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An approach to estimating the range of wild fire firebrands transportation by wind

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Abstract. Forest wild fire prevention that is carried out to minimize of wild fires number and possible damage from them, is inconceivable without the development of fire-prevention procedures, which are based on data from wild fire monitoring. One of the areas of wild fires monitoring is the evaluation of forest wild fires spreading ability to transportation of firebrands by the wind. This way observed at crown-type of forest wild fires, which are formed from ground ones by transferring the flame to the trees crowns when the wind reaches a certain speed. A mathematical model has been developed for the firebrands transportation by the wind. Mathematical model adequacy was evaluated by inclusion of transfer coefficient as a ratio of firebrand speed to wind speed. The modeling of the horizontal firebrands transportation (sphere, cylinder and disc) has been carried out. Experimental conditions are firebrands have various sizes, fall off from a height of 5-20 m, at a wind speed of 1-5 $m \cdot s^{-1}$. Spherical and disc-shaped particles have the best transportation ability. The adequacy of the model of horizontal firebrands transportation has been experimentally proved by conducting our own experiments and analyzing information obtained from the literature on similar studies. The results of the experiments showed that with an increase in the air flow speed up to 10 $m \cdot s^{-1}$, the speed of the burning particle does not exceed the speed of the air flow that stimulates it. Thus, it is shown that within the air flow velocity of 1-10 $m \cdot s^{-1}$, the value of the transfer coefficient does not exceed one.

1. Introduction

Prevention and suppression of forest fires is a complex problem that is part of the activities called forest fire fighting. In order to extinguish a forest fire, it is quite enough to create conditions that prevent its occurrence, growth and spread. However, this is not yet possible, since no approaches have been developed that fully guarantee the prevention of fire.

Each forest wild fire starts as a ground fire, spreading along its edge, burning out ground forest combustible materials (FCM), undergrowth, shrub vegetation, etc. Thus, a vulnerable spot of a forest bottom fire is the process of transition of the combustion zone from one area covered by FCM LGM to another. Wild fire monitoring is not particularly difficult because the increase in the length of its edge along the front, flanks and rear has a constant value, indicated in the reference literature [Richter].

Under certain weather conditions, a forest bushfire can turn into a bushfire. From this point on, predicting its growth and distribution becomes a difficult task, since a riding forest fire occurs in difficult weather conditions, some of which the fire itself creates. The protection of the territory from a top fire is complicated by the ability of the fire to create a swarm of burning particles of the most diverse shapes and sizes, as well as to carry out their transfer in space (in a forest, to a settlement, to an industrial enterprise, etc.). Part of the transported burning particles have time to burn and fall on tree-like plants or grass cover in the form of ash, but some of the particles (larger ones) are able to continue burning and are sources of ignition. If we take into account that the burning particles are carried together, then at the place of their fallout large spots are formed - the centers of a new fire. In this case, the fire takes a spotty shape [3]. The transfer of burning particles may not form a new source of fire, but it will lead to the drying of the FCM and provide favorable conditions for the spread of the fire. Analysis of information on the conditions for the spread of crown fires shows that burning particles can travel up to 1.5 km through the air, and in this case even a water barrier is not a reliable barrier for this.

Extinguishing a forest fire is a procedure for breaking the chain of transmission of the flame from one portion of LFM to another portion. For example, if you remove a fire hazardous ground cover, it will be possible to interrupt the spread of a fire and achieve its extinguishing. This is done by equipping mineralized strips, processing the soil with special tillage implements, which are special plows or bulldozer knives. However, as shown in [Richter], the mineralized strip is not an absolute barrier to the spread of ground fire. The reason for this is the insufficient protective characteristics of the strip itself, allowing even a relatively weak wind to carry burning fragments of LGM over it.

The spread of forest fires occurs in strict accordance with the prevailing natural conditions. A forest fire is completely determined by the actions of the laws of nature. The products formed during combustion rise upward and form a convective column, in which the movement of particles becomes laminar and turbulent [3].

The development of measures to protect against fire is impossible without monitoring the influence of weather conditions on the start of a forest fire, as well as its growth and development. Many authors [3-7] made their attempts to answer the question about the range of transport of burning particles through the air. In [6], an approach was even proposed for the analytical solution of this problem. In [5], a specialized installation was developed for the formation of a swarm of burning particles; in [7], the study of the transfer was carried out in a specially designed wind tunnel. Nevertheless, all works answer only some of the questions posed, but do not in any way discuss the results obtained in the aggregate.

The firebrands transportation range (Lt) is described by the following simple equation [4]:

$$L_t = H \cdot \frac{V_{part}}{V_{wind}}, \tag{1}$$

where H is the height of the falling out of the burning particle from the convective flow, *m;* V_{part} is the particle transport velocity, m·s^{-1}, V_{fal} is the falling velocity of the burning particle, m·s^{-1}.

This equation has simple form but its constituents are complex, and it is difficult to clearly estimate them numerically. Many authors [3-7] declare an answer to the question about firebrands transportation range, while they do not give a answer about firebrands transportation rate in the vertical and horizontal directions. The authors [3-4] have reliably established that the vertical velocity of particle movement does not coincide with the convective gas flow rate. Being in the zone of action of the gravitational field, the particle slides in the ascending gas flow (VGF), thus Vpart≠Vvgf.

In order for the particle to overcome the action of gravity force, the lifting force must be higher than the gravity force. The fact is that when a gas flow acts on a solid body having a definite shape, the transfer force is maximum in the position of the body corresponding to the highest aerodynamic resistance. However, being in suspension, the body, like a pendulum, tries to find the position of the lowest possible location of its center of gravity. In this case, the body tries to turn in the direction of the least aerodynamic resistance to the gas flow. This will lead to a constant rotation of the body relative to a certain center and will continue until the body falls to the ground or completely burns out.

Typical firebrands are solids that must have a certain aerodynamic resistance. The authors of [3-4] cite data that of the burning particles carried by the wind, the most common particles are cylindrical and spherical. The drag coefficient (C_x) of the ball does not change with its position and size. On the other hand, for a cylinder, the aerodynamic resistance to the gas flow varies with its position. The task is further complicated by the fact that all cylinders in shape can be divided into three groups, in fact, a cylinder ($h_c > d_c$), an isodiametric cylinder ($h_c = d_c$) and a disc ($h_c < d_c$). For such bodies, there is a serious difference in aerodynamic drag. So, for a cylinder with a side ratio hc = 2dc, $K_{ar} = 0.82$, for a cylinder $h_c = d_c$ $K_{ar} = 0.96$, and for a disc $h_c < d_c$ $K_{ad} = 1.15$ is in the transverse and 0.1 is in the longitudinal directions [8].

The time of rise of a burning particle to a certain height is not known, therefore the authors of [3-4; 6] do not predict the height of rise of burning particles, but start solving the problem from the moment it falls out of the convection flow. Therefore, in the case of modeling, any value can be assigned to this value - 5, 10, 20 or more meters.

To predict the horizontal transport of a burning particle in [3-4], a mathematical relation was proposed:

$$L_t = V_{part} \cdot t_{fal}, \tag{2}$$

where V_{part} is the firebrand transportation rate, $m{\cdot}s^{-1}$, t_{fal} is the firebrands falling time, s.

In order to calculate firebrands falling time can be used next equation [3]:

$$t_{пад} = \sqrt{\frac{2H}{g}}, \tag{3}$$

where H is the height firebrand fall, m; g is the acceleration of gravity, $m{\cdot}s^{-2}$, ($g = 9.81\ m{\cdot}s^{-2}$). Analysis of equation (3) shows us that firebrands falling time does not depend on its weight, thus, the change in weight of firebrands can be neglected.

The simplicity of equation (2) is very deceiving, since the horizontal rate of firebrands transportation is unknown, and in [3-4] it was suggested that $V_{part} = V_{wind}$. It is not entirely clear from what considerations such a conclusion was made, if in the same works the question of the inequality of vertical rate of firebrands transportation and the vertical gas flow was discussed. It is quite possible that there is a similar approach to evaluation of firebrands horizontal rate will not be equal to the wind rate. Based on the foregoing, the purpose of this work was to develop an adequate model for assessing the horizontal transfer rate of burning particles and to experimentally confirm its adequacy, which, together with an estimate of the height of the falling out of a burning particle from the VGP, will make it possible to estimate the range of transfer of burning particles.

2. Materials and methods

The work used data on the transport of burning particles obtained in laboratory and field conditions from observations of the development of forest fires or modeling of transport [3-5;7].

Own research has been carried out on the effect of air flow on the horizontal transportation of paper ball that imitate the shape and weight of firebrand. The objects under study were created from writing paper. Square shaped paper fragments were cut, and were weighed on an analytical balance (A&D, Japan) with an accuracy of 0.01 g. The samples obtained were tightly rolled up and crimped in a small vice so that their shape was as close as possible to the ball shape. The diameter of paper balls were 5, 9, and 12 mm, respectively. The air flow was produced in closed room using household floor standing fan. An impeller diameter is 380 mm, located at a height of 1.45 m above the floor level. The air flow rate was determined with a Meteoscope-M device (NT-Zashchita, Russia). At the maximum speed of rotation of the impeller, the fan was capable of delivering an air flow at a speed of 3.6 $m{\cdot}s^{-1}$. To exclude internal interfering influences (reflection of the air flow from the walls, the formation of turbulence, etc.), a large room of 12x9 m was chosen, and in order to exclude external interfering factors, the doors and windows in the room were closed during the experiment. To measure the range of paper balls transportation on the floor in the room, a ruler was formed, on which the positions corresponding to the air speed of 3, 2 and 1 $m{\cdot}s^{-1}$, found by direct measurement of the speed of air movement using the Meteoscope-M device, were evaluated.

A paper balls as firebramds immitation were thrown vertically into the air flow at the mark corresponding to the selected wind speed, fell into the field of action of the air flow, and its trajectory deviated from the vertical. When the object fell to the floor, the location of the fall was marked on the ruler and, thus, the magnitude of the transfer range was measured. Two operators repeated the experiment with each paper ball at least five times. The data obtained were averaged to exclude random influences on the measurement process. The transfer force, acceleration and speed of balls were determined on the basis of the laws of classical physics and aerodynamics, and for paper balls the aerodynamic resistance coefficients from [9-11] were used.

3. Results and Discussion

The adequacy of the model of horizontal transport of a burning particle lies in the search for a reliable value of the coefficient Kt connecting the wind speed and the speed of transport of a burning particle:

$$V_{part}=K_t \cdot V_{wind}. \tag{4}$$

This coefficient is dimensionless and can change its value from 0 to 1. This approach to the formulation of the requirements for the adequacy of the model is based on the assumption that the speed of the transported particle cannot be higher than the wind speed. In order to find the numerical value of the transfer coefficient, it is necessary to determine the horizontal velocity of the particle and correlate it with the wind speed.

It is known that the air stream running on the body has a driving force, i.e. able to overcome the situation of friction at rest, and even have a lifting effect [10-11]. The magnitude of the driving force (Ft) is determined by the equation:

$$F_t = \frac{1}{2} Cx \cdot \rho \cdot S \cdot V_{wind}^2 , \tag{5}$$

where C_x is the coefficient of aerodynamic resistance, ρ is the air density, kg·m^{-3}; S is the body cross-sectional area, m^2, V_{wind} is the rate of wind, m·s^{-1}.

All parameters of equation (5) are known and can be accurately measured. If the acting force on the particle is known, it is possible to determine its acceleration using Newton's Second Law (F = ma), and from acceleration through integration, one can go to the velocity of horizontal transportation of the particle. Comparing the particle transportation rate and the rate of wind, we can determine the numerical value of the transfer coefficient (K_t). In the process of modeling, you can use any shape, size and particle weight. Applying equation (1), knowing the time of fall and the rate of horizontal transportation, it is possible to calculate the transportation range (L_t) of a particle for which given shape, size and weight. Table 1 shows the results of calculating the transfer coefficients for ball-shaped firebrands with a diameter of 5 to 12 mm.

Analysis of the data presented in table 1 shows that most of the values of the transportation coefficient (K_t) are less than one, However, some of the K_t values exceed the one. From the point of view of classical physics, $K_t > 1$ is impossible, because when a body moves in a flow, with an increase in its speed, the action of the driving force decreases, and with the equality $V_{part} = V_{flow}$, the particle stops accelerating. In this case, it makes sense to equate the transfer coefficient to one.

Taking into account the values Kt and the idea of the movement of particles in the flow, the transfer ranges of burning particles in the form of a ball that felt out of the ascending convective flow at a height of 5-20 m at wind speeds of 1-5 m / s were calculated. The calculation results are presented in table. 2.

Table 1. Ball-shaped firebrands transportation coefficient calculated for C_x=0.47.

H_{fal}, m	V_{wind}, $m \cdot s^{-1}$	Transportation coefficient value (K_t)							
		d=5 mm	d=6 mm	d=7 mm	d=8 mm	d=9 mm	d=10 mm	d=11 mm	d=12 mm
5	1	0.159	0.133	0.114	0.100	0.089	0.080	0.072	0.066
	2	0.319	0.266	0.228	0.199	0.177	0.159	0.145	0.133
	3	0.478	0.399	0.342	0.299	0.266	0.239	0.217	0.199
	5	0.797	0.664	0.570	0.498	0.443	0.399	0.362	0.332
10	1	0.226	0.188	0.161	0.141	0.125	0.113	0.103	0.094
	2	0.451	0.376	0.322	0.282	0.251	0.226	0.205	0.188
	3	0.677	0.564	0.483	0.423	0.376	0.338	0.308	0.282
	5	1.128	0.940	0.805	0.705	0.626	0.564	0.513	0.470
15	1	0.276	0.230	0.197	0.173	0.153	0.138	0.126	0.115
	2	0.552	0.460	0.395	0.345	0.307	0.276	0.251	0.230
	3	0.829	0.691	0.592	0.518	0.460	0.414	0.377	0.345
	5	1.381	1.151	0.986	0.863	0.767	0.691	0.628	0.575
20	1	0.319	0.266	0.228	0.199	0.177	0.159	0.145	0.133
	2	0.638	0.532	0.456	0.399	0.354	0.319	0.290	0.266
	3	0.957	0.797	0.683	0.598	0.532	0.478	0.435	0.399
	5	1.595	1.329	1.139	0.997	0.886	0.797	0.725	0.664

Table 2. Transportation range of ball-shaped firebrands calculated for C_x=0.47.

H_{fal}, m	V_{wind}, $m \cdot s^{1}$	Transportation range (L_t), m							
		D=5 mm	D=6 mm	D=7 mm	D=8 mm	D=9 mm	D=10 mm	D=11 mm	D=12 mm
5	1	0.36	0.28	0.22	0.18	0.15	0.13	0.11	0.10
	2	1.44	1.10	0.87	0.71	0.59	0.50	0.44	0.39
	3	3.24	2.48	1.95	1.58	1.34	1.12	0.99	0.87
	5	7.21	5.50	4.35	3.52	2.97	2.50	2.20	1.93
10	1	1.02	0.78	0.61	0.50	0.42	0.35	0.31	0.27
	2	4.08	3.11	2.46	1.99	1.68	1.41	1.25	1.09
	3	9.18	7.00	5.53	4.49	3.78	3.18	2.80	2.46
	5	18.09	15.55	12.28	9.97	8.40	7.07	6.23	5.45
15	1	1.87	1.43	1.13	0.91	0.77	0.65	0.57	0.50
	2	7.50	5.71	4.51	3.66	3.09	2.60	2.29	2.00
	3	16.86	12.86	10.16	8.24	6.95	5.85	5.15	4.51
	5	27.13	24.82	22.57	18.31	15.43	13.00	11.44	10.02
20	1	2.88	2.20	1.74	1.41	1.19	1.00	0.88	0.77
	2	11.54	8.80	6.95	5.64	4.75	4.00	3.52	3.09
	3	25.96	19.79	15.64	12.68	10.69	9.00	7.93	6.94
	5	36.18	33.10	30.50	28.19	23.76	20.01	17.62	15.43

Analysis of the data presented in table 2 shows that, according to model concepts (2), the ball-shaped firebrands transportation range can be up to 36 meters when falling from a height of 20 m and a wind rate of 5 m s^{-1}. A fire barrier (mineralized stripe) which 1.5 m wide can be overcome by a firebrands d=8 mm which felt from a height of 5 m at a wind rate of 3 m s^{-1}. And if to take into account that most of these fire barriers are set up with a width of less than 1 m, then their protective characteristics will manifest themselves only in calm weather.

Similar research was carried out for cylindrical and disc-shaped firebrands imitating particles. The results are presented in table. 3-6. As it was shown in [3-4] that cylindrical particles with the aspect ratio $h_c = 4d_c$ have the best transfer ability. This is the form that was used for modeling. The results of assessing the transportation coefficient are presented in table 3.

Table 3. Cylinder-shaped firebrands transportation coefficient (h_c=4d_c) calculated for C_x=0.82.

H_{fal}, m	V_{wind}, m·s^{-1}	Transportation coefficient value (K_t)							
		D=5 mm	D=6 mm	D=7 mm	D=8 mm	D=9 mm	D=10 mm	D=11 mm	D=12 mm
5	1	0.046	0.039	0.033	0.029	0.026	0.023	0.021	0.019
	2	0.093	0.077	0.066	0.058	0.052	0.046	0.042	0.039
	3	0.139	0.116	0.099	0.087	0.077	0.070	0.063	0.058
	5	0.232	0.193	0.166	0.145	0.129	0.116	0.105	0.097
10	1	0.066	0.055	0.047	0.041	0.036	0.033	0.030	0.027
	2	0.131	0.109	0.094	0.082	0.073	0.066	0.060	0.055
	3	0.197	0.164	0.141	0.123	0.109	0.098	0.089	0.082
	5	0.328	0.273	0.234	0.205	0.182	0.164	0.149	0.137
15	1	0.080	0.067	0.057	0.050	0.045	0.040	0.037	0.033
	2	0.161	0.134	0.115	0.100	0.089	0.080	0.073	0.067
	3	0.241	0.201	0.172	0.151	0.134	0.120	0.110	0.100
	5	0.402	0.335	0.287	0.251	0.223	0.201	0.183	0.167
20	1	0.093	0.077	0.066	0.058	0.052	0.046	0.042	0.039
	2	0.185	0.155	0.132	0.116	0.103	0.093	0.084	0.077
	3	0.278	0.232	0.199	0.174	0.155	0.139	0.126	0.116
	5	0.464	0.386	0.331	0.290	0.258	0.232	0.211	0.193

Comparing the results obtained for the cylinders (table 3) and balls (table 1) transportation it can be noted that the values of the transportation coefficients for cylinders are lower than for balls at same diameter. This is the fact that the weight of a cylinder with a similar diameter is higher than that of a ball, because when the aspect ratio is h_c = 4d_c, its volume is larger, which, at equal density, gives a large weight. An increase in weight leads to the need to increase the transfer force, but this is impossible at the same wind rate and cylinder cross-section. For solving the problem, the property of the cylinder was used to turn in the flow towards the wind like a weather vane, i.e. side of the least aerodynamic drag. In this case, the transfer force will be the same, since the length of the cylinder does not affect its cross-sectional area. All of the above was reflected in the estimation of the flight range of cylindrical particles are presented in table 4.

Table 4. Transportation range of cylinder- shaped (h_c=4d_c) firebrands calculated for C_x =0.82.

H_{fal}, m	V_{wind}, m·c^{-1}	Transportation range (L_t), m							
		D=5 mm	D=6 mm	D=7 mm	D=8 mm	D=9 mm	D=10 mm	D=11 mm	D=12 mm
5	1	0.10	0.08	0.06	0.05	0.04	0.04	0.03	0.03
	2	0.42	0.32	0.25	0.21	0.17	0.15	0.13	0.11
	3	0.94	0.72	0.57	0.46	0.39	0.33	0.29	0.25
	5	2.10	1.60	1.26	1.02	0.86	0.73	0.64	0.56
10	1	0.30	0.23	0.18	0.15	0.12	0.10	0.09	0.08
	2	1.19	0.90	0.71	0.58	0.49	0.41	0.36	0.32
	3	2.67	2.03	1.61	1.30	1.10	0.93	0.81	0.71
	5	5.93	4.52	3.57	2.90	2.44	2.06	1.81	1.59
15	1	0.54	0.42	0.33	0.27	0.22	0.19	0.17	0.15
	2	2.18	1.66	1.31	1.07	0.90	0.76	0.67	0.58
	3	4.90	3.74	2.95	2.40	2.02	1.70	1.50	1.31
	5	10.89	8.31	6.56	5.32	4.49	3.78	3.33	2.91
20	1	0.84	0.64	0.51	0.41	0.35	0.29	0.26	0.22
	2	3.36	2.56	2.02	1.64	1.38	1.16	1.02	0.90
	3	7.55	5.75	4.55	3.69	3.11	2.62	2.31	2.02
	5	16.78	12.79	10.10	8.20	6.91	5.82	5.12	4.49

Analysis of the data presented in table 4 shows that, according to model concepts (2), the range of cylindrical firebrands transport (h_c = 4d_c) can be up to 17 meters when falling from a height of 20 m and a wind rate of 5 m s^{-1}. A 1.5 m wide fire barrier will be overcome by a d=6 mm firebrands with felt from a height of 5 m at a wind rate of 5 m s^{-1}. Such size firebrands, according to [3-4], is capable of burning for 3-4 minutes, which indicates an increase in the probability of the edge of a forest fire being transferred through the fire barrier.

Another option is possible when transforming a cylinder into a disc ($h_c < d_c$). The aerodynamics of the disc shows that its C_x = 1.15 in the transverse direction and 0.1 in the longitudinal direction [8]. With an equal diameter, the weight of the disc is less than that of the cylinder, which means that a smaller transfer force will be needed to transfer the disc. The disc-shaped particle $h_c = 0.5d_c$ was chosen for the research. The calculation data are presented in table 5.

Table 5. Disc-shaped (h_c=0.5d_c) firebrands transportation coefficient calculated for C_x =1.15.

H_{fal}, m	V_{wind}, m·s^{-1}	Transportation coefficient value (K_t), m							
		D=5 mm	D=6 mm	D=7 mm	D=8 mm	D=9 mm	D=10 mm	D=11 mm	D=12 mm
5	1	0.520	0.434	0.372	0.325	0.289	0.260	0.236	0.217
	2	1.041	0.867	0.743	0.650	0.578	0.520	0.473	0.434
	3	1.561	1.301	1.115	0.975	0.867	0.780	0.709	0.650
	5	2.601	2.168	1.858	1.626	1.445	1.301	1.182	1.084
10	1	0.736	0.613	0.526	0.460	0.409	0.368	0.334	0.307
	2	1.472	1.226	1.051	0.920	0.818	0.736	0.669	0.613
	3	2.207	1.839	1.577	1.380	1.226	1.104	1.003	0.920
	5	3.679	3.066	2.628	2.299	2.044	1.839	1.672	1.533
15	1	0.901	0.751	0.644	0.563	0.501	0.451	0.410	0.375
	2	1.802	1.502	1.287	1.126	1.001	0.901	0.819	0.751
	3	2.703	2.253	1.931	1.690	1.502	1.352	1.229	1.126
	5	4.506	3.755	3.218	2.816	2.503	2.253	2.048	1.877
20	1	1.041	0.867	0.743	0.650	0.578	0.520	0.473	0.434
	2	2.081	1.734	1.486	1.301	1.156	1.041	0.946	0.867
	3	3.122	2.601	2.230	1.951	1.734	1.561	1.419	1.301
	5	5.203	4.335	3.716	3.252	2.890	2.601	2.365	2.168

Analysis of the data presented in table 5 shows that under certain conditions the value of the transportation coefficient (K_t) is greater than one. This is due to the fact that C_x = 1.15 was used for the calculation, and the weight of the disc, with the same diameter, is less than that for cylinder. Nevertheless, the most stable position for the disc is the horizontal value with C_x = 0.1. Using this value, the values of the transportation coefficients of the discs were calculated (table 6).

Table 6. Disc-shaped (h_c=0.5d_c) firebrands transportation coefficient calculated for C_x =0.1.

Hfal, m	Vwind, m·s-1	Transportation coefficient value (Kt), м							
		D=5 mm	D=6 mm	D=7 mm	D=8 mm	D=9 mm	D=10 mm	D=11 mm	D=12 mm
5	1	0.045	0.038	0.032	0.028	0.025	0.023	0.021	0.019
	2	0.090	0.075	0.065	0.057	0.050	0.045	0.041	0.038
	3	0.136	0.113	0.097	0.085	0.075	0.068	0.062	0.057
	5	0.226	0.188	0.162	0.141	0.126	0.113	0.103	0.094
10	1	0.064	0.053	0.046	0.040	0.036	0.032	0.029	0.027
	2	0.128	0.107	0.091	0.080	0.071	0.064	0.058	0.053
	3	0.192	0.160	0.137	0.120	0.107	0.096	0.087	0.080
	5	0.320	0.267	0.228	0.200	0.178	0.160	0.145	0.133
15	1	0.078	0.065	0.056	0.049	0.044	0.039	0.036	0.033
	2	0.157	0.131	0.112	0.098	0.087	0.078	0.071	0.065
	3	0.235	0.196	0.168	0.147	0.131	0.118	0.107	0.098
	5	0.392	0.326	0.280	0.245	0.218	0.196	0.178	0.163
20	1	0.090	0.075	0.065	0.057	0.050	0.045	0.041	0.038
	2	0.181	0.151	0.129	0.113	0.101	0.090	0.082	0.075
	3	0.271	0.226	0.194	0.170	0.151	0.136	0.123	0.113
	5	0.452	0.377	0.323	0.283	0.251	0.226	0.206	0.188

A decrease in the value of C_x naturally led to a decrease in the coefficient K_t, the values of which now do not exceed 0.5. Exactly what meaning C_x will take is not known. It is known that flying particles are capable to rotate and the truth C_x will lie somewhere in the middle. Taking all this into account, the values of the transfer range of burning particles in the form of a disc were calculated, and the results are presented in table 7.

Table 7. Transportation range of disc-shaped firebrands (h_c=0.5d_c) calculated for C_x=1.15.

H_{fal}, m	V_{winf}, m·s^{-1}	Transportation range (L_t), m							
		d=5 mm	D=6 mm	D=7 mm	D=8 mm	D=9 mm	D=10 mm	D=11 mm	D=12 mm
5	1	0.10	0.08	0.06	0.05	0.04	0.04	0.03	0.03
	2	0.41	0.31	0.25	0.20	0.17	0.14	0.13	0.11
	3	0.92	0.70	0.55	0.45	0.38	0.32	0.28	0.25
	5	2.04	1.56	1.23	1.00	0.84	0.71	0.63	0.55
10	1	0.29	0.22	0.17	0.14	0.12	0.10	0.09	0.08
	2	1.16	0.88	0.70	0.57	0.48	0.40	0.35	0.31
	3	2.60	1.98	1.57	1.27	1.07	0.90	0.79	0.70
	5	5.79	4.41	3.48	2.83	2.38	2.01	1.77	1.55
15	1	0.53	0.41	0.32	0.26	0.22	0.18	0.16	0.14
	2	2.13	1.62	1.28	1.04	0.88	0.74	0.65	0.57
	3	4.78	3.65	2.88	2.34	1.97	1.66	1.46	1.28
	5	10.63	8.10	6.40	5.19	4.38	3.69	3.25	2.84
20	1	0.82	0.62	0.49	0.40	0.34	0.28	0.25	0.22
	2	3.27	2.50	1.97	1.60	1.35	1.13	1.00	0.88
	3	7.36	5.61	4.44	3.60	3.03	2.55	2.25	1.97
	5	16.37	12.48	9.86	8.00	6.74	5.68	5.00	4.38

Analysis of the data presented in table. 6 shows that the range of discs transportation (K_{ad} = 0.1) is comparable to the range of transfer of spherical particles. Such particles are able to overcome up to 16 m of space at a wind speed of 5 m s^{-1} felt from 20 m (table 7). Thus 1.5 m wide fire barrier can stop only large firebrands at low wind rate.

Each model concepts need to experimental support. It carried out our own research, and also used the experimental data [5;7]. The results of calculating the firebrands transportation rate (V_t) and the transportation coefficient (K_t) depending on the air flow rate, particle size and weight are presented in table 8.

Table 8. Experimental and calculated horizontal transportation range (V_{part}) and transportation coefficient (K_t) for ball-shaped firebrands at C_x=0.47.

V_{wind}, m·s^{-1}	L_{exp}, m	m_{part}, g	S_{part}, mm^2	F_t, N	a, m·s^{-2}	V_{part}, m·s^{-1}	L_{calc}, m	K_t
1	0.07	0.04	28.26	0.0000117	0.29	0.16	0.04	0.16
2	0.14	0.04	28.26	0.0000466	1.17	0.63	0.17	0.32
3	0.36	0.04	28.26	0.0001049	2.62	1.43	0.39	0.48
1	0.08	0.11	94.98	0.0000392	0.36	0.19	0.05	0.19
2	0.19	0.11	94.98	0.0001567	1.42	0.77	0.21	0.39
3	0.43	0.11	94.98	0.0003526	3.21	1.74	0.47	0.58
1	0.03	0.4	226.86	0.0000936	0.23	0.13	0.03	0.13
2	0.12	0.4	226.86	0.0003743	0.94	0.51	0.14	0.25
3	0.28	0.4	226.86	0.0008422	2.11	1.14	0.31	0.38

Analysis of the results presented in table. 8 makes it possible to determine a good convergence of experimental data with theoretical calculations, but only within the air flow velocities of 1-3 m s^{-1}. The capabilities of the experimental setup do not allow creating a high air flow rate. It is noted that the value of the transportation coefficient Kt changes depending on the air flow rate, and the value of the coefficient also grows with rate increasing. So, in the case of V_{wind} = 1 m s^{-1}, the K_t = 0.13-0.19, and in the case of V_{wind} = 3 m s^{-1}, the K_t = 0.38-0.48. The experimental data good agree with the calculated ones within 10%. So a ball-shaped particles falling from 1.45 m, weighing 0.04 g, with a cross-sectional area of 28 mm^2, at a wind rate of 3 m s^{-1} can move in the horizontal direction of 0.39 m, while experiment shows that the particle has moved on average by 0.35 ... 0.37 m, which are 89% of the experiment. The maximum firebrands transportation rate was experimentally recorded in [5], where at an air flow rate of 10 m s^{-1}, the particle moved to 4.3 meters. The calculation shows that its rate was 9.91 m s^{-1}, which is 99% of the air flow rate (K_t = 0.99).

A research some intermediate transportation conditions of 5 and 7 m s^{-1}, carried out in [7], and showed that disc-shaped firebrands with a diameter from 12 to 24 mm and a thickness from 5 to 10 mm falling from 1.8 m are able to overcome a range of 0.6-2 m. The results of calculations of firebrands transportation rate and range are presented in table 9.

Table 9. Experimental and calculated horizontal transportation range (V_{part}) and transportation coefficient (K_t) for ball-shaped firebrands at C_x=1.15 (using data [7]).

V_{wind}, m·s^{-1}	L_{exp}, m	m_{part}, g	S_{part}, mm^2	F_t, N	a, m·s^{-2}	V_{part}, m·s^{-1}	L_{calc}, m	K_t
5	0.34	113.04	0.0019	5.57	3.37	1.30	1.02	0.61
7	0.34	113.04	0.0037	10.9	6.61	2.00	2.00	0.61
5	1.25	452.16	0.0076	6.06	3.67	1.00	1.11	0.61
7	1.25	452.16	0.0148	11.9	7.19	1.60	2.18	0.61
5	2.45	452.16	0.0076	3.09	1.87	0.60	0.57	0.61
7	2.45	452.16	0.0148	6.05	3.67	1.00	1.11	0.61

Analysis of the results presented in table. 8 shows that for disc-shaped particles transfer range are in rather close agreement with the experimental values. The authors of the work [5] do not indicate how the transfer of the disc was carried out, i.e. whether it rotated in the air during transfer. The authors described only the initial position of the discs during the experiment. The disc was located inside the wind tunnel on a shelf with the flat side down. In this case, its Cx = 0.1 and then the calculated range of transfer of such particles was 0.05-0.19 m, which is significantly lower than the experimental data obtained 0.60-2.00 m. Nevertheless, when using the maximum value of the transportation coefficient, the calculated and experimental data coincide, which indicates the possibility of rotation of the disc in air flow, and it is quite probable that at wind speeds of more than 7 m s^{-1}, the values of the transfer coefficient for them will be close to unity. This is due to the good scheduling properties of the disc, its shape resembles that of a wing. A further increase in the air flow velocity (more than 10 m / s) forms a lifting force capable of holding particles in suspension for a long time, regardless of their shape, which is used when organizing pneumatic transfer of bulk materials [10-11]. This is what explains the transfer of burning particles during strong crown fires at a range of 1.0 km or more.

4. Conclusion

The results of the research are:

- A model for air flow firebrands transportation has been developed. To taking into account their size, weight, wind rate and the height of the particle falling out. To assess the adequacy of the model of firebrands transportation, the concept of transportation coefficient (K_t) was introduced, which relates the firebrands transportation rate to the rate of an air flow.
- Calculations of the ball-shaped, cylinder-shaped and disc-shaped firebrands transportation ranges, have been carried out. It is shown that the best transfer properties are possessed by disc-shaped particles, and the worst cylinder-shaped; the transportation of ball-shaped particles takes some intermediate position. Moreover, the values of the ball-shaped and disc-shaped firebrand transportation coefficient at some conditions can exceed one, i.e. move faster than wind rate, which is not quite physically justified.
- To prove the adequacy of the proposed transportation particle model, experimental research of the ball-shaped particles transportation range was carried out, which showed that the discrepancy between the calculated and experimental data is no more than 10% at air flow velocities of 1-3 m s^{-1}. In addition, on the basis of the literature data, the transfer coefficients for particles in the form of a cylinder and a disc were estimated and it was shown that at air

flow velocities above 7 m s^{-1}, the transportation coefficients tend to one, thus the transfer rate of particles is close to the rate of the air flow.

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