

Physical–chemical explanation of fire-fighting efficiency of FHF (fast-hardening foam) based on structured silica particles

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Abstract Report is dedicated to thermophysical and chemical explanation of the ways of increasing the fire-extinguishing process of solid combustible materials. As a result of research such indicators are obtained as speed of extinguishing, specific consumption, I_{FFE} (index of fire-fighting efficiency) with help of fast-hardening foam. Fire-extinguishing mechanisms of fast-hardening foam are considered and evidences of their positive features are given. Application areas of fast-hardening foam are pointed. At the Fig. 1 thermal insulating capabilities of the fast-hardening foam, which hinder the flame to impact on opened parts of body are clearly presented.

Graphical Abstract



Keywords Fire-fighting · Fast-hardening foam · Sol–gel · Silica · Solid combustible material

1 Introduction

Burning is the main process at the fire. Unorganized diffusive burning at the fire especially burning of the solid combustible materials (SCM) is difficult multifactorial and poorly studied phenomenon. That is why usually for studying this process burning of the one wood fire seat is considered to simplify the complicated set of the thermo-physical and mass transfer processes of the SCM burning.

Meanwhile a SCM burning usually occurs in the two modes simultaneously. The first one is a homogeneous flame burning above the fire seat where pyrolysis products of SCM in the mixture with air are burning. The second one is a heterogeneous flameless mode. It is called smoldering what occurs in the most heated top layers of the seat where the oxygen is entering

This simplified schematic approach is even more justified if we consider fire-extinguishing mechanisms at the SCM fires.

2 Common fire-extinguishing mechanisms

From physical and engineering points of view fire elimination means: (1) stop of the SCM burning process in all modes and forms; (2) impossibility of the repeated ignition without external exposure.

For this purpose it is necessary: (1) to cool the heated layer of burning SCM to temperature below its pyrolysis temperature to exclude capabilities for pyrolysis products appearance which is necessary for the flame burning (for the most of SCM this temperature is 200–250 °C) (let this main mechanism is called “cooling”); (2) to protect the burning SCM surface from the external heating influence of the fire area (let this mechanism is called “screening”); (3) to

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insulate the burning material with the layer of the fire-fighting agent from the oxygen access (let this secondary mechanism is called “insulating”).

If we meet these three conditions then the burning process of SCM will be stopped in the all forms and modes and it will not be able to be ignited by itself. It means the fire will be extinguished. It is quite difficult to estimate contribution of the each considered mechanism. Despite that it was determined by us that we need to remove about 1000–1250 kJ of the heat from each square meter of the burning surface for 30–35 s to realize the first dominant mechanism. For that it is necessary to evaporate 0.4–0.5 L/m² of water from the SCM surface. For the full cooling of the burning SCM surface to the safe temperature 20–50 °C we need to remove about 1500–1850 kJ of the heat from each square meter for 35–40 s. It is equal to evaporation of 0.7–0.75 L/m² of water. And for the practical realization of these conditions we have to drench heated layer of the SCM with additional 0.8 L/m² of water.

Thus, it is necessary to evaporate about 1.5 L of water from each square meter of the burning SCM surface for 30–40 s only due to the heat inside the heated layer of the SCM. This amount of water is equal to its thickness of

1.5–2 mm. But it is difficult to hold this layer during 30–40 s even on the horizontal surface especially on the inclined one. And it is impossible to do that on the vertical surface. On practice the water layer is approximately ten times less. It is about 0.15–0.2 mm. That is why in the fire-extinguishing process of SCM water flows down intensively. And total losses of water reach 90–95% during the fire elimination.

For realization of screening mechanism for SCM against external heating streams from the fire area we should decrease them approximately in ten times, from 50–80 to 5–8 kJ/m²*s. For realization of the insulating fire-extinguishing mechanism due to stopping the smoldering we should decrease oxygen concentration from 20–21 to 5–6%. All this requires additional consumption of the fire-fighting means. And it leads to additional losses of water during the fire elimination of the SCM which may reach 95% [1, 2].

That is why all the methods of fire-extinguishing with water (which is used for the most of fires) are so ineffective.

3 Sol-gel generation of FHF

The formation of FHF is a complex of multicomponent chemical interactions with dispersing the air phase proceeding in the flow of the liquid phase (water) (Figs. 1 and 2).

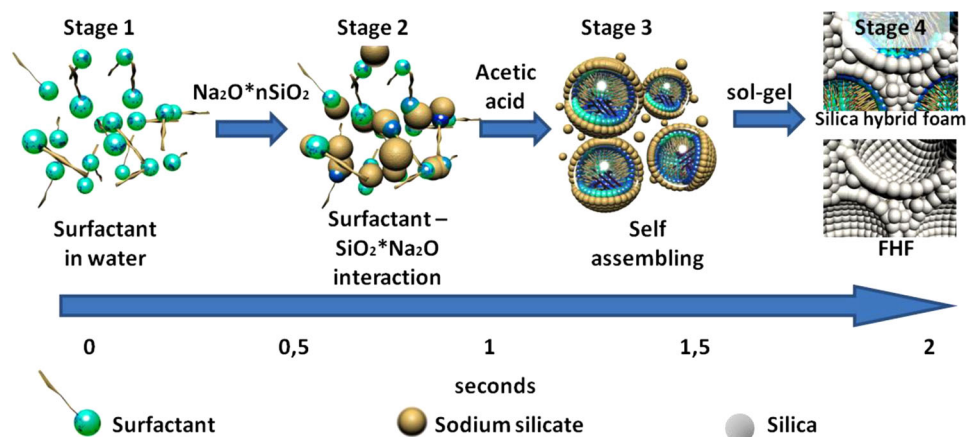
FHF formation can be separated into two different steps. The first one is surfactant interaction with sodium silicate in aqueous media (Fig. 2, stages 1, 2). The second one is sol-gel transition of sodium silicate into silica after the acetic acid solution injection (Fig. 2, stages 3, 4). The full mechanism of phase transition is presented in Fig. 2.

Injection of hydrolysis catalyst in the hydrodynamic flow of the liquid phase promotes effective dispersion of the “hardener” in aqueous media and the beginning of the sol formation stage (Fig. 2, stage 3). The concentration of



Fig. 1 Opened fire source exposure on the fragment of FHF

Fig. 2 Chemical mechanism for the formation of FHF



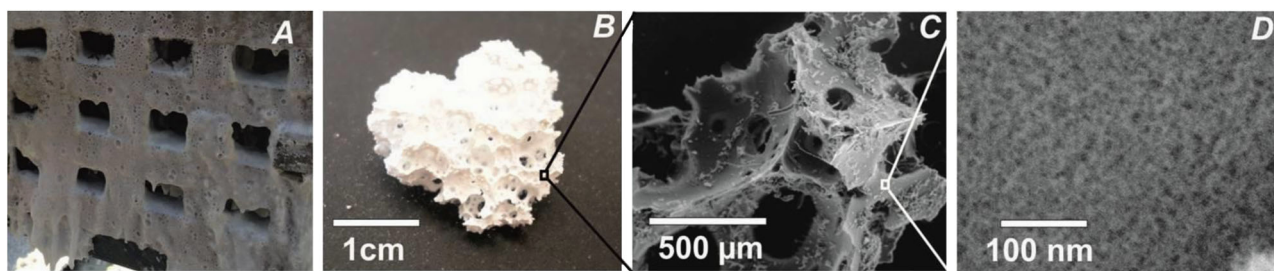


Fig. 3 Photographs (a, b) and SEM images (c, d) of FHF

acetic acid was selected so that, after adding to the sodium silicate solution, viscosity does not reach 20 mPa*s within 2 s, ensuring the stable operation of the foam generator [3].

The structure of the foamed mass after removal of the solvent (water) reproduces the structure of the formed framework (Fig. 3) as confirmed by the SEM data (Fig. 3c).

Moreover, the removal of the liquid phase while drying up to 200 °C results in the compression and structurization of the surface topography (Fig. 3d). This morphology promotes fire-resistance properties and high adhesion to the substrate what will be described below [3].

4 Experimental section

4.1 Fire-fighting with FHF

Results obtained by us during fire-fighting of the wood stack (Fig. 4) with Fast-hardening foam (FHF) show that “miracles” of the fire-extinguishing efficiency can be explained only by synergistic effect of all three fire-extinguishing mechanisms. And moreover we have fourth mechanism which does not let pyrolysis products to go out into the fire area even before the temperature of the heated layers of SCM will be decreased below its pyrolysis temperature. It means fire elimination of the wood is coming not in 30–40 s as according to the considered fire-extinguishing process which was confirmed with a lot of investigations and many years of fire-fighting practice, but just in 4–6 s (Fig. 5)! It is occurring by the cooling, screening and insulating mechanisms which are proceeding at the same time and very effectively. These two additional mechanisms are realized due to the sol-gel foam transformation. Foam becomes solid in 2–3 s after it contacts with surface of the burning material (Fig. 6). This hardened foam cools surface as effectively as water does. In the same time it hinders pyrolysis products to go out into the fire area. It accelerates the fire-extinguishing process in 5–6 times and decreases its time to unbelievable 4–6 s! This synergistic effect is also confirmed by amazing and almost fantastic low specific consumption of the fire-extinguishing agent what



Fig. 4 Model fire seat (class A)



Fig. 5 Fire-extinguishing process of the model fire seat (class A)

was demonstrated during the fire-extinguishing of the wooden fire seat.

Calculated specific consumption of water for extinguishing of the SCM is $q = 0.8\text{--}1.5 \text{ L/m}^2$. Practically achieved result is $q = Q/S = 5 \text{ L}/4.72 \text{ m}^2 = 1.06 \text{ L/m}^2$ (approximately 1 L/m²),

q specific consumption of the fire-fighting agent, L/m²;
 Q total consumption of the fire-fighting agent, L;
 S square of the burning surface.

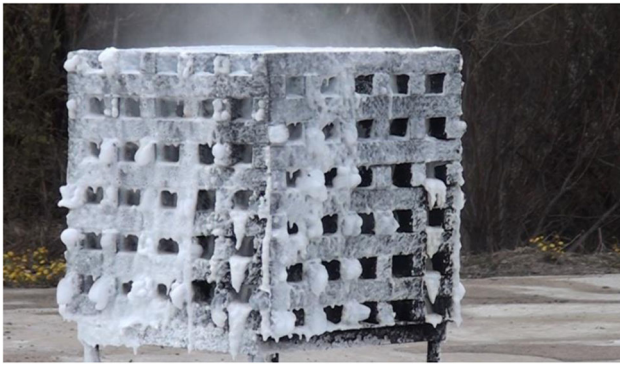


Fig. 6 Model fire seat with fixed fast-hardening foam after extinguishing

So on practice we have achieved 1 L/m² of specific consumption while the theoretical and estimated value of this important index is 0.8–1.5 L/m²! And it has been reached even without evaluation of the losses of the extinguishing mean during the fire-fighting process. Thus, obviously unbelievable low extinguishing time and fantastic low specific consumption consist in the synergistic effect of the main fire-extinguishing mechanisms of the fire elimination of SCM with fast-hardening foam and additional effect of isolation of the SCM pyrolysis products (until the fool cooling of the surface) from the fire area [4].

Application of the fast-hardening foam for the SCM extinguishing has led to the totally unexpected results. This foam possesses high spreading ability on the SCM surface during the first seconds of the contact with surface. Also foam has high heat absorption capacity from 2600 till 1500 kJ/L during the transfer from liquid to solid. And foam manages to remove required 1000–1250 kJ/m² from the burning SCM surface for optimal 30–40 s. Thus, foam realizes cooling mechanism very effectively and reliably.

FHF has enormous adhesion and becomes infinitely resistant (Fig. 6). Due to that the foam performs screening

and insulating mechanisms automatically already in the first 3–5 s after the contact with burning SCM surface [4]. That is why we have reached such results (in the same test conditions) as shown below, Table 1.

Extinguishing time with fast-hardening foam is only 5 s. It is seven times less than extinguishing with water. It is five times less than extinguishing with foam based on the same foam maker. And it is four times less than extinguishing with foam based on the foam maker type AFFF.

Fire-extinguishing efficiency is almost 50 times higher than the same index for water. It is very significantly for the internal fires of SCM, forest fires, fires at the ammunition storages where it is very complicated or even impossible to deliver the fire-fighting mean from different directions.

$$\text{Index of fire – fighting efficiency is } I_{\text{FFE}} = \frac{S}{Q \cdot t},$$

where S is the square of the burning surface, m²; Q the total consumption of the fire-fighting agent, L; t the extinguishing time, s.

So I_{FFE} for water is 0.004 m²/L*s, I_{FFE} for synthetic hydrocarbon foam is 0.008 m²/L*s, I_{FFE} for film-forming fluorinated foam is 0.012 m²/L*s, I_{FFE} for FHF is 0.187 m²/L*s. Thus, fire-extinguishing efficiency is approximately 50 times higher than the same index for water. By the way, extinguishing cost of the model fire seat with FHF is practically the same as extinguishing cost with the foam based on the same foam maker [4, 5].

4.2 Fire-resistance of FHF

But the main result of these trials is that hardened foam is practically inseparable from SCM surface and it becomes absolutely fire-resistant material which is not destroyed even under exposure of opened fire source with temperature 1000 °C during more than 3–5 min. Thanks to thermal insulating properties of this foam wood (under foam layer about 1–3 cm) does not warm up more than 50–60 °C

Table 1 Extinguishing time of the model fire seat 1A

Extinguishing mean	Extinguishing time (s) ^a	Specific consumption (L/m ²)	Result of the direct flame exposure
Water	35	7.45	Re-ignition after 10 s
Foam based on the synthetic hydrocarbon foam maker ^b (6% solution)	25	5.32	Re-ignition after 20 s
Foam based on the foam maker type AFFF (aqueous film-forming foam) ^c (6% solution)	20	4.26	Re-ignition after 35 s
FHF (fast-hardening foam)	5	1.06	Absence of the re-ignition for >5 min

^a Delivery intensity—12.7 L/min

^b Foam expansion—20

^c Foam expansion—20

during pointed time.

Test results shown that wood fire seat which was extinguished with water was re-ignited under opened fire source influence with temperature 1000 °C after 10 s. Fire seat which was extinguished with ordinary hydrocarbon foam was re-ignited after 20 s. Fire seat which was extinguished with foam based on the AFFF re-ignited after 35 s. But after extinguishing with fast-hardening foam (FHF) fire seat has not been re-ignited after 5 and even more minutes under opened fire source influence.

It makes re-ignition of the extinguished wood or wood just treated with foam layer 1–3 cm practically impossible.

Thereby, SCM treated with fast-hardening foam becomes incombustible even in real fire conditions. It provides enormous competitive benefits to FHF for fire-extinguishing of solid and liquid combustible materials. And especially for fire-fighting and fire-localization of forest fires (Fig. 7) and internal fires [6, 7].

For application of the fast-hardening foam there were created range of handle, stationary and mobile means and complexes (Fig. 8) [8].



Fig. 7 Fire-resistant protective line which has stopped the fire



Fig. 8 FHF delivery by fire-fighting tracked vehicle “Yamal-201”

Besides high efficiency, fire-resistance and other important properties of FHF it is significantly to mention environment issues after FHF application.

As it was pointed the basis of FHF is silica which is completely biocompatible product.

We performed tests to determine the time of the induction period (T_{ind}) using surfactant-unadapted sludge. Biochemical testing of the induction period show the half-life time of decomposition and can be classified like isometric value with T_{ind} . Received data shown that T_{ind} for FHF is about three days what means that FHF is completely safe for environment due to its bioinertness and biocompatibility [3].

5 Conclusion

At this study we have shown exceptional possibilities and opportunities of the fast-hardening foam bases on structured silica particles. It is absolutely new mean in the fire-fighting sphere which can lead to revolution in the methods, approaches and tactics of fire extinguishing and fire and explosion prevention.

It was shown how fast-hardening foam can be used for solid combustible materials extinguishing. Thanks to its unique features this foam provides extremely high fire-fighting efficiency as compared to all existing means. Moreover it is impossible to re-ignite object after extinguishing even if we impact on that with flame during more than 30 min. Besides foam is even not destroyed. This advantage gives undeniable opportunities to fire-fighters especially when they have to not only extinguish fire but also have to save people lives.

Compliance with Ethical Standards

Conflict of interest The authors declare no conflict of interest.

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