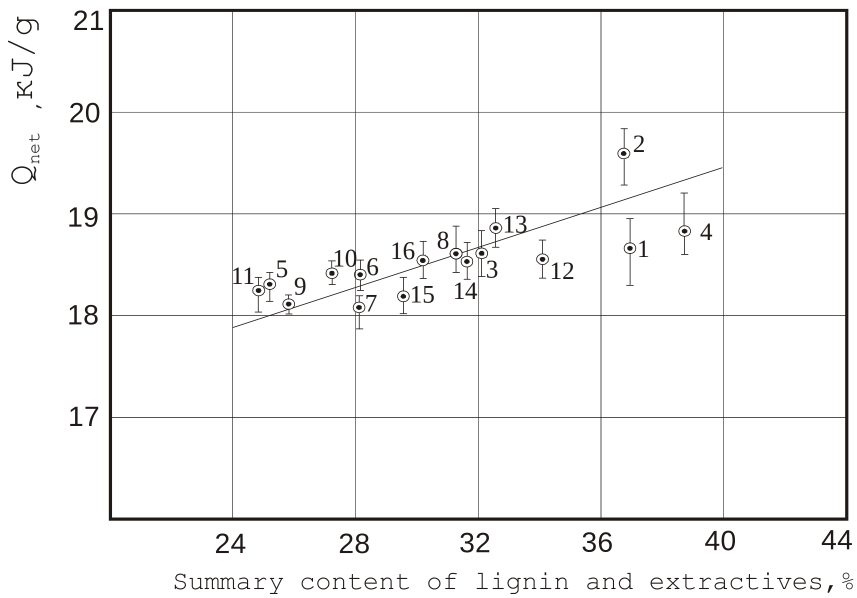

Figure 1. The dependence of net (lower) complete combustion heat of wood samples on summary content of lignin and extractives. Numbers correspond to that mentioned in Table1.

The equation (2) can be used to assess the relative importance of the contribution of different wood components into net (lower) complete combustion heat of wood materials. If summary content of lignin and extractives is equal to zero: $X_l + X_{ext} = 0\%$, in this case, a lower heat of complete combustion for rest part of wood, that is, holocellulose, has to be equal to 15.45 kJ/g. In other extreme case, when $X_l + X_{ext} = 100\%$, the value of a lower heat of complete combustion for a mixture lignin and extractives has to be equal to 25.45 kJ/g.

Such conclusions are just, if to adopt the following assumption:

1. The values of lower complete combustion heat for cellulose and hemicellulose are the same or very near ones.
2. The relative energy contribution of lignin and extractives into total heat release at wood combustion is proportional to their content in wood.

The functional dependence established in the present work on summary content lignin and extractives shows that chemical composition of wood rather than wood category is the main factor which affects heat release characteristics.

Elementary composition of lignin from different wood species is practically identical and in average it includes 63.54% C; 5.54% H and 30.92% O (by the difference) [1]. Then, lower heat of complete combustion of lignin, calculated by Mendelejev equation (1), has to be equal to 23.91 kJ/g. Because of information lack about chemical composition of extractives, their role in heat release is fairly uncertain. It has been supposed that the effect of terpenes and resins in extractive composition on heat release is especially considerable [1].

Let make use of the results obtained to evaluate the values of lower complete combustion heat for wood extractives. For instance, summary content of lignin and extractives into cedar wood
is 38.6 % (Table 1). The fraction of lignin is 0.798 and the fraction of extractives is 0.202. Since a lower complete combustion heat for summary content of lignin and extractives is 25.45 kJ/g (see above), the following equation can be presented:

$$25.45 = 0.798\, Q_{net}^{l} + 0.202\, Q_{net}^{ext}, \qquad (3)$$

where Q_{net}^{l} and Q_{net}^{ext} are the complete combustion heat values for lignin and extractives.

From the equation (3) it is easy to calculate a net (lower) complete combustion heat for extractives of cedar wood:

$$Q_{net}^{ext} = (25.45–0.798Q_{net}^{l})/0.202 = (25.45-0.798x23.91)/0.202 = 31.85\ kJ/g$$

Like that it can be evaluated the values of net complete combustion heat for the compounds extracted from other wood species. So, for pine wood extractives we have Q_{net}^{ext} = 30.2 kJ/g. The quantities obtained in the work are in qualitative agreement with the published values for gross complete combustion heat of pine resins (35-37 kJ/g) [8].

The examples given for two wood samples show that the combustion heats of extractives from different wood varieties are not identical. This fact is probably the result of the distinctions in chemical composition and the main constituent’s proportions of extractives.

In real fires, the heat release process at the combustion is complicated by charring wood. The char layer forming on the wood surface executes the role of barrier delaying heat transfer into material and thus protecting the wood from excessive increase of temperature. The calculation of heat release characteristics at wood combustion has to be based on an effective heat of combustion of wood material with taking account of the combustion efficiency coefficient.

The combustion of organic materials is usually accompanied by smoke release. Smoke is aerosol in which the particles of condensed phase in the form of solid soot and/or liquid combustion products depending on initial material and heating conditions are distributed. To determine the influence of wood variety on smoke ability at oxidative decomposition and the combustion, smoke index, D_m^{max}, is most useful. This index is maximum mass optical density of smoke into test volume, V, with the optical path length through the smoke, L, normalized to initial mass of sample:

$$D_m^{max} = (V / L\ m) \ln (T_o / T_{min}),\ m^2 / kg \qquad (4)$$

where T_o and T_{min} - light transmittance without smoke and in smoke accordingly, %.

Fig.2 shows the change of maximum mass optical density of smoke for each of wood species studied when the intensity of external radiant heat flux is increased. The curves obtained have a complex shape. At first smoke index increases with q_e growth up to certain value (20-25 kW/m^2) and then D_m^{max} decreases. Extremum on the curves of $D_m^{max} = f(q_e)$ corresponds to a spontaneous ignition of volatile combustible products of wood pyrolysis. Smoke character changes when the regime of thermal oxidative decomposition and smoldering is replaced by flame combustion one. Carbon soot is become a main component of condensed phase in smoke. Extremum location corresponds to the value of critical heat flux below which flame combustion of wood without initiating source of ignition has not been realized. From Fig.2 it is seen that foliate wood species have the lower values of critical heat flux for self-ignition (20-23 kW/m^2) than coniferous ones (25-26 kW/m^2). The samples of coniferous wood varieties (thongkaribe, Russian pine, vansham) have the highest smoke indices at limit of the smoldering combustion (853-1066 m^2/kg).

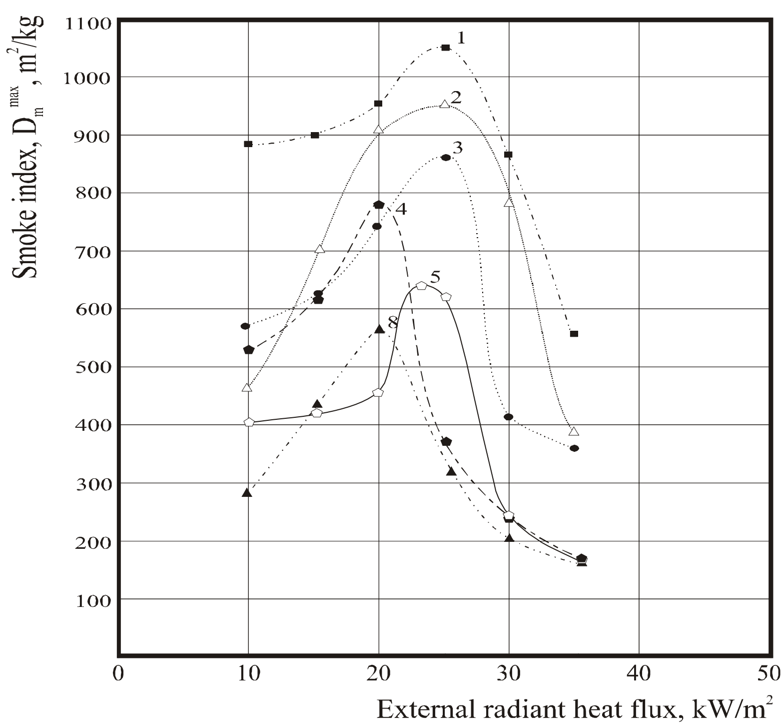

Figure 2. The dependence of smoke index, D_m^{max}, for coniferous and foliate wood species on the intensity of external radiant heat flux, q_e: 1- vansham; 2- pine; 3- thongkaribe; 4 – keo lay; 5 – keo tay tion; 6 – bachdan.

After spontaneous ignition of wood materials at the intensive action of radiant heat flux (q_e =35 kW/m^2) smoke indices are essentially decreased. However, the values obtained are the higher than the indices fixed at flame regime with initiating pilot ignitor. There are different conditions to achieve lower concentration limit for self-ignition and the ignition of volatile combustible products of wood decomposition and also corresponding temperature of gas phase. In this case at same heat flux q_e = 30 kW/m^2 for pine wood, as example, delay times of self-ignition and the ignition are not equal: τ_{sign} = 70 s > τ_{ign} =23 s. It should be noted that although the differences between the wood species tend to decrease for high heat fluxes, at flame combustion coniferous wood samples display the higher smoke formation ability than foliate ones.

It is known that thermal decomposition of solid materials is limiting stage of the combustion process. Global parameters such as pyrolysis temperature, average devolatilization rate, char residue yield, amount and the composition of liquid and gas fraction, their relative proportions depend on chemical composition of wood varieties [9]. For instance, pyrolysis temperature of wood is decreased when summary content hemicellulose and extractives is increased as regards cellulose content. Char residue yield is increased with lignin content. Amount of liquid fraction, which is mainly responsible for smoke production at wood combustion, depends on holocellulose contribution.

The general smoke characteristics are a concentration and volume fraction of particles into aerosol, the shape, sizes and the number distribution of the particles by sizes. They determine optical properties of smoke and visibility in smoke medium. Visibility is expressed in terms of a distance, l, at which an object is clearly visible under the room lighting conditions. Visibility depends on optical density of smoke expressed by coefficient of extinction, μ, the illumination in enclosure, whether the object is light emitting or light reflecting. The relationship between visibility and extinction coefficient can be presented as:

$$l_v = B / \mu, \quad (4)$$

where B is a constant;

$$\mu = (1/ L) \ln (T_o / T_{min}),\ m^{-1} \quad (5)$$

For usual objects, B value is equal to 2, for light refflecting ones, B = 2-4 and for light emitting signs, B = 6-8. Russian standard GOST 12.1.004-91 recommends to evaluate a critical coefficient of extinction at fire in buildings using the value of B =2.38 and regulated l_v. If it is adopted that l_v =20 m, critical extinction coefficient can not be above 0.119 m^{-1}. Dynamics of visibility decrease in smoke medium has been determined by mass burning rate of wood materials with corresponding smoke formation ability:

$$V (d\mu /d\tau) = D_m^{max}\ \psi , \quad (6)$$

where ψ - mass burning rate of wood material, kg/s.

Thus, heat and smoke release at wood combustion has to depend both on chemical constituent's proportions in different wood categories and the conditions of heat action.

CONCLUSIONS

The effects of variety, chemical composition of wood and also the intensity of external radiant heat flux on heat and smoke release characteristics at wood combustion have been investigated. It has been established that chemical composition and relative proportions of main components of wood (holocellulose, lignin and extractives) rather than wood category (softwood or hardwood) affect net (lower) heat of complete combustion of wood samples.

The values of lower complete combustion heat for 16 coniferous and foliate wood varieties, determined by oxygen bomb calorimetry and also calculated on the basis of elementary composition, are within the range from 18.04 to 19.62 kJ/g. The linear correlation between the combustion heat and summary content of lignin and extractives in wood samples has been found. The estimation of the values of lower complete combustion heat for lignin and extractives from different coniferous species of wood has been presented. For lignin Q_{net} is equal to 23.91 kJ/g. For extractives from cedar and pine wood Q_{net} are equal to 31.85 and 30.2 kJ/g accordingly. The difference in chemical composition and main constituent's proportion of extractives from different wood species is probably reflected on Q_{net} values.

Smoke release at the thermal decomposition and the combustion of coniferous and foliate wood varieties depending on external radiant heat flux within the range 10-35 kW/m^2 without pilot ignitor has been studied. Extremum dependence of smoke index, D_m^{max}, on the heat flux intensity has been found. Coniferous wood species show the highest values of D_m^{max} at limit of smoldering combustion of the samples (853-1066 m^2/kg). After spontaneous ignition of wood smoke index decreases. However, even at heat flux of 35 kW/m^2 the values of D_m^{max} essentially exceed that at flame combustion of wood with initiating pilot ignitor.

The difference between tropical hardwood and softwood species by their smoke release behaviour is revealed in the higher critical heat flux required by softwood category for self-ignition (about 25-26 kW/m^2 against 20-23 kW/m^2). This is a consequence of the higher summary content of lignin and extractives in the wood samples and also higher temperature of lignin degradation.

REFERENCES

1. Nikitin, V.M., Chemistry of Wood and Cellulose, 1951, Goslegbumizdat, Leningrad, (in Russian).
2. Parker, W.J., LeVan, S.L., Kinetic Properties of the Components of Douglas-Fir and the Heat of Combustion of Their Volatile Pyrolysis Products, Wood and Fiber Sci. 1989, 21**,** No.3, 1989, pp.289-305.
3. Tran, H.C., Experimental Data on Wood Materials, In: Heat Release in Fires (Babrauskas, V., Grayson, S.J. Eds), Elsevier Applied Science, New York, cxdsew 1992, pp.357-372.
4. Hilado, C.J., Flammability Handbook for Thermal Insulation, 1983, Technomic, Lancaster.
5. Flisi Umberto, Testing the Smoke and Fire Hazard, Polymer Degradation and Stability, 30**,** 1990, pp. 153-168.
6. Sweet, M.S., Fire Performance of Wood: Test Methods and Fire Retardant Treatment, Proceedings of 4-th Annual BCC Conference on Recent Advances in Flame Retardancy of Polymeric Materials, May 1993, Stamford, USA.
7. Kalninsh, L.Ya., Wood, Encyclopaedia of Polymers, Soviet Encyclopaedia, Moscow, 1, 1972, p.764.
8. Howard, E.T., Heat of Combustion of Various Southern Pine Materials, Wood Sci. 5, No.3, 1973, pp. 194-197.
9. Di Blasi, C., Branca, C., Santoro, A., Hernandez, E.G., Pyrolytic Bechaviour and Products of Some Wood Varieties, Combustion and Flame, 124, No.1, 2001, pp. 165-177.