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Parameters and operation modes optimization of specialized truck for extinguishing forest fires

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Abstract. Recently, due to the warming of the climate, frequent forest fires have begun to cause significant damage to the environment. To effectively solve this problem, it is necessary to use a specialized forest fire truck designed for extinguishing forest fires. The rationale for optimizing the parameters and operating modes of a forest fire truck is given. As the objective function of the mathematical optimization problem, the production capacity is accepted, namely the area that a forest fire truck is able to extinguish. The parameters of the main and auxiliary equipment, the thermophysical properties of structural materials and the time of the estimated period of the production process of the forest fire truck are considered as control factors. The solution of the nonlinear optimization problem will allow us to calculate the production capacity, determine the required thermal and physical properties and offer new structural fire-resistant materials, recommend the main and auxiliary equipment, improve the ergonomic performance of cabins during fire extinguishing, increase the safety of the working conditions of the operator of a forest fire truck, and, as a result, to reduce the negative impact of forest fires on the environment.

1. Introduction

Recently, due to the warming of the climate, frequent forest fires have begun to cause significant damage to the environment. Practice shows that an effective fight against forest fires is only possible with the use of modern specialized equipment, which reliably protects people from fire.

Forest fires that occur on the territory of the Russian Federation cover hundreds of thousands of hectares and cause monetary losses (Table 1). In this regard, there is an acute problem of fighting the fire element. It is advisable to use specialized forest fire truck (FFT) to extinguish fire at large source of ignition. During fire extinguishing, the FFT perceives increased thermal loads. Thus, the tasks of ensuring the operability and optimization of the parameters and operating modes of the FFT, the development and creation of new fire-resistant materials, improving the ergonomics of the cabin and the safety of the operator's working conditions continue to be relevant [1-4].

Manufacturers of FFT in Russia are:

- "Onezhsky Tractor Plant", which produces tractors "Onezhets-310" (Table 2) and LHT-100A-12;
- "Altai Tractor Plant" producing TT-4 (Alttrak TLP-4M-031);

- "Velikoluksky Leskhozmash Plant", producing TLP 55.5.00.000 VL;
- "Scientific and Production Corporation "Uralvagonzavod", creating the LPA-521 unit;
- "Muromteplovoz" with the MT-LBu-GPM-10 machine;
- and others.

Table 1. Area of forest fires in Russia

Indicator	Year					
	2015	2016	2017	2018	2019	2020
Area, million hectares	2.7	2.5	1.4	3.2	5	5
Damage, billion rubles	26.7	24	15	34	50	50

Fire crawler truck RAC, which is produced in Germany, combines traditional and modern fire extinguishing technologies to fight large-scale fires at oil wells, oil and gas pipelines, chemical plants and forests. The world-famous manufacturer of the Canadian company KMK-Kootrac produces a specialized high-speed KMC 210 FT crawler machine, specially designed for forestry and working on forest fires. The Chinese company Lannmarket, produces a tracked forest fire truck FFV 09.

Table 2. Composition of equipment of FFT of the "Onezhsky Tractor Plant "Onezhets 310"

Name of the parameter	**Parameter value**
Pusher	
Pusher blade	Welded, lightweight, for performing auxiliary work
Rear mounted device	
Stamp	SNL-3 or PF-4628010 Articulated four-link hydraulic drive according to ISO 730/1
Fire fighting equipment	
Tank capacity	3500 l
Combined centrifugal Fire Water Pump NCPC-40/100-4/400V1T	Designed for the supply of water and aqueous solutions of foaming agents. The feed and the corresponding head of the normal pressure stage are 40 l/s and 100 m, respectively. In the high-pressure stage – 4 l/s and 400 m
Fire engine pump	Designed for water supply
High-pressure fire-fighting installation	Designed for water supply
High-pressure Spray Barrel with Sleeve coil SRVDK-2/400-60A	Designed for the formation and direction of a solid or finely sprayed jet of water and air-mechanical foam
Portable carriage barrel LS-P20U	Used in fire-hazardous areas for extinguishing fires, cooling construction and technological structures, precipitation of clouds of toxic or radioactive gases, vapors and dust
Universal manual barrel with a foam generator ORT-50	Used to form a jet of fire extinguishing agent and direct it to the source of the fire at a distance of up to five meters

In the process of fighting fires, the spread of the fire edge is consistently stopped, the localization and extinguishing of the burning foci remaining inside the fire is carried out.

To combat the riding fire at large fire centers, the FFT operator uses manual fire barrels of low and high pressure, both in the mode of working with water and water solutions with foaming agents. The front mounted pusher and the rear mounted device are erected fire-fighting mineralized strips, which are an effective means for preventing a grass-roots fire and preventing its spread to neighboring territories.

Thus, the main purpose of the work is to determine the parameters and optimize the operating modes of the FFT in emergency situations – when extinguishing forest fires.

To do this, it is necessary to solve the following tasks:

- to construct and implement a mathematical problem of optimization and FFT operation modes, to determine the target function and control factors;
- determine the production capacity (PC) of the FFT;
- calculate the optimal values of the operating modes and parameters of the main and auxiliary equipment of the FFT.

2. Method

2.1. Optimization problem statement

It is proposed to use mathematical methods to solve the problem of optimizing the operation of the FFT. Any mathematical optimization problem includes control factors, an objective function, and admissible set. In addition, the optimization task may include additional restrictions on the control factors, as well as various parameters or constants [5-8].

In this article, a nonlinear optimization problem is solved by the geometric method using the MS Excel software for numerical calculations and plotting.

It should be noted that there is a literature with an analysis of tasks for calculating and optimizing various parameters of the organization of fire extinguishing. However, the problems with the thermal effect on the FFT are not considered [9, 10].

The cyclic processes of fire extinguishing and refueling the tanks of fire engines with water are considered, as well as the analysis and comparison of strategies for planning the work of fire truck [11]. At the same time, attention is paid to the task of extinguishing only oil fires.

There are also studies that investigate the problem of planning the movement of fire trucks in multi-point forest fires, the purpose of which is the optimal direction of a limited number of fire trucks for extinguishing fires [12]. The disadvantage of these articles is the lack of consideration of problems with thermal effects on FFT.

The paper presents the results of numerical modeling of the effect of high temperatures on the fences of FFT cabins, which are covered with a new fire-resistant structural material [13]. The model takes into account the heat transfer during the laminar movement of hot gases near the surface of the FFT cabin fence, heat transfer due to radiation from the source of thermal impact – fire, as well as thermal conductivity inside the structural materials and the cabin fence. To describe the processes under consideration, used partial differential equations, namely the Navier-Stokes equations, the energy equation, the equation of radiation transfer in a transparent medium, and the heat equation for solids. This system of equations is supplemented by initial and boundary conditions. The finite volume method is used for numerical analysis of the model. The calculations were carried out in a free software product Open FOAM. As a result of the computational experiment, the fields of air temperature and the studied composite material are obtained. The mathematical model allows to predict the unsteady temperature distribution in the layer of composite material and on the walls of the cabin, to calculate the time of reaching the limit state of the fire-retardant material, and also to show the dependence of the time of reaching this state on the thickness of the deposited layer. It is shown that the time to reach the self-ignition temperature of the noise-insulating felt material is equal to

$\tau_{FFT}^{cr} = 381\text{s}$. In this paper, felt is considered as a heat and noise insulation material, the self-ignition temperature of which is equal to 287°C [13-15].

The following element of the tactical scheme of the organization of extinguishing a forest fire is considered. The fire crew, including the FFT, arrives at the fire extinguishing site with a full tank of water and (or) water solutions of foaming agents and extinguishes it in the immediate vicinity of the edge of the fire, as a result of which the FFT is exposed to heat. This situation may occur, for example, in case of an unforeseen spread of fire during extinguishing or during a rescue operation, since usually the FFT is installed at a safe distance from the edge of the fire.

2.2. Model

Time of the estimated period of the production process of the FFT operation τ_{FFT}, s it is determined depending on the indicator of the technological efficiency of the FFT unit – the tank volume V_v, l and the performance of the FFT equipment – the supply of water and water solutions of foaming agents under pressure at the fire extinguishing site – $Q_{FFT}, l/s$

$$\tau_{FFT} = \frac{V_v}{Q_{FFT}} \tag{1}$$

At the same time, the maximum (critical) time of the production process of the FFT is determined depending on the self-ignition temperature of the heat-noise insulation material t_{hni}^{si}, °C:

$$\tau_{FFT}^{cr} = f\left(t_{hni}^{si}, ^\circ\text{C}\right) \tag{2}$$

Indicate τ, s the actual working time of the FFT, which is limited by the equation (1), because after the full consumption of the tank volume, the FFT must be refilled. Or by equation (2), because before the self-ignition temperature of the heat and noise insulation material is reached, it is necessary to finish the work and drive to a safe place.

Obtain: $\tau = \min\{\tau_{FFT}, \tau_{FFT}^{cr}\}$.

To extinguish forest fires, it is necessary to ensure the intensity of water supply [9]:

a) in case of a riding fire $J_r^{\min} = 1, l/(m^2 \cdot s)$;

b) in case of a lower fire $J_l^{\min} = 0.1 \div 0.15, l/(m^2 \cdot s)$.

Indicate $\text{U}, \text{m}^2/s$ – the rate of extinguishing the edge or area of the fire, which is a function that depends on the speed of water supply Q_{FFT}. Enter the value $\text{k}, l/m^2$ as the number of liters of water required to extinguish1, m^2 of the fire area, then $U = \frac{Q_{FFT}}{k}$. Obtain : $\text{k} = \tau_{FFT} \cdot J$.

For the mathematical optimization problem, the production capacity is taken as an objective function PC, m^2 – this is the area that the FFT is able to extinguish.

Thus receive:

$$\begin{aligned} PC &= \text{U}\tau = \frac{Q_{FFT}}{k}\min\{\tau_{FFT}, \tau_{FFT}^{cr}\} = \\ &= \frac{Q_{FFT}}{k}\min\{\frac{V_v}{Q_{FFT}}, f\left(t_{hni}^{si}, ^\circ\text{C}\right)\} = \min\{\frac{V_v}{k}, \frac{Q_{FFT}}{k} f\left(t_{hni}^{si}, ^\circ\text{C}\right)\}. \end{aligned} \tag{3}$$

There are FFT having the following values of tank volume and equipment performance $V_v \in \{2500\, l, 5000\, l, 7000\, l\}$ and $Q_{FFT} \in \{7\, l/s, 40\, l/s\}$[9]. Consider different values of equipment performance on the segment from1 $l/s$to 40 l/s.

Thus, we get the following mathematical optimization problem:

$$\begin{cases} PC(V_v, Q_{FFT}) = \min\{\frac{V_v}{k}, \frac{Q_{FFT}}{k} f\left(t_{hni}^{si}, ^\circ\text{C}\right)\} \to \max \\ V_v \in \{2500, 5000, 7000\} \\ Q_{FFT} \in [1,40] \end{cases} \tag{4}$$

where V_v and Q_{FFT} – controlling factors and k, t_{hni}^{si} and $J^{\min}$ – fixed parameters.

However, this problem has a trivial solution: ${V_v}^{\max}$ and $Q_{FFT}^{\max}$. Therefore, you can consider a more complex option. Suppose that the set of valid values V_v is discrete and for each value, we denote the maximum value of the production capacity $PC^{\max}(V_v)$. For each value of V_v it is necessary to find the minimum value of Q_{FFT}:

$$\begin{cases} \{(V_v, Q_{FFT}): Q_{FFT} \rightarrow \min, PC(V_v, Q_{FFT}) = PC^{\max}(V_v), \forall V_v\} \\ PC(V_v, Q_{FFT}) = \min\{\frac{V_v}{k}, \frac{Q_{FFT}}{k} f(t_{hni}^{si})\} \\ V_v \in \{2500, 5000, 7000\} \\ Q_{FFT} \in [1{,}40] \end{cases} \quad (5)$$

Thus, for each FFT having a given tank volume, it is possible to determine the minimum equipment for water supply. In addition, it is possible to consider heat-noise insulation materials with different self-ignition temperature and different thickness of the structural material.

3. Results and discussion

To solve the mathematical optimization problem, a geometric method is used, with the construction of graphs of the dependence of PC on control factors (Figures 1–4). This method allows us to determine the solution of the optimization problem by the type of the objective function and the set of acceptable values of the parameters of the main and auxiliary equipment. MS Excel software was used for plotting graphs.

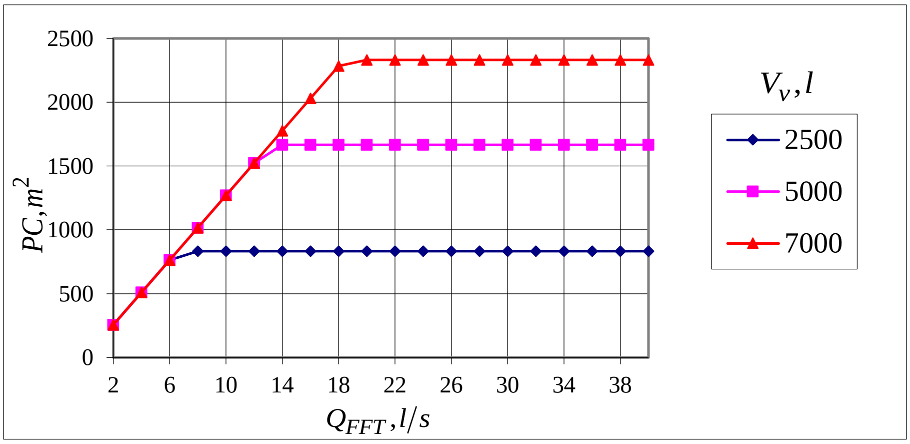

Figure 1. The dependence of the production capacity PC, m^2 on the equipment performance $Q_{FFT}, l/s$ at the specified tank volume values $V_v, l \in \{2500, 5000, 7000\}$.

In this graph (Figure 1), the optimal values of equipment performance $Q_{FFT}, l/s$are considered when the self-ignition time of heat-noise insulation is equal to 381s [13]. You can determine the intersection points using two equations of straight lines:

$$y = \frac{V_v}{k}; y^* = \frac{Q_{FFT}}{k} f(t_{hni}^{si}, °C). \quad (6)$$

Receive:

$$\frac{V_v}{k} = \frac{Q_{FFT}}{k} f(t_{hni}^{si}, °C) \quad (7)$$

or

$$V_v = Q_{FFT} \cdot 381. \quad (8)$$

We determine the solution of the optimization problem (5) or the optimal values of equipment performance for each tank volume value:

$$Q_{FFT} = (2500/381;\ 5000/381;\ 7000/381) = (6.56;\ 13.12;\ 18.37)\, l/s.$$

Thus, the minimum values of equipment performance are determined, at which the maximum value of PC, m^2 is achieved at different values of the tank volume and a given time of self-ignition of the heat-noise insulation material.

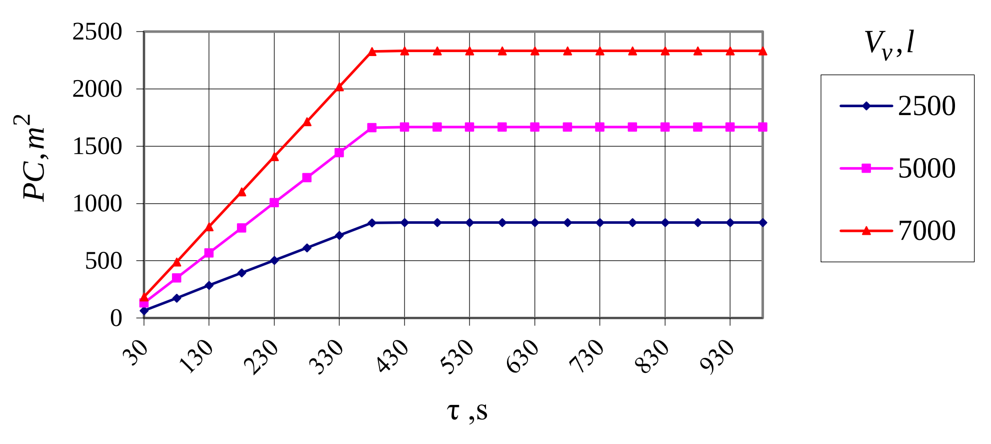

Figure 2. The dependence of the production capacity PC, m^2 on the time of self-ignition of heat-noise insulation at the specified values of the tank volume $V_v, l \in \{2500, 5000, 7000\}$and equipment performance $Q_{FFT}, l/s \in (6.56;\ 13.12;\ 18.37)$ respectively.

This graph (Figure 2) of the dependence of production capacity on the time of self-ignition of heat and noise insulation allows us to verify the correctness of finding a solution to the mathematical optimization problem (5). Here, all straight lines and intersection points indicate the optimal values of the self-ignition time of heat and noise insulation 381s at the specified tank volume values of $V_v, l \in \{2500, 5000, 7000\}$ and equipment performance $Q_{FFT}, l/s \in (6.56;\ 13.12;\ 18.37)$respectively. This graph confirms that the solution of the optimization problem (5) is correct, since the values of the self-ignition time of heat-noise insulation at the intersection points coincide with the initial value equal to 381s [13].

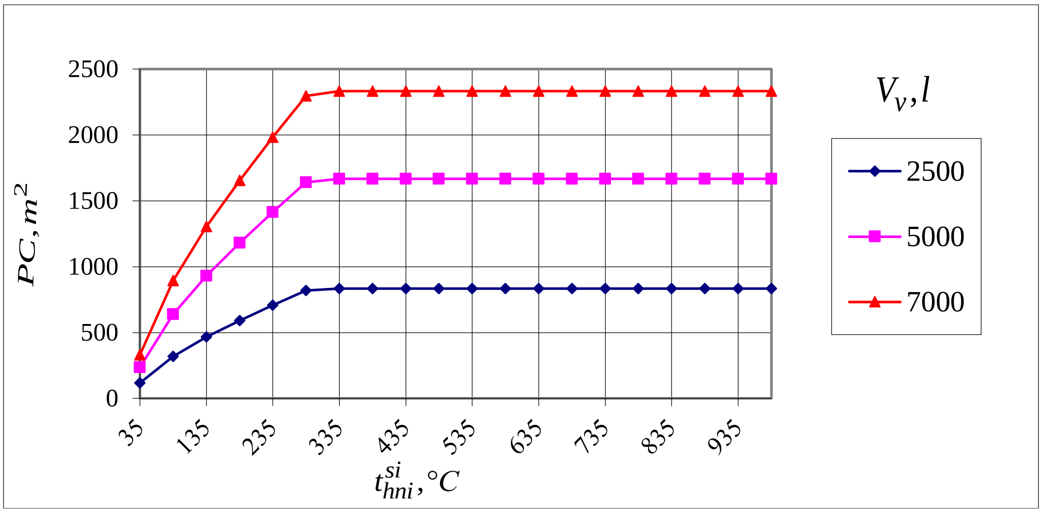

Figure 3. The dependence of the production capacity PC, m^2 on the self-ignition temperature of heat-noise insulation at the specified values of the tank volume of $V_v, l \in \{2500, 5000, 7000\}$ and the equipment capacity $Q_{FFT}, l/s \in (6.56;\ 13.12;\ 18.37)$ respectively.

The graph (Figure 3) of the dependence of the PC, m^2on the self-ignition temperature of the heat and noise insulation also allows you to check the correctness of finding a mathematical solution to the optimization problem (5). In addition to this, it allows you to determine the minimum values of the self-ignition temperature of heat and noise insulation, at which the maximum value of PC, m^2 is achieved at different values of the tank volume and a given value of the equipment performance. Here, the intersection points indicate the optimal values of the self-ignition temperature of heat-noise insulation 287°C at the specified values of the tank volume of $V_v, l \in \{2500, 5000, 7000\}$ and the equipment capacity $Q_{FFT}, l/s \in (6.56;\ 13.12;\ 18.37)$ respectively.

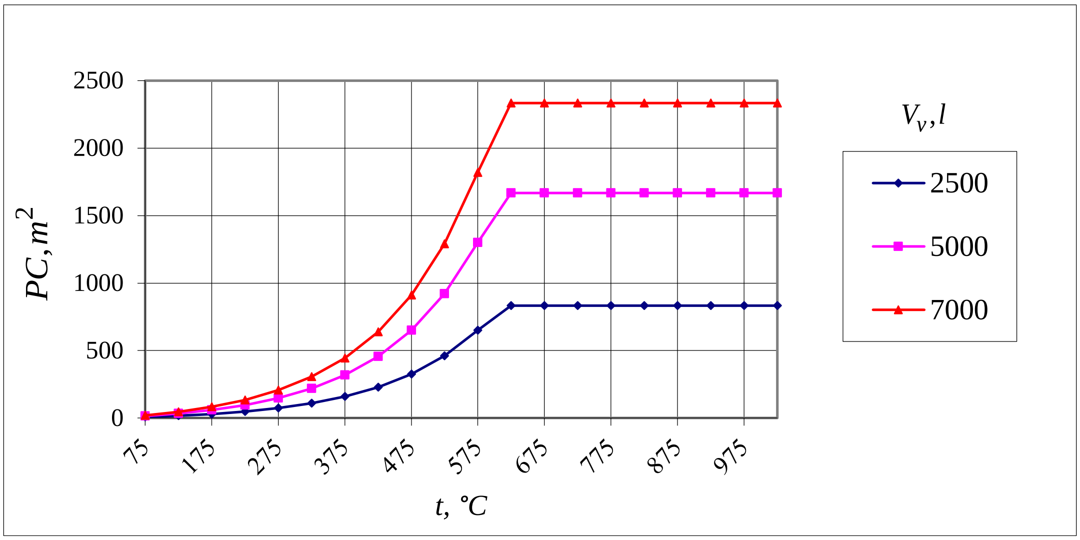

Figure 4. The dependence of the completed production capacity PC, m^2on the temperature of the thermal impact from the fire at the specified values of the tank volume of $V_v, l \in \{2500, 5000, 7000\}$and the equipment capacity $Q_{FFT}, l/s \in (6.56;\ 13.12;\ 18.37)$ respectively.

This graph on Figure 3 confirms that the solution of the mathematical optimization problem (5) is correct, since the values of the self-ignition temperature of the heat-noise insulation material at the intersection points coincide with the initial value 287°C [13].

The intersection points denote the temperature of external heat exposure, at which the maximum value of PC, m^2 is reached. The graph of the dependence of the PC, m^2on the temperature of the thermal impact from the fire (Figure 4) allows you to determine the optimal conditions and operating modes of use FFT at different values of the tank volume and the specified values of the equipment performance and the time of self-ignition of the heat and noise insulation material.

4. Conclusion

A problem of optimizing the parameters and modes of FFT operation in the emergency mode, when extinguishing forest fires – is constructed and implemented. As an objective function, the production capacity of the FFT is considered, namely the area that the FFT is able to extinguish, depending on the main and auxiliary equipment. The following factors are considered as control factors:

- the time of the estimated period of the production process of the FFT operation;
- the performance of the FFT equipment is the supply of water and water solutions of foaming agents under pressure at the fire extinguishing site;
- an indicator of the technological efficiency of the FFT unit – the tank volume;
- thermophysical properties of structural materials.

The nonlinear optimization problem is solved by the geometric method using the MS Excel software for numerical calculations and plotting. The solution of the optimization problem (5) will make it possible to determine the parameters and operation modes of FFT: to determine the production capacity of FFT, to recommend the main and auxiliary equipment of FFT, to provide the required fire-resistant properties of FFT, to improve the ergonomic performance of cabins during fire fighting. As a result, this will lead to increased safety of the FFT operator's working conditions and a reduction in the negative impact of forest fires on the environment.

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