Fire exoskeleton to facilitate the work of the fire-man

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Abstract. Classification of existing exoskeletons is given, variants of their possible application are considered. The review of fire exoskeletons is presented, their design features are given. Advantages and disadvantages of fire exoskeletons are analyzed. The stability of the robotic device is proved by calculation. The concept of fire exoskeleton-nozzleman to facilitate the work of firefighters is proposed. As a result of computational-analytical and practical researches, the concept of a fire exoskeleton-nozzleman is developed for simplification of operative work of the nozzleman during a fire. Practical application of the exoskeleton-nozzleman firefighter allows to normalize the working conditions of the nozzleman, to release three combat units of the personnel, to increase the efficiency of firefighting.

At present, many developed countries of the world continue experimental development works on creation of exoskeletons for different purposes started in the 60s of the last century. Exoskeleton is a robotic device designed to compensate for lost functions, increase the strength of muscles and expand the amplitude of movement of human body parts due to the external rigid frame and actuating mechanisms. This device repeats the biomechanics of a person for proportional increase of efforts at his movements.

The first exoskeleton, developed in 1966, belongs to the world-famous firms General Electric and United States military. The exoskeleton G.E. Hardiman was made jointly by these companies and it was able to lift 110 kg with the force applied to the lifting of 4.5 kg, but because of the significant weight of 680 kg was impractical and did not find an application [1].

The existing exoskeletons are used in various fields of human activity, including medicine, orthopedics, military science, loading and unloading operations, rescue operations, sports, protection from high temperatures and harmful environments, management of complex processes and avatars, as well as firefighting.

In relation to application in various spheres of activity of the human being exoskeleton are systematized on following classification signs: a field of application, type of management, feedback, a kind of operated gauges, type of a drive and its sensor, type of a working body, a kind of an energy source, type of connection the motor-reducer, type of a reducer of a drive, presence of the isolated compartment.

In 2015, Professor A.A. Vorobiev and his co-authors proposed the following as the main classification features of exoskeletons: type of actuator, presence of a joint

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amplification drive, anatomical arrangement of reinforced joints, presence of an integrated energy source, type of power drive used, method of obtaining a control signal, type of power plant and energy source, field of practical application [2].

The modern classification of exoskeletons is based on the following seven characteristics: energy source and drive operation principle, application point (localization), conditional cost, application area, design weight, number of functions and mobility of the whole device.

On the first attribute passive and active exoskeletons are allocated; on the second exoskeletons of the top extremities, the bottom extremities, exoskeletons suits; on the third - low cost (1000-1000000 $), an average price category (10000-50000 $), high cost (> 50 000 $); on the fourth - military, medical, industrial, space exoskeletons; on the fifth - light (up to 5 kg), average weight category (from 5 to 30 kg), heavy exoskeletons (> 30 kg); on the sixth - exoskeletons of simple purpose, dual purpose, with expanded functions; on the seventh - mobile and fixed (stationary) exoskeletons [2].

Fire exoskeleton firefighters occupy a special niche in the industrial category of the robotic devices under consideration in all the variety of existing versions. The specificity of fire exoskeletons is related to the particularly difficult and dangerous for human life working conditions of firefighters. Firefighters in combat clothing with a set of fire-fighting tools and equipment weighing about 20 kg should climb and descend along the smoky stairways of multi-storey buildings in insulating breathing apparatuses, lay sleeves on the upper floors, deliver special heavy equipment to the place of fire, carry out the special heavy equipment from the burning building of the affected people, control high-performance trunks when extinguishing fires, overcoming the significant reactive forces of the formed fire-extinguishing jets.

From the firefighters of exoskeletons existing now, the Advanced Firefighting Apparatus (AFA) device (fig. 1) developed at the Monash University in Melbourne (Australia) by Ken Chen deserves attention [3].
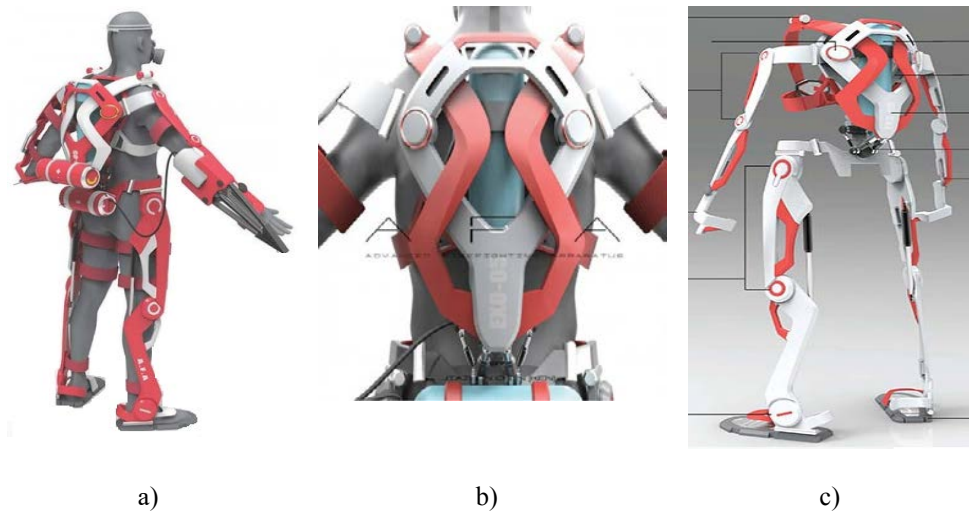

a)	b)	c)

Fig. 1. AFA fire exoskeleton developed in Australia by Ken Chen.

The AFA exoskeleton provides the firefighter with additional power to walk, control and carry loads of up to 100 kg. The entire device weighs about 23 kg. The AFA exoskeleton is equipped with efficient "joints" that allow you to remove heavy objects from

the aisle and knock down closed doors. The device is attached to the fireman's waist and is controlled by convenient joysticks. Two electric batteries ensure uninterrupted operation of the fire exoskeleton for 2 hours [3]. No less interesting is the fire exoskeleton Auberon (Fig. 2), developed by a specialized car manufacturer Trigen Automotive in Singapore [4].

Fig. 2. Fire exoskeleton Auberon Pneumatic Exoskeleton, developed by the specialized car manufacturer Trigen Automotive in Singapore.

Auberon's fully mechanical device allows a firefighter in full outfit to move freely in smoky stairwells with an additional weight of about 40 kg. The firefighter's hands remain free to work in the fire, and all the main and additional loads are transferred to the floor through the frame and exoskeleton shoes, in this way relieving the shoulders and back of the firefighter. The device operates on compressed air from two cylinders with a capacity of 6.8 liters each and is equipped with a mechanism that allows the firefighter to quickly get rid of the exoskeleton if necessary [4].

There are other versions of fire exoskeletons equipped with various devices that allow performing a number of operational functions, including the supply of fire extinguishing jets (Fig. 3).

Fig. 3. Extinguishing of fire with an AFA fire exoskeleton equipped with a barrel and high-pressure hose.

Existing designs of fire exoskeletons, along with the above mentioned advantages and ample opportunities, are burdened with some disadvantages, which, above all, should include the increased weight of the entire device. This is due to the lack of suitable lightweight, but strong enough materials for the manufacture of a rigid frame and reliable

actuators. Titanium alloys, carbon fiberglass compositions and other suitable for the manufacture of the frame new materials are still quite expensive.

Not less serious lack of design of fire exoskeletons is rather limited in hours term of independent work of power supplies used nowadays, in particular, storage batteries, cylinders with oxygen and capacities with compressed air. Possible alternative power sources, such as internal combustion engines, electrochemical fuel cells and solar panels, are also not solving the issue positively.

A special problem in the design of fire exoskeletons is servo drives because standard hydraulic cylinders have a significant weight, not high enough operational reliability and require an extensive network of hoses and tubes operating under pressure, hydraulic pump and tank with working fluid. Pneumatic actuators are more reliable in operation, but not accurate in terms of movement processing, as compressed gas is spring loaded and reactive forces push actuators unnecessarily.

The disadvantage of the design of the existing fire exoskeleton is also imperfect control and regulation of excessive and undesirable movements of firefighters working in the exoskeleton.

To eliminate the main drawbacks noted in the design of fire exoskeletons in the work is proposed the concept of fire exoskeleton to work with the trunk and perform other operational functions in extinguishing the fire.

The main specifics of nozzleman's work on fire is to hold and control the fire-fighting agent supply barrel at the operating pressure in the pressure hose line of about 0.6-1.0 MPa, as well as to provide a quick change of combat position without dismantling the pressure hose line. Practice shows that this hard work cannot be done by a single firefighter, and for its satisfactory execution, as can be seen below in Fig. 6, at least two nozzlemen are required.

For trunks of different capacity, knowing the geometric dimensions of their flow sections, it is possible to determine the reactions of the jets formed by the formula [5]:

$$R = 2 \cdot s \cdot P,\qquad(1)$$

where R - is the value of the reaction of the jet formed by the trunk, N;
s - area of the trunk through the section, m^2;
P - working pressure in the pressure hose line, Pa.

Dependence of the values of reactions of the formed fire-extinguishing jets on the working pressure in the pressure hose line at different diameter of the through section of the trunk is shown in Fig. 4 [6].

Fig. 4 shows that as the working pressure in the pressure hose line and the diameter of the through section of the barrel increases, the reactions of the formed fire-extinguishing jets increase significantly, and, consequently, the force required to hold the barrel, as well as overturning and rotating moments that violate the vertical stability of the barrel. Therefore, the installation of barrels with a cross section diameter of more than 25 mm on fire exoskeletons without outriggers, which ensure the vertical stability of the entire robotic device, is inexpedient for safety reasons.

The AFA example shows the effect of the reaction R of the formed fire-extinguishing jet (jets) when placing one fire trunk (Fig. 5, a) and two fire trunks (Fig. 5, b) on the fire exoskeleton.

Knowing the most optimal shoulder effect of the reaction of the formed jet H (Fig. 5), equal to the average height of the bent hand of the gunner (H = 1.1 m), it is possible to determine the characteristic overturning moment Mov, which occurs when working stationary on the hand of a single trunk:

$$M_{OПP.} = R \cdot H,\qquad(2)$$

where R - is the reaction of the formed fire-extinguishing jet, kN.
   H - optimal shoulder effect of the reaction of the formed fire-extinguishing jet, m;
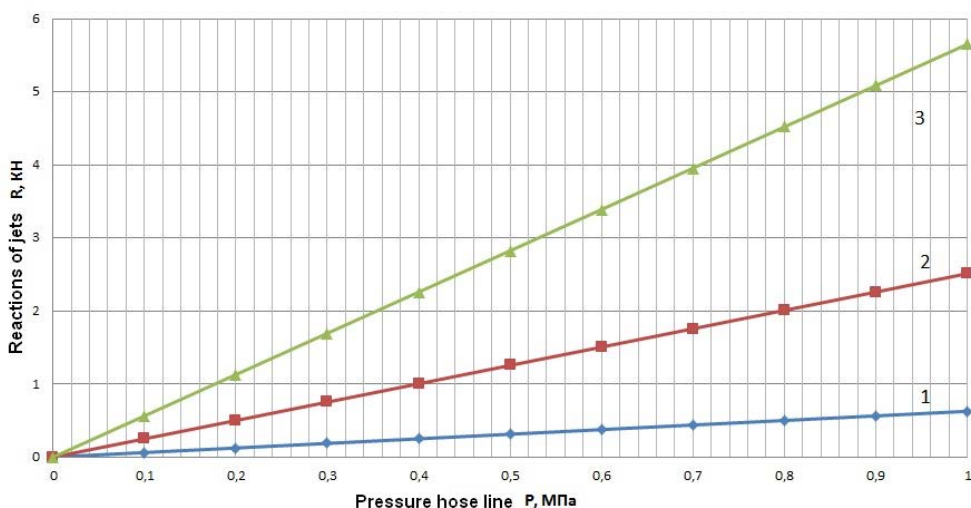

Fig. 4. Values of reactions of formed jets depending on pressure in a pressure hose line at different diameter of through section of a trunk, mm: 1 − diameter of branch pipe is 20 mm; 2 − diameter of branch pipe is 40 mm; 3 − diameter of branch pipe is 60 mm;
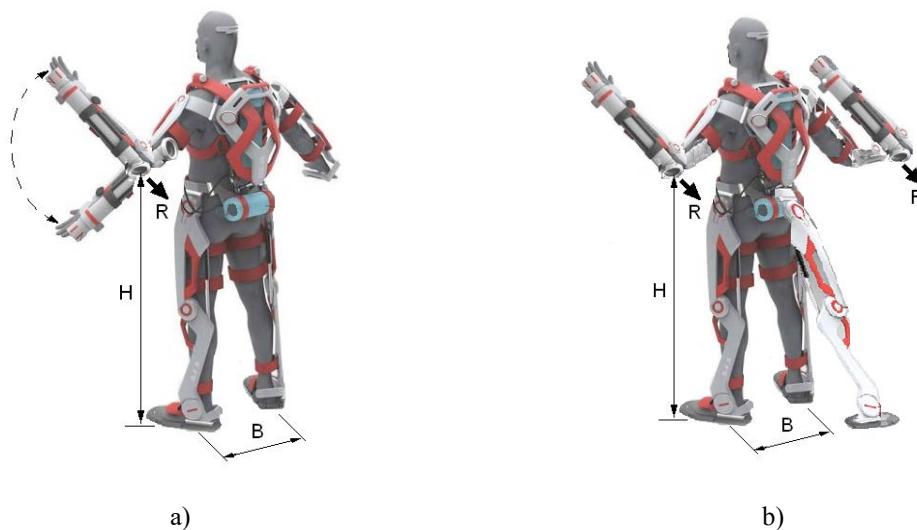

Fig. 5. Schemes of the reactions of the formed fire-extinguishing jets:
 a) - when one trunk is installed; b) - when two trunks are installed

   The maximum overturning moment for a fire exoskeleton with a permanently mounted barrel will be

$$M_{onp.\max} = R_{\max} \cdot H, \tag{3}$$
$$M_{onp.\max} = 0{,}6 \cdot 1.1 = 0.66 \kappa H \cdot \text{м}$$

In this way, in order to freely hold a fire monitor with a capacity of 20-40 l/s, operating at a pressure in the pressure hose line of 0.6-1.0 MPa, it is necessary that the force of the actuator holding the hand with the barrel, was not less than the maximum value of the reaction of fire-extinguishing jet, which is on the graph of Fig. 4 of the order of 0.6 kN.

$$F_{y\partial.} \geq R_{\max}$$

In this case, to ensure the vertical stability of the fire exoskeleton when working with the trunk outrigger robotic device (Fig. 5, b) should provide a holding torque that exceeds the value of the maximum tipping torque from the two trunks, amounting to about 1.3 kN·m

$$M_{y\partial.} \geq M_{onp.\ \max}$$

Knowing the maximum effect of the reaction of the formed jet in the transverse plane at the height of H, equal to B/2 (Fig. 5), it is possible to determine the maximum value of the turning moment:

$$M_{pa3b.\max} = R_{\max} \cdot B / 2,$$
$$M_{pa3b.\max} = 0.6 \cdot 0.5 / 2 = 0.15 \kappa H \cdot м$$
(4)

In order to avoid the unfolding moment from the reaction of the fire-extinguishing jet formed by the trunk fixed on one left or right hand of the fire exoskeleton, it is advisable to install two trunks on both hands of the gunner. The vertical stability of the entire robotic device can be calculated using the overturning moment, the maximum values of which are more than four times the value of the opening torque.

Taking into account the installation of the two barrels on the exoskeleton on both hands of the gunner, the design diagram shown in Fig. 5,b, determine the value of the torque of the robotic device

$$M_{y\partial.} = G_{\Sigma} \cdot Sin\alpha \cdot g \cdot h + r \cdot b,$$
(5)

where G_{Σ} – is the highest total weight of robotic devices, trunks, firefighting equipment

and equipment, $G_{\Sigma} = 30 + 80 + 20 + 10 = 140$ кг;

α – outrigger tilt angle, taken 30^{0};

g – freefall acceleration, 9,8 м/с^{2};

h – Shoulder of action of the horizontal component of G_{Σ}, is assumed to be 1.25 m;

r – vertical component of the outrigger reaction, kN;

b – shoulder of action of the vertical component of the outrigger reaction, assumed to be 0.6 m

$$M_{y\partial.} = 140 \cdot 0.5 \cdot 9.8 \cdot 1.25 + 1.0 \cdot 0.6 = 1.5 kH \cdot м$$

When calculating the vertical stability of the entire robotic unit, the position from which the bale wrapper will operate must be taken into account (Fig. 6).
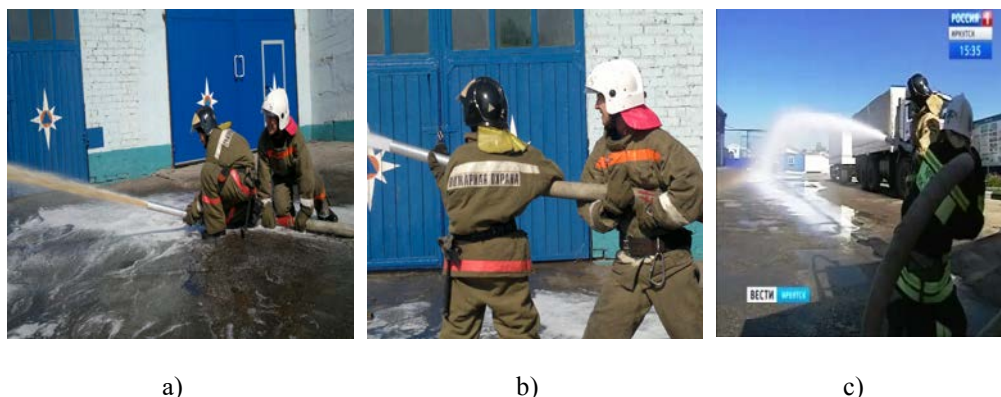
a)   b)   c)

Fig. 6. The positions of the nozzlemen without exoskeleton: a) - when working from the "ground"; b) - when working from the "bent hand"; c) - when working from the "shoulder".

Overturning moments (Fig. 7) are defined for different positions of the barrel when working with manual fire hoses of different capacities [7] [8].
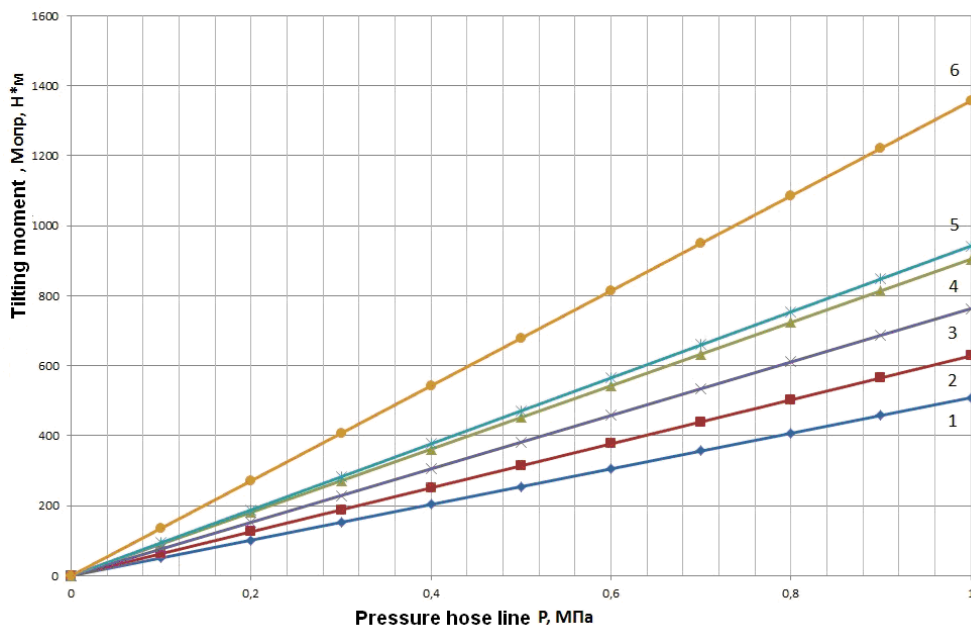

Fig. 7. Tilting moments acting on the nozzleman, depending on the position occupied, at different operating pressures in the hose line: 1) - at the through section of the barrel 18 mm and working with "bent arm" H = 1.1 m; 2) - at the diameter of 20 mm and working with "bent arm" H = 1.1 m; 3) - at the diameter of 18 mm and working with "shoulder" H = 1.5 m; 4) - with a diameter of 24 mm and working with a "bent arm" H = 1.1 m; 5) - with a diameter of 20 mm and working with "shoulder" H = 1.5 m; 6) - with a diameter of 24 mm and working with "shoulder" H = 1.5 m

The following nozzleman positions are considered: a) - when working from the "ground", when the stem connector nut is pressed against the ground, the height of H = 0 m, and the tilting moment tends to zero, with the pressure hose pressed by the knee to the ground, both hands of the gunner control the position of the barrel (Fig. 6,a); b) - when

working with "bent arm", nozzleman standing position, average height of the barrel H = 1,1 m (Fig. 6,b); c) - when working with "shoulder", nozzleman standing position, height of the barrel H = 1,5 m (Fig. 6,c).

Having considered and balanced the forces and moments acting on the robotic device while working with the barrel(s), it is possible to return to the development of the fire exoskeleton-nozzleman concept.

The exoskeleton-nozzleman firefighter should have a rigid frame made of strong lightweight material such as carbon fiberglass, and active upper and lower extremities, providing nozzleman with easy performance of basic operational tasks and mobility of movements with pressure hose lines when changing the combat position.

The actuation mechanisms of the exoskeleton-nozzleman firefighter should be driven by quick-release cylinders with compressed air, which are taken out to the fire with the necessary reserve. The force of the mechanism holding the arm with the barrel should be not less than 6 kN, which corresponds to the maximum value of the reaction of the fire-extinguishing jet formed by the barrel. It is important for the pneumatic actuator to ensure the accuracy of movement processing and smooth operation of actuators by balancing the reactive forces.

In order to isolate nozzleman's breathing from the harmful environment, the exoskeleton-nozzleman firefighter must be equipped with a compressed air insulating device, which is more harmless to human health and less explosive in operation than the oxygen-insulating mask..

In order to increase the number of fire extinguishing agents supplied twice, to release three nozzlemen in the fire and to increase the vertical stability of the robot, it is advisable to equip the exoskeleton-nozzleman with two barrels fixed on the left and right hands.

In order to ensure the safety of fire exoskeleton-nozzleman operation, the latter must have an outrigger, which together with the support stops creates a holding torque of at least 1.5 kN・m, which exceeds the maximum overturning moment from the reactions of two fire-extinguishing jets, giving the entire robotic device the necessary vertical stability.

Fire exoskeleton-nozzleman must have extended functions, weigh about 30 kg and be included in the main purpose fire engine compartment in terms of dimensions. At the same time, the cost of a fully equipped robotic device should fit into the average price category, that is, 10000-50000 $.

In addition, the exoskeleton-nozzleman firefighter should be equipped with a mechanism that allows nozzleman to quickly get rid of the exoskeleton if necessary.

In the development of fire exoskeleton-nozzleman, the existing recommendations for the creation of robotic devices should be taken into account and the developed mathematical models of exoskeletons, increasing the muscular strength of a person and coordinating its capabilities with the movement of actuators should be used [9, 10].

Following the developed concept, with the diameter of the left and right barrels of about 24 mm each, the exoskeleton-nozzleman firefighter, according to the schedule shown in Fig. 8, will be able to supply at least 30 liters per second of fire extinguishing agents for extinguishing the fire by means of a medium-capacity fire truck, performing the functions of a high-performance mobile carriage trunk.
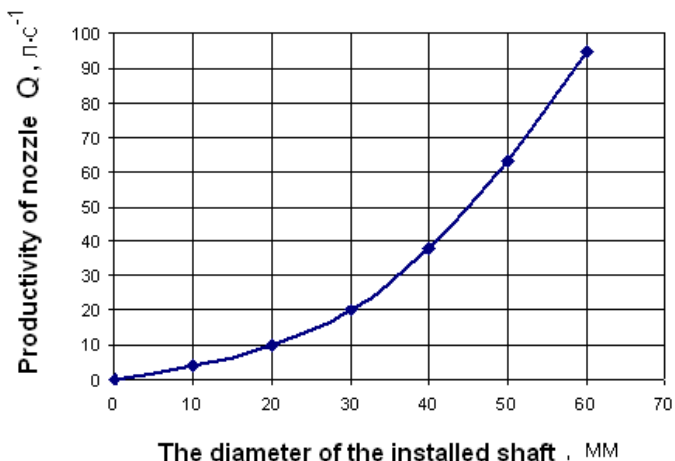
Fig. 8. Dependence of the capacity of the exoskeleton-nozzleman shaft firefighter on the diameter of the installed shaft

At such productivity of the installed trunks, the exoskeleton-nozzleman firefighter will be able to extinguish the open fire on the area of about 1 000 square meters according to the diagram presented in Fig. 9.
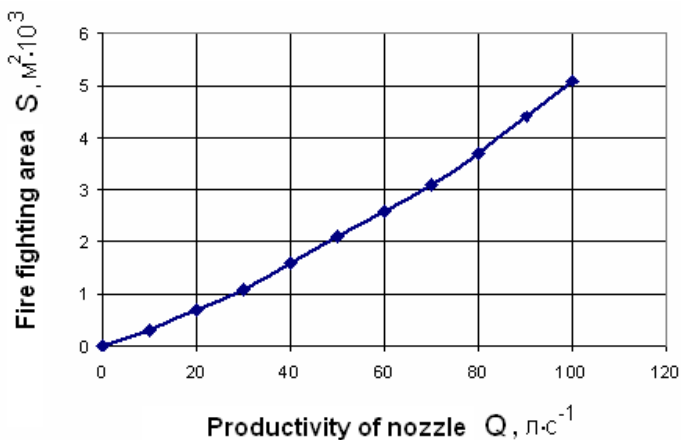

Fig. 9. Dependence of the firefighting area on the productivity of the fire exoskeleton-nozzleman.

In this way, thanks to the fire exoskeleton, a single nozzleman can effortlessly supply a large quantity of extinguishing agents for extinguishing a fire with two trunks, depending only on the pumping capacity of a modern fire engine.

Since one exoskeleton-nozzleman firefighter will be able to work with two productive barrels at the same time, release up to three firefighting units of the personnel, ensure the safety of nozzleman and increase the efficiency of firefighting by increasing the intensity of fire extinguishing agents supply, the expediency of its practical application in a complex operational environment in extinguishing open large fires is not in doubt.

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