

Conclusion

Centuries of experience have given humanity a fairly reasonable idea of the high fire hazard of timber. Modern fire statistics only confirm this opinion about timber, which is still one of the most popular construction materials. It is no coincidence that the problem of reducing the fire hazard of timber and timber products is a major preoccupation. Successfully solving this problem depends on an understanding of the mechanisms of the onset smoldering and flaming timber combustion, fire propagation in buildings and structures with timber structures, and the conditions for preventing combustion.

Despite the vast amount of experimental work in this area, it is often difficult to compare the results, not only because different research methods were used but also because of the timber specimen used without mentioning their species and variety or any description of their characteristics. Evidently, this experimental setup of many works was due to the still-prevalent outdated approach to timber as some kind of generalized substance with properties that differed very little between them.

Rapid growth of theoretical works on pyrolysis and thermo-oxidative decomposition, flammability, and flame spread over the surface of timber and other synthetic materials with allowance for carbonization of these materials began only in recent decades.

To a certain extent, the monograph summarizes the results of the recent development of this line of timber research. The basis for this work is the concept that many properties of timber, including fire-hazardous properties, are simultaneously a function of both the physical macro- and microstructure and the chemical composition of this complex composite material created by nature itself. Therefore, the specific reaction of timber on exposure to high temperatures and fire is examined in terms of the diversity of its species and types, which should necessarily affect the physical, thermochemical and thermophysical properties, and chemical composition of the specimens.

Timber is a product of the vital activities of a living plant. The genetic basis for the diversity of this biological form of living substance on Earth, its adaptation to the habitat, and resistance to adverse impacts has still not been fully revealed.

In the next few years of the twenty-first century, we should expect revolutionary scientific breakthroughs in knowledge of the complete genome of woody plants, the fine mechanisms of biochemical synthesis of plant tissues and the main chemical components of timber, and discovery of the genes controlling this synthesis.

The concept we have used helps us to understand the fire behavior of various timber species and the change in their fire-hazardous properties during natural and artificial aging.

An analysis of the influence of the content of main components in the chemical composition of various deciduous and coniferous timber species on the lower total combustion heat of timber, which is a thermodynamic characteristic of any specific substance, clearly confirms the correctness of this concept.

The authors have tried to organize and summarize the available results from scientific publications on pivotal experimental and theoretical works that provide insight into the relationship between the structure, composition and properties of timber, and the mechanisms of timber combustion in various conditions of heat exposure.

The authors have attempted to describe the overall status of this problem in Russia and the prospects of solving it by using their own results of long-term research and the experience of colleagues at the Academy of the State Fire Service of EMERCOM of Russia and other organizations involved in fire safety of construction projects.

It should be noted that the design and development of modern technologies for manufacturing new timber- and plant-based materials in our country are ahead of the regulatory foundation for their safe use in the construction industry. A striking example of this is the production of new types of laminated timber structures and the restriction on using them in low-rise housing construction due to the absence of the relevant construction standards and regulations in Russia.

The most economic means of legal use of new materials in the construction of medium-rise frame wooden buildings structures is probably to adapt existing international standards and regulations to this sector.

Trends toward basic study of the fire behavior and fire hazard characteristics of timber with allowance for species diversity are very clearly strengthening in world practice.

Although the combustion and fire-hazardous properties of timber are considered as an important area of timber research, it should be emphasized that many aspects of the problem of timber combustion remain unresolved.

There have been almost no studies of the long-term processes occurring in timber during low-temperature heat exposure. The conditions and factors influencing the occurrence of smoldering timber combustion and its transition to flaming combustion are unclear. An understanding of the extent to which both the content of main components in timber and the constituents of these components and their chemical nature will affect timber combustion and its critical conditions is still ahead.

In this context, an analysis of the changes in some important indicators of the fire hazard of timber when it is naturally and artificially aged is of interest. It is clear that the details of the solid phase processes are very important for the gas-phase processes of flaming combustion.

Timber charring during a fire affects the fire resistance of wooden load-bearing structures and enclosures. Data on the timber charring rate as a function only of timber density (specific weight) obtained during tests under standard fire conditions frequently disagree or are contradictory. However, a general trend emerges: all other conditions being equal, coniferous species char at a faster rate than deciduous species. If we take the significant contribution to timber charring of one component, namely, lignin, into account, the observed contradictions become more comprehensible.

We suggest concentrating on the quality of the charred surface layer that forms during the combustion of timber and timber products and the potential for targeted control of the pore structure and properties of the coke layer. This will affect its thermal properties and the temperature distribution in material in close proximity to the charring front and thus the temperature dependence of the mechanical properties of the structural member as a whole.

The optimum balance of combined fire protection methods and achieving a mutual synergistic effect among them is a way to significantly increase the fire resistance and fire safety level of wooden building structures.

The development of verifiable models of the mechanism of fire protection connecting design parameters with its composition, structure, and characteristics of its main constituents will promote the development of effective fire protection measures for timber.

Index

A

- Activation energy
 - after aging of timber constructions, 230–238
 - main components of timber, 126
 - pyrolysis of timber species, 101
 - thermal decomposition of starch oxidate, 221
 - thermal oxidation of timber species, 64–71
- Aging of timber building members
 - in accelerated artificial conditions, 259–263, 265, 267, 271, 272, 277
 - in natural conditions, 263
- Alcohols
 - coniferyl, 21, 122, 165
 - n*-coumaric, 21
 - sinapic, 21, 59, 122, 165
- Analysis of chemical composition of timber, 7, 32, 55, 100, 171, 236, 248, 253
- Antiseptics for timber, 35, 254, 255
- ASTM E 1354 cone calorimeter, ISO 5660, 110, 128, 129, 209
- Autoignition of timber, 99, 100, 103, 104, 214
 - criteria, 100

B

- Barrier, 7, 11, 181, 193, 199, 204, 224
- B complex, 185
- Beer-Lambert Law, 166
- Biodegradation of timber species, 229
- Biogenetic aspects of timber diversity, 12, 30
- Bio-markers for smoke gases, 165
- Bio-moisture-fire protective composition, 256

C

- Calculation of calorific value
 - by elemental composition, 113
 - by group contributions, 124, 221
- Calorimeter methods, 110, 128, 129, 132, 133, 209, 224
- Cell membrane (tissue)
 - cell structure, 19, 28, 32, 34, 219, 229–238
 - chemical composition, 19, 27, 32, 34, 54, 55, 57, 219, 229–238
- Cell wall, 18–21, 26, 31, 32, 34, 36–39, 48, 89, 90, 95, 262
- Char layer thickness, 83–85, 100, 154, 158, 249
- Charring of timber constructions, 11, 193, 195, 200, 201, 215, 216, 248, 249, 251, 276
- Charring rate of timber
 - at constant heat flow, 223
 - during standard fire, 187–190
- Chart introduced by N.N. Semenov, 90
- Chemical composition of timber
 - changes after artificial aging, 263, 265, 270, 272, 274, 275
 - changes after natural aging, 229–256, 259, 262, 272
 - coniferous species, 2, 17, 18, 20–22, 25, 29, 45, 46, 48, 65, 82, 100, 111, 122, 133, 136, 141, 168, 190, 191, 229, 237, 244, 249, 263, 266, 270
 - deciduous species, 2, 18, 20, 21, 24, 29, 33, 39, 41, 46, 48, 55, 62, 65, 84, 100, 109, 111, 112, 115, 133, 167, 169, 171, 186, 187, 189, 232, 237, 244, 263, 266

Chromosome theory, 26, 29

Classes of structural fire hazard of
 timber buildings and structures, 5, 178,
 187, 190, 229, 231
 timber constructions, 177–196, 201, 203,
 210, 214, 215, 220, 232, 246, 260

Classification criteria, 12, 91, 93, 96, 100, 101,
 112

Combustion efficiency, 128, 158, 171, 185

Combustion gases, 170, 172

Combustion products toxicity, 6, 8, 129, 139,
 172, 184

Components of foaming coatings
 chemical foaming agents, 217, 219
 physical foaming agents, 217, 219

Compounds' density, 31

Conditions of decomposition process, 8, 62,
 67, 245
 diffusion controlled, 65, 76, 97
 kinetically controlled, 76, 97

Conflict between pyrolysis and thermo-
 oxidative decomposition rates,
 66–68, 70

Constructive methods of fire protection,
 199–225

Content in timber
 cellulose, 126, 127, 235, 236
 extractives, 127
 hemicelluloses, 126, 127, 235, 236
 lignin, 126, 127, 235, 252, 264

Corpuscular inclusion bodies
 in chloroplasts, 26, 27
 in chromosomes, 29
 in mitochondria, 26, 27
 in nucleus, 26, 27, 29
 in ribosomes, 26, 27

Criteria for self-ignition
 of gas phase, 9, 101, 104
 of solid phase, 8, 102, 106

Critical conditions for combustion
 flaming, 90, 95, 100, 101
 heterogeneous (flameless), 90–96, 130

Critical fire duration, 184–186

Critical mass flow, 95, 100, 112, 114, 115, 212

Critical rate of heat release, 115, 116

Cross-laminated timber (CLT), 10, 177, 202

CROW model of carbonization, 140

D

Damkohler number, 146, 147, 149

Damping limit of flame spread, 149

Degree of fire resistance, 180–182
 of timber buildings and structures, 181–182

Density of timber species
 effect of moisture, 48, 84
 true density of wood matter, 34, 35

Deoxyribonucleic acid (DNA), 26, 27, 30, 31

Determining fire hazard of materials
 class of combustibility, 172, 214
 class of flame propagation, 139–160
 class of flammability, 6, 31, 36, 89, 102,
 105, 124, 141, 211, 246, 247, 256,
 273
 smoke-generation capacity, 129, 196,
 208–210, 212, 246–248
 toxicity of combustion products, 6, 8, 129,
 172, 184

E

Effective heat of combustion, 128, 130

Effective kinetic parameters of pyrolysis
 main timber components, 54–63, 255
 model compounds, 64

Effect of aging on
 chemical composition, 230–238, 246,
 248
 density, 265, 272, 277
 energy of decomposition activation,
 244
 heat of complete combustion of, 119–127,
 246, 272
 indices of fire hazard, 128, 129, 131,
 272–278
 thermal properties, 263–278

Effect of oxygen concentration, 67–70, 92, 96,
 97, 122, 132, 142, 147, 170, 172,
 180, 184, 215
 mass loss rate, 68, 215, 223

Intumescence coefficient, 207–209

Extinction coefficient, 166

F

FIGRA index, 130–132, 136, 167, 209

Fire and biological protective preparations,
 256

Fire hazard(s), 3, 91, 141, 155, 167, 170,
 172, 179, 180, 184–186, 196, 205,
 207–210, 214, 215, 245, 246

Fire hazard class, 167, 180, 181, 196, 207, 208,
 214

Fire hazard factors, 172, 180, 184–186
 during fire growth in compartment,
 184–186

Fire protection efficiency, 203, 206, 209, 210,
 214, 222–225

Fire protection of timber constructions
 deep impregnation, 203, 214, 215
 intumescent fire retardant coatings, 200, 218
 structural protection, 11, 190, 191, 200–202
 surface impregnation, 203, 211, 212, 214

Fire-protective coating (VPM-2), 207

Fire-protective general purpose preparation (SGK-1), 207

Fire protective impregnating preparations, 201, 203, 212, 220, 224, 256

Fire protective lacquer coatings, 260

Fire protective preparation (OK-GF), 205

Fire resistance, 4, 5, 11, 12, 77, 177–196, 200–210, 241, 248, 259, 262, 276

Fire-resistance degree, 180–182
 calculation, 180

Fire resistance of timber, 12, 190–196, 200–210, 248, 276

Fire retardants, 200, 203–218, 221–224, 277

Fire statistics, 4

Flame propagation index, 139–160, 186

Flame propagation on timber surface, 139–160, 186

Flame propagation rate, 141–143, 145, 148, 149, 152, 154, 155, 158–160

Flame retardants, 11, 196, 210, 272, 276–278

Flame spread index for timber species, 142

Flame spread rate
 on thermally thick specimens, 78–80
 on thermally thin specimens, 72, 79

Flow calorimeter OSU, ASTM E906, 129

G

Gasification heat, 84–86, 151, 158
 the influence of anisotropy, 37

Gasification heat of timber
 per unit of material mass, 128, 157, 158, 170
 per unit of volatile mass, 81, 86, 116, 169–172

Gas permeability, 35, 91

Generation of smoke, 128, 163–172

Genes, 25, 27, 30, 31

Genome of poplar, 2, 25, 31

Genomes, 25–27, 30, 31, 33

Glued laminated timber (glulam), 10, 177–179, 187, 188, 190–192, 195, 196, 200–202, 207, 208

Graphites expanding when heated, 207

H

Heat emission rate, 158, 186, 211

Heat flow of ignition
 critical, 83, 100, 108, 109, 211
 minimal, 98, 99, 101, 106, 142

Heat of complete combustion of coke, 224

Heat of complete combustion of compounds
 of cellulose, 127
 of extractives, 127
 of hemicelluloses, 127
 of lignin, 127

Heat of complete combustion of timber
 lower heat value, 124
 in relation to chemical composition, 119–136
 upper heat value, 122–123

Heat of pyrolysis reaction, 80, 81, 94

Heat release characteristics, 119–136

Heat release rate (HRR)
 effect of heat flow density, 134
 effect of moisture, 48, 84, 94, 135, 255
 maximum value of HRR_{max} , 130

Heat transfer coefficient, 108

Heavy timber constructions, 190

Hygroscopic limit, 32, 264

I

Ignition of timber species
 piloted flaming, 105–116
 smoldering, 91–98
 time before ignition, 109, 112

Incipient ignition, 115

Indicators of heat emission, 95

Indicators of toxicity of combustion products, 170

Inflammability limits, 102

Inflammation delay time
 of the samples of intermediate dimensions, 73
 of thermally thick samples, 73, 108
 of thermally thin samples, 73

ISO 9705 method, 129

K

Kinetic parameters of pyrolysis
 of components, 60
 of model compounds, 61
 of timber, 245

L

Libri-form fiber, 21, 23, 24

Light frame timber buildings, 191, 200

- Lignification, 20
- Lignin
 coniferous species, 20, 21, 122, 123
 deciduous species, 20, 21, 122
 of hardwood, 191
 of softwood, 136
- Limit of fire resistance of
 load-bearing timber constructions,
 182, 191
 nonbearing timber constructions, 182
- Lower heat of complete combustion
 extractives, 127
 hemicelluloses, 127
 timber species, 119–136
- M**
- Macrostructure, 17, 18
- Major timber
 cellulose, 8, 19, 20, 34, 35, 55, 56, 58–62,
 65–69, 76, 86, 91–93, 101, 103, 119,
 121, 126, 127, 150–152, 165, 169,
 217, 232, 234–236, 242, 243, 251,
 265–267, 276
 extractives, 34, 38, 55–57, 60, 119, 120,
 122–127, 141, 165, 232, 234, 235,
 242, 252, 265, 266, 275, 276
 hemicelluloses, 19, 20, 35, 55, 56, 58–60,
 66, 103, 119–122, 125–127, 169,
 232, 235, 242, 251, 252, 262, 264,
 266, 267, 275, 276
 lignin, 20, 21, 35, 55, 56, 58–61, 66, 67, 72,
 103, 119–127, 165, 169, 187, 232,
 234–237, 242–244, 249, 251, 252,
 262, 264–267, 272, 275, 276
- Mass loss rate, 62, 64, 68, 72, 76, 77, 80–82,
 85, 95, 129, 130, 185, 209–211, 215,
 223, 249, 270, 272, 273
- Maximum temperature of adiabatic flame 113,
 128, 145, 152
- Mechanical properties of timber
 coniferous species, 2, 18, 20–22, 25, 29,
 45, 46
 correlation equations between different
 parameters, 35, 41, 46
 correlation equations with basic density, 45
 deciduous species, 18, 20, 21, 24, 29, 33,
 39, 41, 46, 48
 effect of heating, 49
 effect of moisture, 48
- Mechanism of timber decomposition, 252
- Methods of accelerated artificial aging,
 259–263
- Methods of impregnating
 deep, 203, 214, 215
 surface, 203, 211, 212, 214
- Microstructure
 of hardwood, 21, 22
 of softwood, 22–24
- Microstructure of timber
 coniferous species, 17–25
 deciduous species, 17–25
 with diffuse-porous structure, 19, 22, 24
 with ring-porous structure, 18, 19, 22, 124
- Modeling flame spread on timber surface
 with concurrent oxidizer flow, 156, 157,
 160
 with opposed oxidizer flow, 144
- Model of cellulose pyrolysis, 65
- Model of timber smoldering, 91, 212, 214,
 256
- Models of timber pyrolysis
 analytical, 72
 differential (numerical), 71, 72, 77
 integral, 71, 77, 78, 81, 82
- Mutations
 chromosome mutations, 30
 cytoplasmic mutations, 30
 gene mutations, 30
 genome mutations, 30
- O**
- Optical smoke density, 165–167, 172
- Oxidative modification of plant raw material,
 218–222
- Oxidized polysaccharides, 221, 277
- P**
- Parameters of char layers, 278
- Period before smoldering combustion, 53, 82,
 90–93, 95–98, 105, 159, 160, 168,
 170, 204, 212, 372
 anisotropic effect, 40, 41, 104
- Permeability coefficient, 35, 36
- Per unit mass, 86, 116
 of volatile products, 116
- Phenomenological two-phase, 65
- Pilot ignition, 93, 100, 105–108, 110–114
- Plant cells
 parenchymal, 18, 19, 24, 25
 prosenchymatal, 18
- Polymorphism of woody plants, 30
- Porosity, 26, 35, 73, 82, 89–92, 155, 249, 267,
 275

- Porosity of timber, 26, 35, 73, 82, 89–92, 155, 249, 267, 275
- Principle of fire resistance calculation, 195
- Profiles of oxidizer flow
 homogeneous flow (Oseen), 145
 parabolic flow (Hagen–Poiseuille), 146, 151, 153
- Proterm wood, 202, 207, 208
- Protoplast
 cytoplasm, 26, 27, 30
 membrane, 18–20, 25, 26
 vacuole, 26
- Pyrolysis models for carbonizing materials, 79
- Pyrolysis of timber species
 main timber components, 255
 model compounds, 61
- Pyrolysis products, 9, 59, 61, 62, 74, 75, 86, 100, 101, 103, 112, 114, 148, 150, 152, 212
- Pyrolysis timber products
 char, 53, 81
 noncondensable gases, 62, 63
 tar, 60, 61, 73, 75
- R**
- Ray cells, 232
- Ribonucleic acid (RNA), 26, 27
- S**
- SBI, EN 13823 method, 128, 130, 166, 209
- Schemes of pyrolysis reactions
 cellulose pyrolysis, 58
 lignin pyrolysis, 59
- Self-actuating fire extinguisher (OSP-1), 201, 207
- Simulation of fire protection, 186
 calculation of optimal thicknesses, 209
- Simulation of self-ignition, 247
- Slabby fire-protective materials, 201
- SMOGRA index, 167
- Smoke-generation capacity, 129, 196, 208–210, 212, 246–248
- Smoke generation rate, 167
- Smoke optical density, 185
- Smoking ability of timber species
 at flaming combustion, 164, 165, 167
 at smoldering combustion, 168
- Smoldering initiation temperature, 95, 160
- Smoldering propagation rate, 140, 159, 160
- Soot generation in flame, 164
- Soot particle concentration, 165
- SOTERM-1M-plaster, 201
- Species composition of forests
 of hardwood, 191
 of softwood, 136
- Specific heat, 36–39, 71, 108, 114, 155, 209, 219
 dependence on temperature, 36–39, 209
- Standard temperature mode, 11, 160, 187, 192, 201, 208, 215, 249, 276
- Statistical fire data, 4–6, 169
- STFI calorimeter, 132
- Surface temperature of combustion, 97, 106
- T**
- Temperature
 char layer surface, 7, 215, 277
 distribution in timber construction, 200, 201
 flame, 106, 113, 114, 145, 152
 timber surface, 101
- The distribution of structural elements, 24
- The genetic theory of inheritance, 26
- The genome of poplar, 31
- The heat flow emerging from flame, 93
- Thermal analysis
 of components, 55–57
 of timber, 263–272
- Thermal conductivity, 7, 36, 38, 39, 71–75, 77–79, 82, 95, 96, 102, 103, 108, 145, 147, 148, 152–155, 158, 189, 217, 259, 262, 271
 depending on density, 38
- Thermal diffusivity, 36, 39, 40
- Thermal effects, 8, 10, 41, 94
- Thermally thick materials, 78, 108, 146–148, 152, 158
- Thermally thin materials, 73, 78, 145, 147, 148, 152
- Thermal models of inflammation, 9, 78, 107
- Thermo-oxidative decomposition rates, 68, 69
- Thermo-oxidative timber decomposition, 53–86
 kinetic parameters, 54–57, 60, 61, 65, 66, 68, 71, 72, 75, 77
- Thermophysical properties, 7, 36–40, 71, 72, 75, 107, 112, 139, 145, 151, 216
- Thermo-physical properties of coke, 7
- Thermophysical properties of timber
 specific heat
 effect of anisotropy, 37, 112
 effect of moisture, 48, 84, 94, 135, 255
 effect of temperature, 39, 219
 thermal conductivity, 7, 36, 38, 39, 71–75
 thermal diffusivity, 36, 39, 40
 thermal inertia, 39, 40, 112

- The thickness of carbonized layer, 155, 275
- Thickness of coke layer, 84, 85
the influence of heat flow density, 7
- Timber ageing
artificial, 249, 259–278
natural, 229–256
- Timber charring rate, 84, 187–190, 194, 195, 202, 216
calculation, 85
- Timber constructions from
glulam, 10, 177–179, 187, 188, 190–192, 195, 196, 200–202, 205, 207, 208
laminated strand lumber (LSL), 178
laminated veneer lumber (LVL), 10, 177, 190, 191
logs, 177, 180
oriented strand board (OSB), 10, 178
parallel strand lumber (PSL), 178
- Timber density
basic, 32, 44–46
normalized, 32
true specific density, 34
- Timber inflammation, 70, 81, 102, 105, 140, 144, 145, 148, 151–156, 256, 267
- Timber microanalysis, 120
- Timber moisture content, 48
- Timber pyrolysis
primary, 54, 58, 60–62, 75
secondary, 58, 61, 62, 75
- Timber self-ignition
influence of timber chemical composition
on self-ignition, 120, 265
influence of timber species on self-ignition, 140, 142
- Timber structures
carrying, 260
cladding, 200, 201, 205, 206
- Total heat release, 130, 134, 209, 215, 224, 225, 275, 276
- Total smoke release, 167
- Toxicity of smoke products, 170, 210, 212, 214, 246, 256
- Tracheids, 21–24, 35, 232, 252
- Transport system, 24, 25
- Transport system of woody plants, 25
- U**
- Units of polysaccharide macromolecules, 218, 219
- Unsteady inflammation (flashes), 106, 115
- V**
- Vermiculites, 201, 202, 207
- Vessels, 18, 125
- Visibility in smoke, 165, 166, 180
- Volatile products of timber decomposition, 55, 62, 90, 99, 103, 113, 114
- W**
- Water dispersible preparation (OGRAMS-V-SK), 202, 207
- Wood matter density, 34
- Y**
- Yield of char residue, 56, 62, 100, 204
- Z**
- Zero-strength timber layer, 201, 202