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UNMANNED FIRE-FIGHTING AMPHIBIOUS AIRCRAFT WITH DISTRIBUTED TURBOELECTRIC PROPULSION SYSTEM

A.N. Varyukhin [1], M.A. Ovdienko [1], A.V. Vlasov [1], V.S. Zakharchenko [1]

[1] Central Institute of Aviation Motors (CIAM), Russia

Abstract

The paper considers the problem of extinguishing forest fires by aviation. The design of an unmanned amphibious aircraft with a turbo-electric distributed propulsion system is done. Its aerodynamic and hydrodynamic performances are estimated. Flight firefighting missions with different range are analyzed and efficiency of firefighting UAV is calculated for this missions.

Keywords: firefighting UAV, hybrid electric propulsion, seaplane

1. Introduction

In recent years, there has been an active fight against carbon dioxide emissions around the world. For example, ICAO aims to reduce CO2 emissions of aviation. Considerable resources are allocated for this goal. However, every year, 8 billion tons of CO2 are released into the atmosphere due to forest fires. This is about 10 times more than the CO2 emissions of aviation. Forest fires annually claim thousands of lives and cause huge economic and environmental damage. At the same time, forest fires number is growing year after year. It is directly due to climate change caused by global warming. Global warming in turn is linked to the excess carbon dioxide in the atmosphere absorbed by forests, which is released in a forest fire. Thus, from the point of view of ecology, a forest fire deals a double hit to the environment.

The CO2 emissions of the fires amount to 8 billion tons, which is comparable to the emissions of the all-China economy (Table 1). During a large forest fire in 2019, in Australia, in just a few weeks, the as much CO2 was released as the all-Australia economy produces in a year.

Table 1 – CO_2 emission in other states

State	CO_2 emission
China	9.8 billions of tons
USA	5 billions of tons
EU	3.3 billions of tons
Russia	1.5 billions of tons
The whole world	34 billions of tons

Fires also cause economic damage. For example, the economic damage from fires in California in 2018 amounted to 25 billion dollars, which is comparable to the GDP of countries such as Cyprus and Iceland.

The most effective way to extinguish forest fires is to dump the flame-extinguishing liquid from the air tanker. At the same time, this method is the most expensive, and also quite dangerous for the crew and equipment. Specialized equipment, its maintenance and repair, and fuel are expensive. Costs of the pilots and other crewmembers are relatively large. Especially expensive is to use heavy aircrafts that allow you to dump a large volume of water. For example, the cost of a flight hour of a BE-200 firefighter aircraft is 5,000 dollars. The high cost of maintaining a fire aircraft leads to the fact that often the cost of extinguishing a fire exceeds the predicted damage because of fire. In addition, only sufficiently wealthy nations can afford to have a fleet of specialized heavy fire-fighting aircrafts.

Therefore, the task of developing a relatively inexpensive, but at the same time highly effective fire-fighting aircraft is very relevant.

2. Requirements for an advanced firefighter aircraft

There are two types of firefighting aircraft, land-based and amphibious. Land-based aircraft are usually made on the basis of existing aircraft, usually with a relatively small residual resource. Boeing-474, DC-10 in the United States, and IL-76 in Russia are used for this purpose. The advantage of such aircraft is a large volume of water, so for Boeing-it is 200t, for IL-76-40t, and a high cruising speed.

The disadvantage is a long water loading process at the airfield, a small number of available airfields, a high minimum water discharge speed. At this speed a significant part of the discharged water does not provide the required irrigation density. The inability to discharge water from a low altitude is also important disadvantage.

Amphibious fire-fighting aircraft are highly effective. The most common are the Canadian Bombardier CL-415 and the Russian Be-200, while in Japan the Shim Mayva US-2 is used for this goal. Amphibians allow you to take water on the hydroplaning mode in a couple of minutes. And despite the relatively small volume of water (CL415 has no more 6 tons, Be-200 has no more 12 tons), the efficiency of such type of aircraft (in terms of the amount of water dropped per unit of time) is higher than the listed land-based aircraft have (if there is a suitable reservoir at a relatively small distance).

Figure 1 - Be-200 water bombing

In addition, amphibious aircraft can also take water at land airfields. Moreover, the number of airfields available for small aircraft is much greater than for heavy ones.

Small aircraft that can discharge 2.5-3 tons of water at a time at low speed, from a low altitude, can also be extremely effective, and their operation will be relatively inexpensive, especially if it is amphibious and unmanned aircraft.

When aircraft discharge water in flight it breaks into small drops under the action of airflow [1]. It can be seen in Figure 2. As a result, not all the water discharged from aircraft effectively prevents the fire.

Figure 2 – Be-200 water bombing

According to studies carried out in the United States [2], the water density should be at least 0.8¬¬-1 liters/m2 when forming an irrigation zone in the path of the fire front, and more than 3-5 liters/m2 when water is discharged to the fire source. Figure 3 shows the typical distribution of water density on earth.

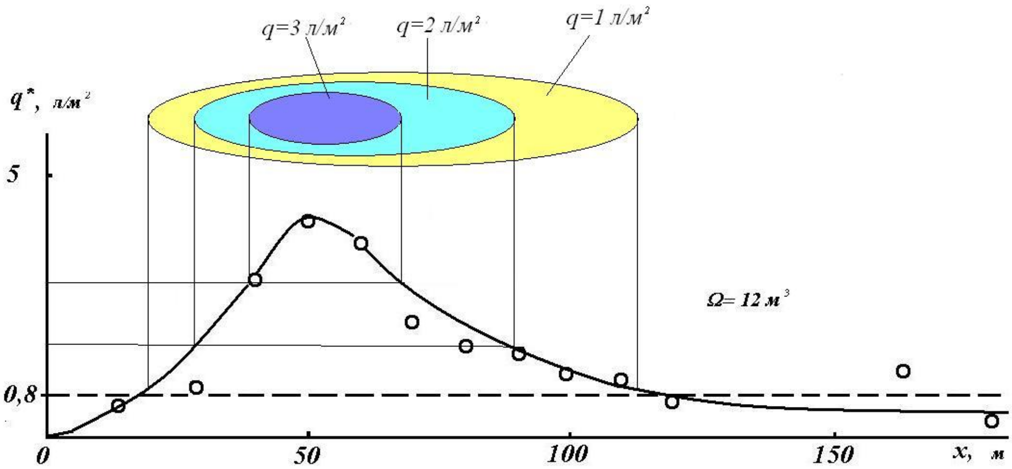


Figure 3 – Watering zone

In research [1], on the base of a large number of full-scale and model experiments on the discharge of a flame-extinguishing liquid, the so-called optimal height of the water discharge was defined

$$\bar{H}_0 = \frac{H_0}{\sqrt{\sigma}} = A(æ)\frac{\lambda}{\bar{q}Fr^2} \qquad (1)$$

where σ – area of the aircraft tank discharge hatch,

V – aircraft speed during water discharge,

$Fr = Vg^{-1/2}\sigma^{-1/4}$ – Froude number,

$\lambda = l^2\sigma^{-1}$ – discharge hatch aspect ratio,

q - required irrigation density.

At flight altitude $H < H_0$ the irrigation area and the length of the irrigation zone are approximated as:

$$\overline{S}_0 = \frac{S_0}{\sigma} = 0,85\frac{\overline{\Omega}}{\overline{q}^{3/2} Fr^2}, \quad \overline{L}_0 = \frac{L_0}{\sqrt{\sigma}} = 0.6\frac{\overline{\Omega}^{0.5}}{\overline{q}Fr} \tag{2}$$

where $\overline{\Omega} = \Omega\sigma^{-3/2}$ and Ω – volume of aircraft water tank.

These results show that the maximum effective drop height increases with decreasing airspeed. The irrigation area and the length of the irrigation zone with a fixed tank volume and the required irrigation density also increase significantly with a decrease in flight speed.

Therefore, the main requirement for an advanced firefighter aircraft is a small minimum horizontal flight speed at which water can be discharge effectively.

Moreover, the low flight speed not only increases the efficiency of the water discharge, but also allows do it more accurately. In addition, the low speed of horizontal flight means a low speed of take-off and landing, which is very important for amphibians, because it allows you to take off and land on small reservoirs and increases seaworthiness.

Based on the results of a research [1], it can be concluded that the acceptable minimum flight speed is 90-100 km/h.

The next requirement is - the absence of the crew, i.e. unmanned. UAVNESS significantly reduces the cost of aircraft. Firstly, the requirements for the UAV and its propulsion system are much lower than for the manned one. Secondly, there is no need to provide the aircraft with life support systems. Third, operational overloads may be increased and, in some cases, the safety margin can be reduced. And finally, the absence of a crew allows you to discharge water from a low altitude and in other dangerous conditions, for example, in gorges and mountains. The flight speed of 90-100 km/h, and water bombing the flight altitude of 10-15 m allows you to use 90% of the water to extinguish a fire. For comparison, in aircraft such as the Boeing-747 and DC-10, only no more than 20% of the water creates an effective irrigation zone.

Another requirement is a relatively high cruising speed. This is required in order to collect water, deliver it to the extinguishing site and return as quickly as possible. We will accept it at the level of at least 280-300 km/h.

Another important parameter that defines the efficiency of amphibious aircraft operation, and that directly affecting the ability to conduct fire-fighting operations, is the level of seakeeping. That means the maximum wave height at which an aircraft can take-off [3]. If we talk about Russia, the forests are located in the continental part, far from the seas, where there cannot be high waves. Nevertheless, even for aircraft that will take-off from big lakes and rivers the minimum wave height should be at least 0.5m.

As a result, the main requirements for a fire-fighting aircraft:

- UAV
- Stall speed 90-100 km/h
- Cruising speed 280-300 km/h
- Takeoff water roll 200-250 m
- Seakeeping at least 0.5 m of wave height
- MTOW less than 8600 kg
- Max weight of water at least 3000 kg
- Maximum operating range at least 1500 km
- Flight duration at least 5 hours

3. Aircraft design

The requirements significantly limit the number of possible architectures and designs of aircraft. It can be said that the most acceptable design is a flying boat with a high-positioned wing, with advanced mechanization and distributed propellers along the leading edge of the wing, providing uniform blowing of a wing.

The uniform blowing of the wing with the advanced released mechanization ensures the implementation of the high lifting force that occurs on the wing (Figure 4). It provides a low stall speed. A large amount of research was carried out at NASA during the realization of the X-57 Maxwell project [4, 5]. There are a huge number of studies about the X-57 Maxwell aircraft with a DEP.

Figure 4 – NASA X-57 Maxwell

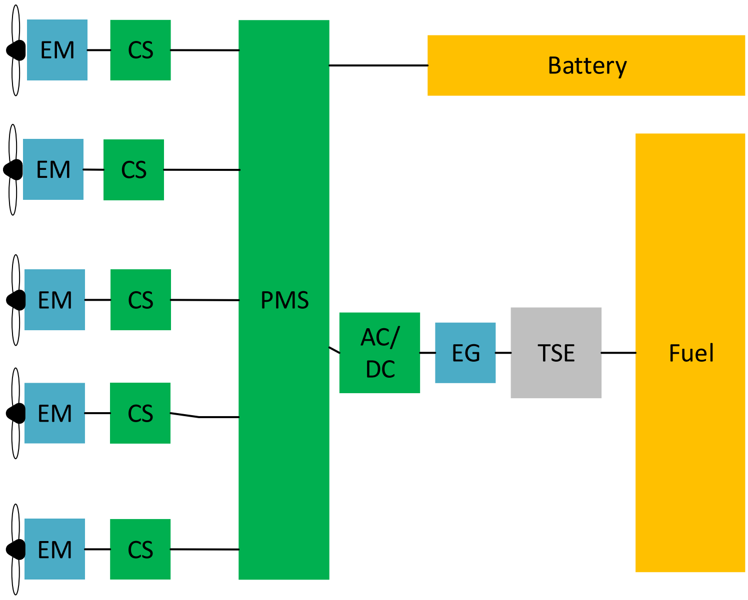
Based on the analysis of the use of fire aircraft, it is advisable to create a fire amphibious UAV with a DEP, capable of carrying 2.5–3 tons of water. The maximum take-off weight of such an aircraft should be about 8600 kg (Figure 5). To achieve the greatest effect of the increase in lift due to the use of DEP, it is necessary to locate the axis of rotation of the screws below the wing [6]. This location of the screw lead to a risk of splashes and jets hitting the propeller, so the wing should be lifted. As a result, the height of the fuselage increases significantly, that reduces the lift to drag ratio of the aircraft, but allow to reach high take-off lift coefficient values. It is very important for amphibious seaplanes. The width of the fuselage near the step is 1.6 m. As a DEP, it is assumed to use a system of 10 distributed screws, as shown in Figure 5.

Picture 5 – Firefighter UAV with DEP design

4. Propulsion system

Using distributed propulsion system together with a conventional propulsion system is impractical due to the high mass of the transmission. For this aircraft, the most promising HEP architectures are serial (Figure 6) and turboelectric (Figure 7-8) propulsion systems. In a serial HEP, the main source of energy is a turbo generator running in all flight modes. The energy of the generator is transferred to a high-voltage network and distributed among a number of electric motors that rotate the propellers. Also, energy from the battery packs is transferred to the high-voltage network during take-off and climb flight modes. In cruising mode, the batteries are charged.

A feature of the flight profile of a firefighter UAV is a large number of descents and climbs for water intake and discharge, short sections of cruising flight. Probably, the time to recharge batteries will not be enough. So the use of a battery is impractical. In this regard, it is proposed to use the turbo-electric architecture of the HEP (Figure 7-8).



EM – electric motor; CS – control system; PMS – power management system; EG – electric generator; TSE – turboshaft engine.

Figure 6 – Serial hybrid electric distributed propulsion system

In the turbo-electric architecture, there is only one power source on board – the turbo generator. The turbo-electric architecture can be implemented in different ways. So in the first version in Figure 7, the same electric motors and propellers are installed along the wing, operating in all flight modes. The disadvantage of this architecture is the need to install a large number of variable pitch propellers.

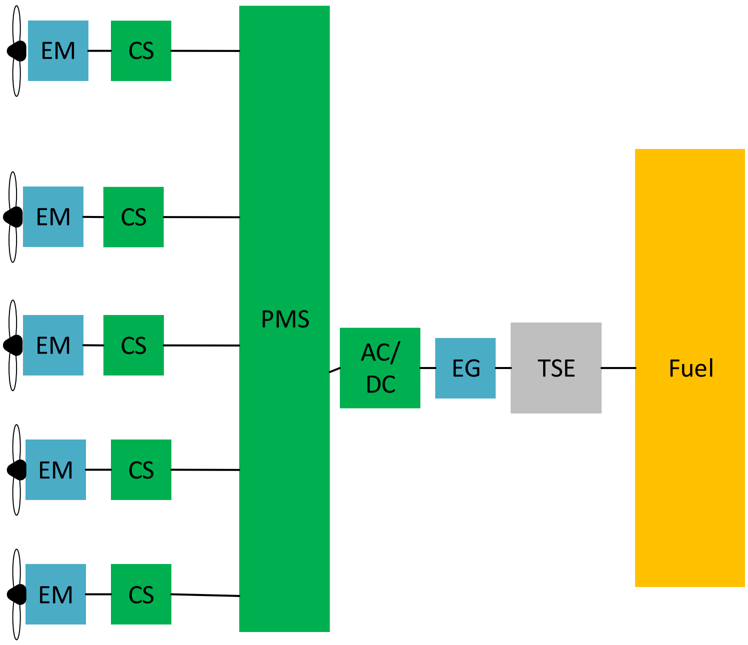


Figure 7 – Turboelectric distributed propulsion system

In the second variant, two powerful electric motors rotate the variable pitch propellers. The auxiliary electric motors rotate fixed-pitch propellers that fold up in flight.

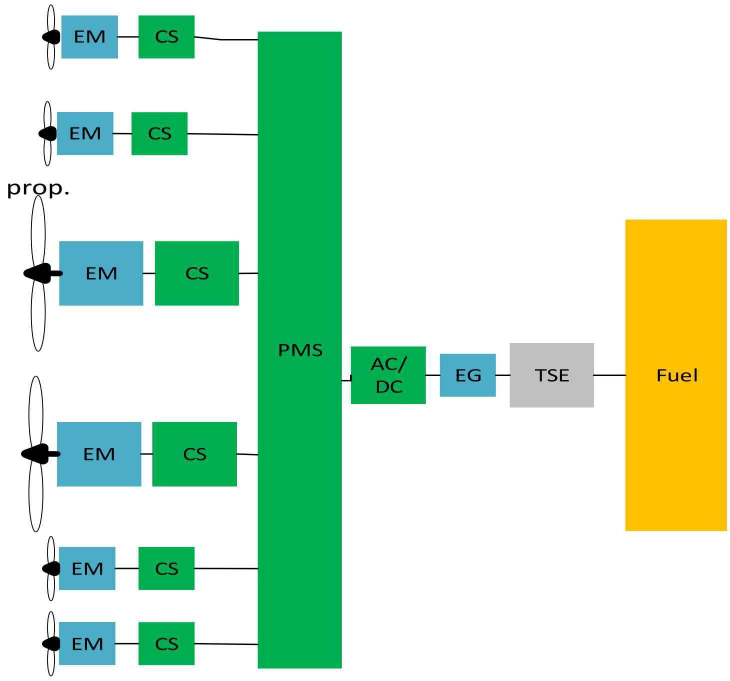


Figure 8 – Turboelectric propulsion system with auxiliary distributed electric propulsion with foldable propellers

As the drive of the electric generator, the most suitable is the VK-2500 turboshaft engine. Its performances are represented in table 2.

Table 2 – VK-2500 performances

Performance	**Value**
Takeoff power	1765 kW
Max continues power	1400 kW
Weight	290 kg
Cruise SFC	0,266 kg/(kW*h)
Turbine shaft rotation speed	15500 rpm

The altitude characteristics of the VK-2500 engine were calculated using the software package developed by CIAM. Figure 9 shows the power of the turboprop engine, and Figure 10 shows the specific fuel consumption.

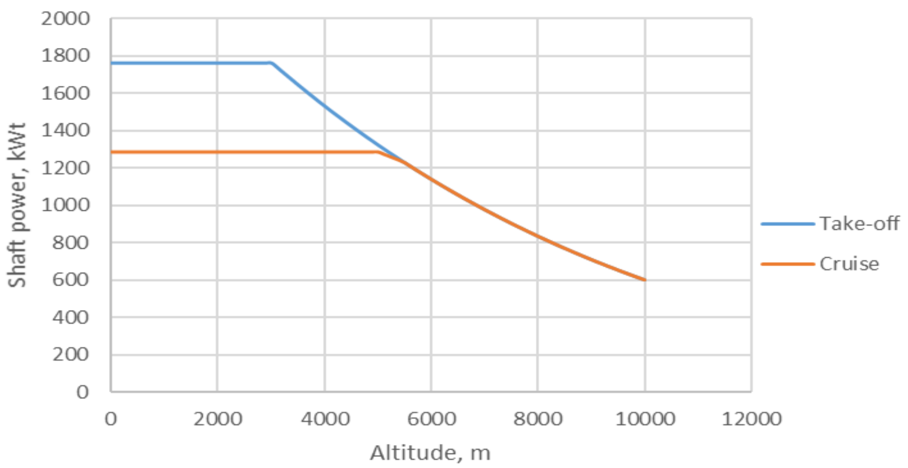


Figure 9 – Engine shaft power

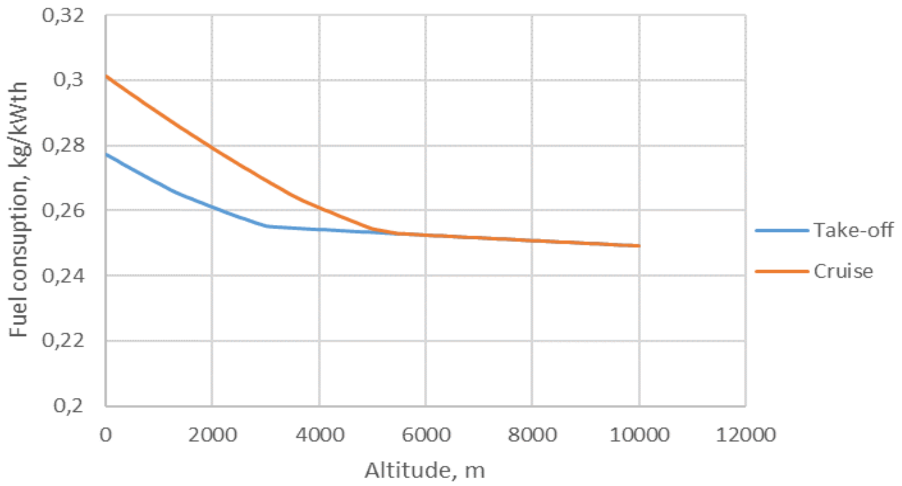


Figure 10 – SFC per hour

The propulsion system also includes electrical components, such as an 1800 kW electric generator, inverters, and ten 180 kW electric motors. CIAM has extensive competencies in the research, development and experimentation of these elements. Estimations have shown the required electric generator with a maximum power of 1800 kW, a nominal power of 1300 kW, a frequency of 15500 rpm will have an efficiency of 96% and a weight of 180 – 200 kg. Electric motors with a peak power of 180-190 kg will have the following performances: peak power-190 kW, rated power-120 kW, frequency-2000-2500 rpm, efficiency-94%, weight-30-35 kg.

5. Estimation of hydrodynamic performances

An interpolation method based on experimental data was used to calculate the hydrodynamic performances of a firefighter UAV [7]. The one of the main parameter is the step specific load:

$$C_{\Delta_0} = \frac{G_0}{\rho D_{st}^3} \tag{3}$$

where G_0 – aircraft TOW,

ρ – water density,

D_{st} – step wide.

For the reference aircraft with a take-off weight of 8600 kg, this value is . The results of calculations based on the available experimental data are represented in Figures 11-12.

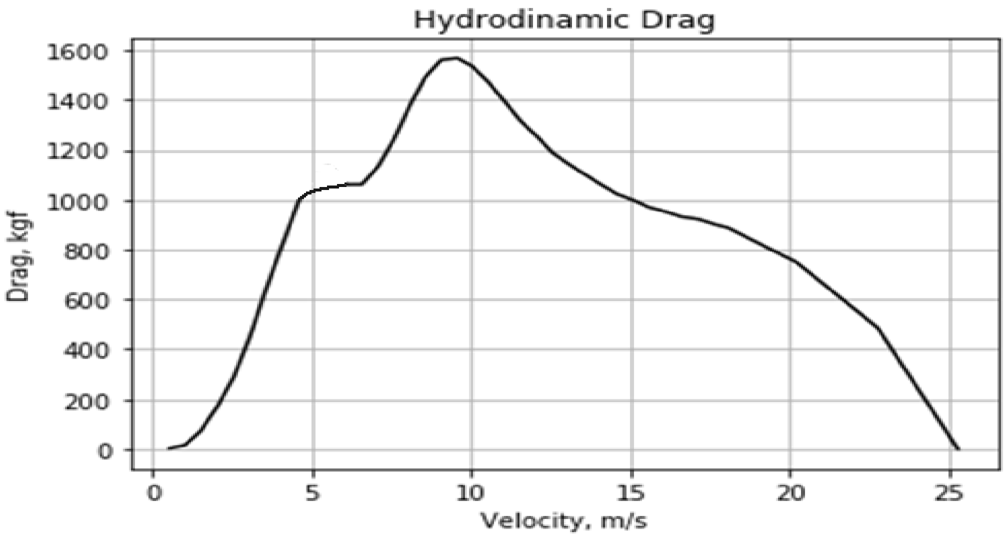


Figure 11 – Firefighter UAV hydrodynamic drag

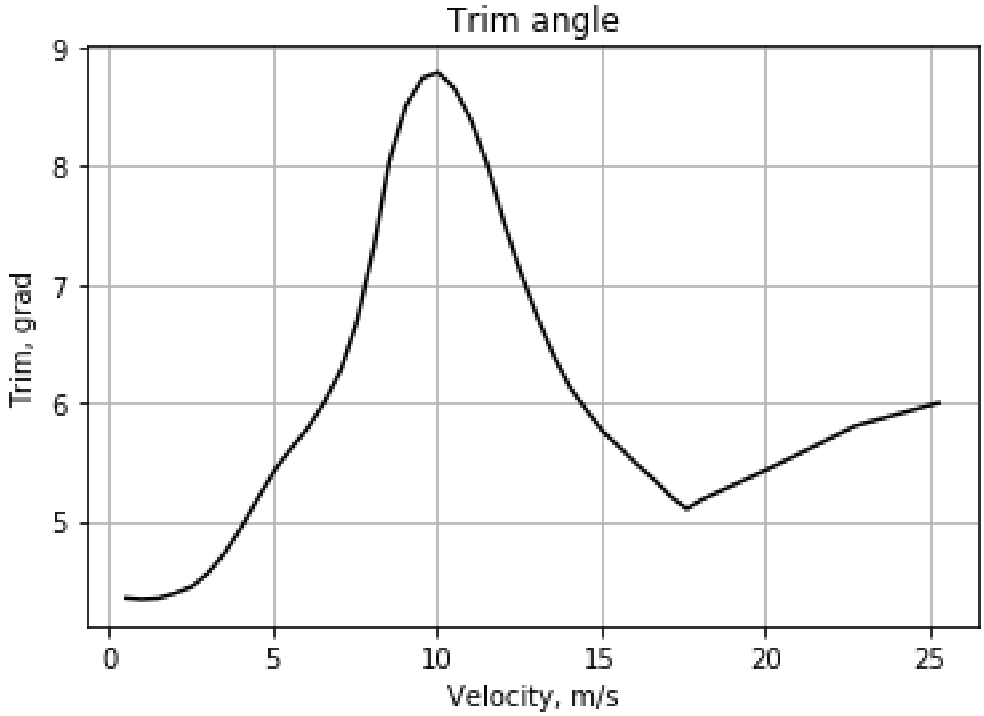


Figure 12 – Firefighter UAV trim angle

6. Estimation of aerodynamic performances

To calculate the increase in lift due to the blowing of the wing by the propeller, it is possible to use different methods. The most complete detailed information can be provided by the use of CFD methods. But this technique requires significant time and computational costs. A simplified model is required to make the preliminary design. The semi-empirical Zolotko technique can be used to solve some problems [8]. This method gives good results in comparing with experimental data [9], but does not take into account some nuances, such as the location of the screws. Figures 13-14 show that the aerodynamic characteristics of the X-57 Maxwell aircraft, taking into account the blowing, calculated by the Zolotko method have close values to the results of CFD calculations using the active disk method [10].

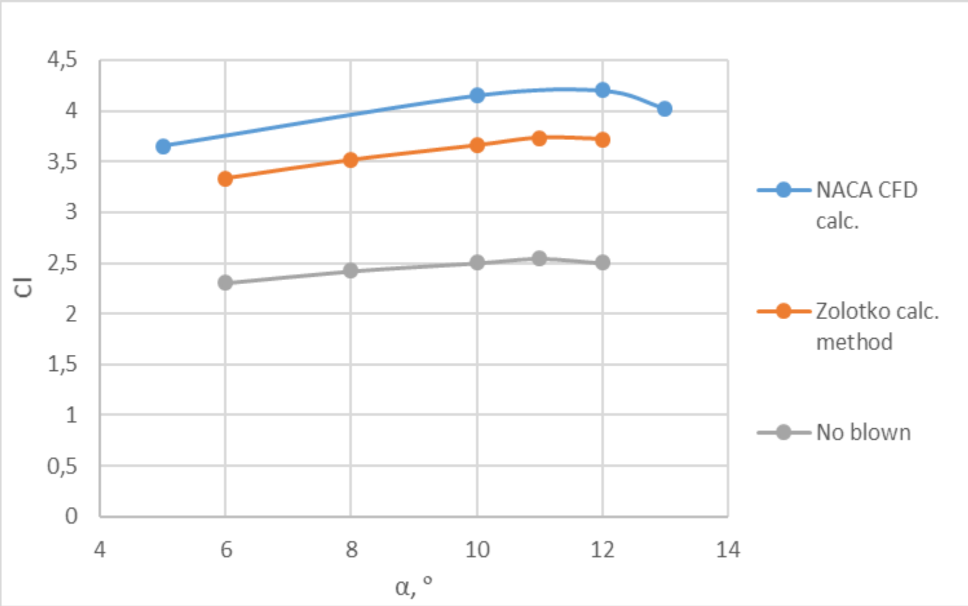


Figure 13 – Lift coefficient of X-57 Maxwell

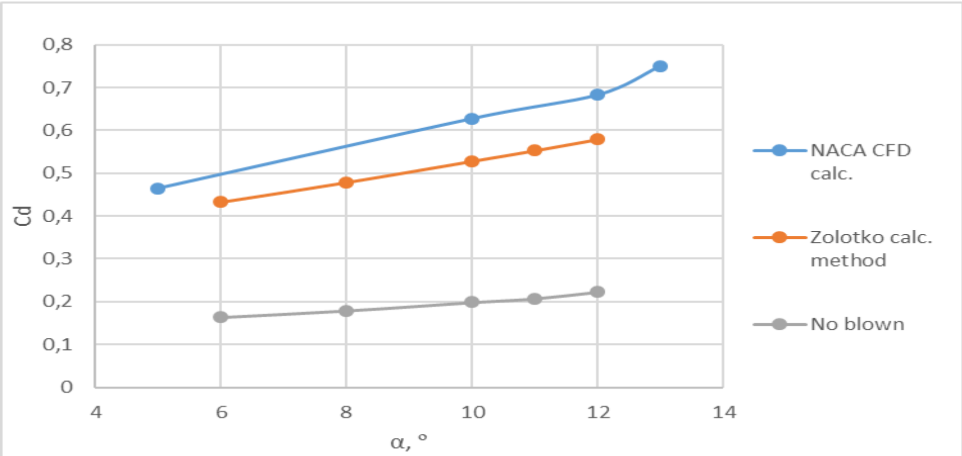


Figure 14 – Drag coefficient of X-57 Maxwell

To estimate the aerodynamic performances of the aircraft, CFD calculations of the GAW-1 airfoil with a 3-slot flap in 3 configurations (take-off, cruise and landing) were performed. The calculations showed high values of the aeroperfomance of this profile. Then, using the technique [9], the characteristics of the entire aircraft were obtained with the help of calculation of airfoil. The aeroperfomance is shown in Figures 15-16.

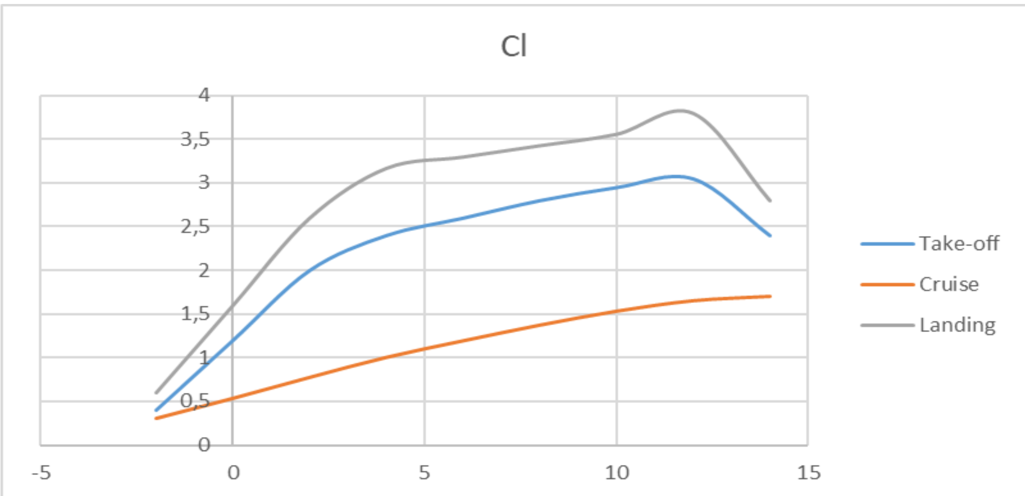


Figure 15 – Firefighter UAV lift coefficient without blown effect

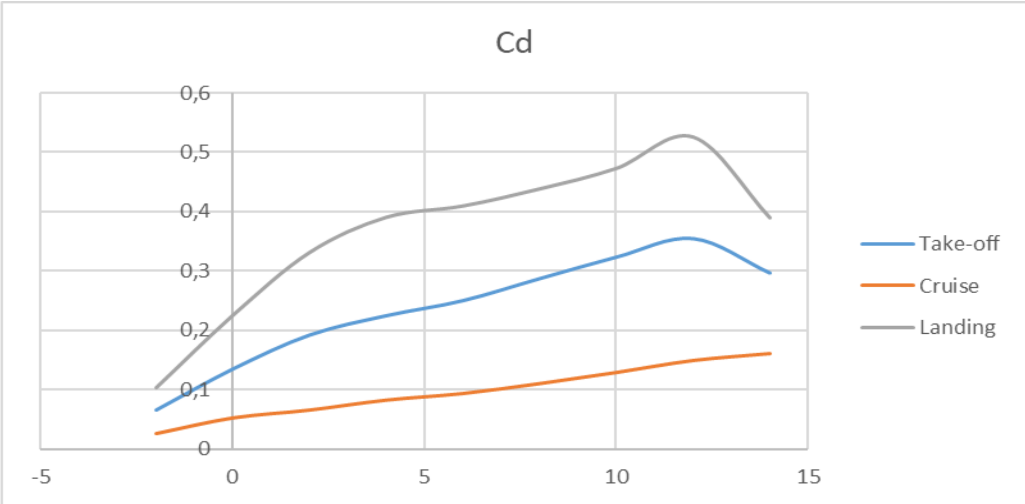


Figure 16 – Firefighter UAV drag coefficient without blown effect

Calculations of take-off distances during take-off from the runway and from the water, as well as take-off, landing and cruising speed, taking into account the blowing of the wing by the distributed propeller system were made for wing sizing (Table 3). In the case of take-off from water, the total drag is sum of hydrodynamic and aerodynamic drag:

$$W = C_D \frac{\rho V^2}{2} S + W_{Hydro} \quad (4)$$

where W – full drag;

S - wing area;

W_{Hydro} – hydrodynamic drag.

Table 3 – Takeoff and landing perfomances

S_{wing}, m	**25**	**30**	**35**	**38**	**40**	**45**	**50**
$V_{takeoff}$, kmph	124	113	104	100	97	91	90
$V_{landing}$, kmph	105	95	88	84	82	77	73
Max speed, kmph	403	383	366	357	351	338	326
Cruise speed, kmph	383	363	347	338	332	320	308
Ground take-off run, m	322	257	213	193	181	156	151
Ground runway length, m	270	210	169	151	140	118	114
Water takeoff run, m	659	474	364	317	291	236	228
Water runway length, m	607	27	320	275	250	198	191
Climb length, m	52	47	44	42	41	38	37

To effectively use a fire-fighting UAV from different sized bodies of water, it is needed to reach a short take-off up to 200 m. This value of the run - up on the water corresponds to the wing of 45 m^2.

7. Weight breakdown estimation

Using the SUAVE software package [11], which uses semi-empirical formulas to estimate the weight of the aircraft elements, the weight breakdown of the firefighter UAV was calculated (Figure 17).

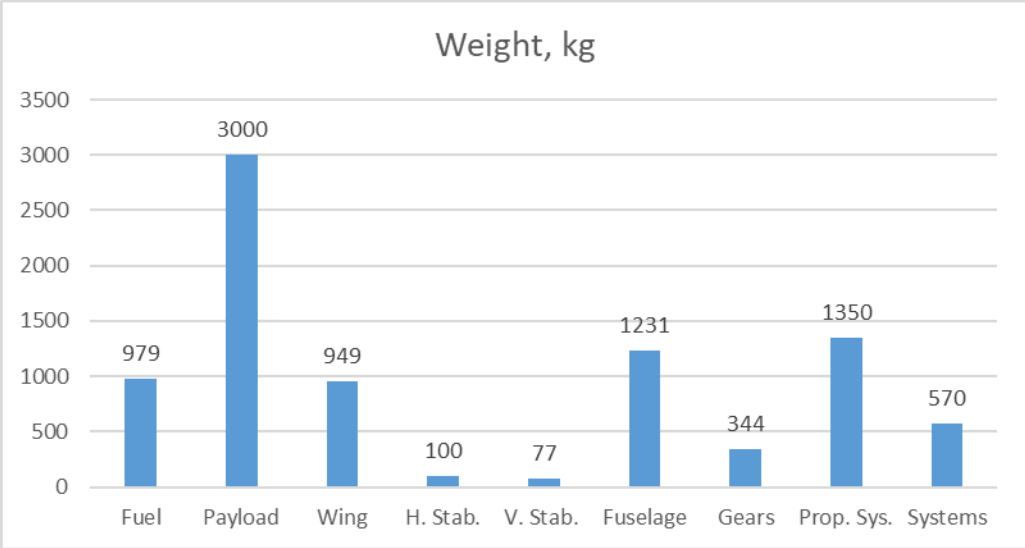


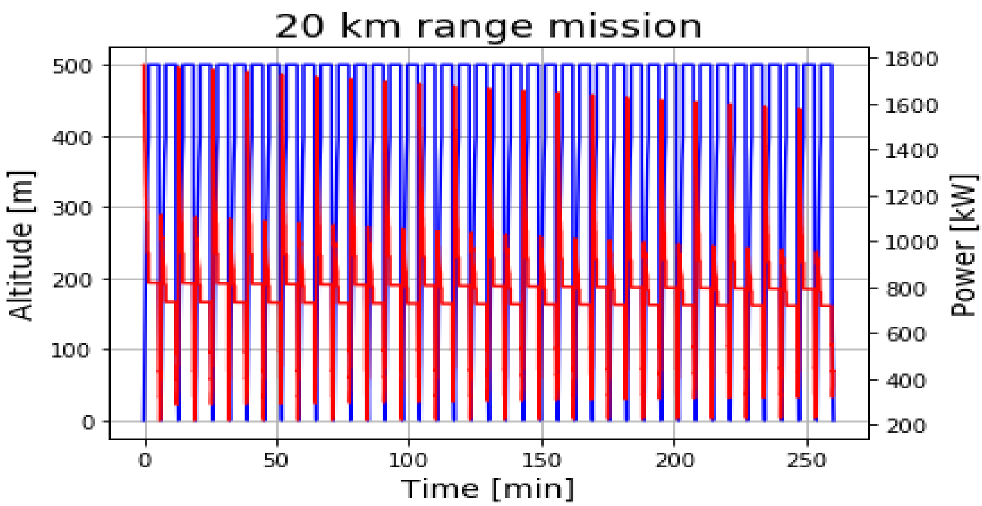
Figure 17 – Firefighter UAV weight breakdown

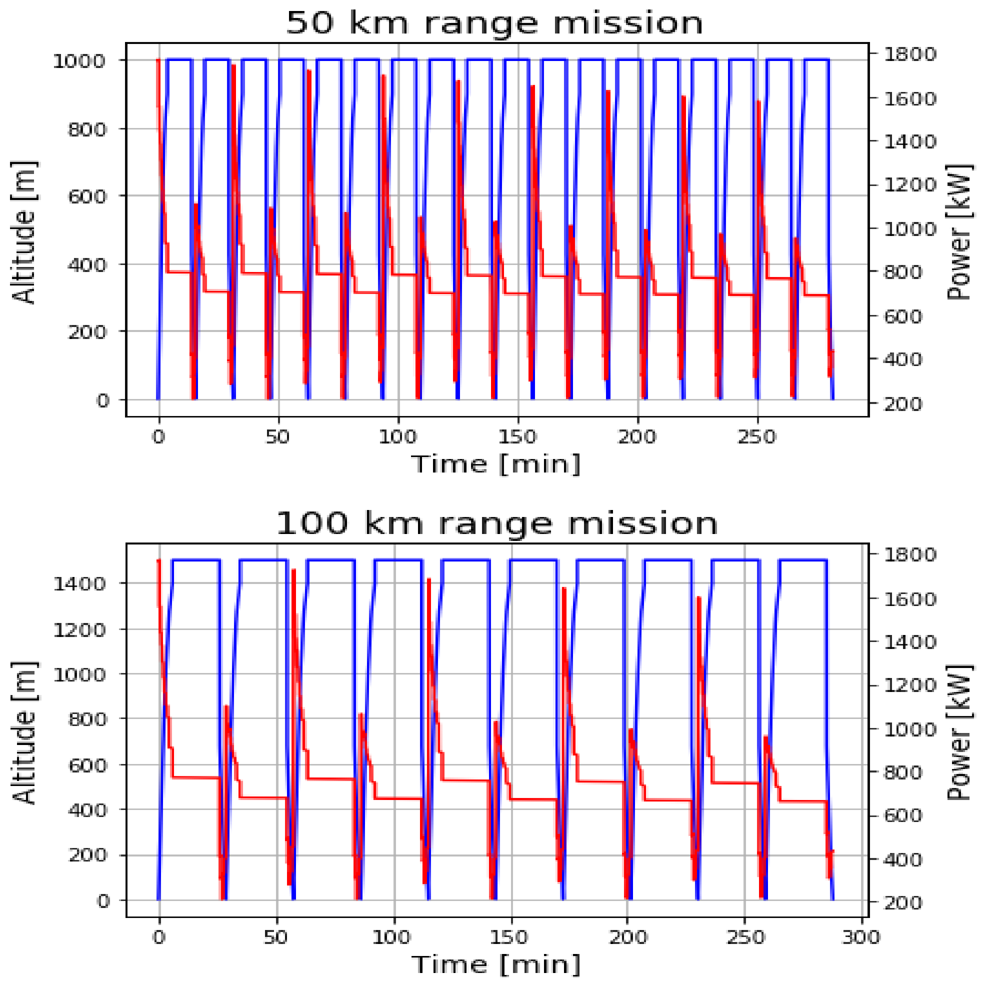
8. Estimation of firefighting efficiency

The most effective method of extinguishing – conveyor. I.e. amphibious aircraft in the mode of hydroplaning takes water on the reservoir, located relatively close to the front of the fire. Then it discharge water and flies back. Naturally, the efficiency is higher when the distance between water reservoir and fire is small. Unfortunately, large bodies of water is not always available, especially, where large aircraft, such as the Be-200, can be used. Therefore takeoff and landing speed is very important. The lower it is, the less take-off and landing distance we need, the less distance we need to get water.

At the same time, if the reservoir is far away, it is necessary to have a high cruising speed in order to quickly get to the front of the fire.

For a advanced fire-fighting seaplane, a flight conveyor missions of extinguish a fire at a distance of 20 km, 50 km and 100 km were calculated (Figure 18).





Picture 18 – Fire fighting missions for 20 km, 50 km and 100 km

The graphs show the required power according to the flight mission of the firefighter aircraft. For these missions, firefighting efficiency (mass of discharged water) was calculated (Table 4).

Table 4 – Mass of discharged water

Range, km	**Number of discharge**	**Mass of water, tons**
20	20	60
50	9	27
100	5	15

Thus, it can be said that the use of a fire-fighting UAV can be very effective at a relatively short distance of 20-30 km. This can be achieved because of the short take-off distance.

9. Conclusion

The requirements are done and the design of a advanced unmanned aircraft for extinguishing forest fires with a maximum take-off weight of 8600 kg is proposed. The aircraft is a typical seaplane with a moderate load on the step. To provide a low take-off and landing speed of 90 km/h, a distributed turboelectric propulsion system is used. Aircraft needs a distance of about 200m, to takeoff from the water. So short take-off distance provides the ability to take water from a large number of reservoirs. It is shown that when the distance between fire source and the reservoir is 20 km, the aircraft is able to discharge a total of 60 tons of water. At the same time, due to the low stall speed, which is provided by a distributed propulsion system, the water use efficiency is almost 90%.

Returning to the question of the effectiveness of fire-fighting aviation, it should be borne in mind that one type of aircraft cannot provide all the needs. The fire-fighting fleet must have all types of aircraft. These are heavy ground aircraft type like the Il-76, heavy amphibious aircraft like Be-200 and light unmanned amphibians. The high fire-fighting efficiency of the UAVs is provided by the use of a distributed propulsion system.

10. Contact Author Email Address

Mailto: anvaryukhin@ciam.ru, Anton N. Varyukhin

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