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ORIGINAL ARTICLE

Assessment of engine's power budget for hydrogen powered hybrid buoyant aircraft

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Abstract It is well known that hydrogen has less undesirable exhaust emissions as compared with other types of liquid fuels. It can be used as an alternative fuel for a hybrid buoyant aircraft in which half of the gross takeoff weight is balanced by the aerostatic lift. In the present study, weight advantage of liquid hydrogen as an ideal fuel has been explored for its further utilization in such aircraft. Existing relationships for the estimation of zero lift drag of airship is discussed with special focus on the utilization of such analytical relationships for the aircraft whose fuselage resembles with the hull of an airship. Taking the analytical relationship of aircraft and airship design as a reference, existing relationships for estimation of power budget are systematically re-derived for defined constraints of rate of climb, maximum velocity and takeoff ground roll. It is perceived that when the propulsion sizing for liquid hydrogen is required, then the presented framework for estimation of its power budget will provide a starting point for the analysis. An example for estimation of the power requirement is also presented as a test case.

1. Introduction

Different modes of transport are available today but due to high fuel prices, transportation cost to reach the destination in minimal time is increasing with additional penalty due to emissions. A century ago, airships were a suitable

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Nomenclature

B	buoyant
B_R	buoyancy ratio
$C_{L,(L_{aero}/D)_{max}}$	coefficient of lift for maximum lift to drag ratio
$C_{L_{max\_aero}}$	maximum aerodynamic lift coefficient
C_{L_md}	coefficient of lift for minimum drag
$(C_{\_D\_0})_{less\_hull}$	zero-lift drag coefficient, less of the hull
$C_{\_D\_0}$	zero-lift drag coefficient
$C_{\_D\_min}$	coefficient of minimum drag
C_f	skin friction drag
HB	hybrid buoyant
FF	form factor
FR	fineness ratio
hp	horsepower
K	drag due to lift factor
IC	internal combustion
l	characteristics length, (unit: m)
L_{buoy}	aerostatic lift
LTA	lighter than air
$\left(\frac{L_{aero}}{D}\right)_{max}$	maximum lift to drag ratio
LH_2	liquid hydrogen
m_z	gross mass at end of cruise segments
m_y	gross mass at start of cruise segments
m_x	gross mass at start of climb segments
m_w	gross mass at warm-up/takeoff
S_{aero}	characteristic reference area of aerodynamic lift
SFC	specific fuel consumption
NO_x	nitric oxide and nitrogen dioxide
rpm	revolution per minute
$\left(\frac{R}{C}\right)$	rate of climb
$\left(\frac{R}{C}\right)_{max}$	maximum rate of climb
$\left(\frac{R}{C}\right)_{min}$	minimum rate of climb
STOL	short takeoff and landing
V	velocity
V_{max}	maximum velocity
V_{stall}	stall velocity
$V_{(L/D)_{max}}$	velocity for maximum lift to drag ratio
Vol	volume of lifting gas inside the hull
W_{GTM}	weight corresponding to gross takeoff mass
W_{net}	net weight

Subscripts

MC	mid cruise
TO	takeoff
TR	thrust required

source in aviation transportation with less environmental concerns, which were later led by low and high speed aircraft. It is well known that with the passage of time, size and number of aircraft grew bigger and less focus is there on environmental concerns. As per a recent data published online, "*worldwide, flights produced 705 million tons of CO_2 in 2013. Globally, humans produced over 36 billion tons of CO_2*" [1]. One of the triggering elements for air pollution is byproduct of burning of fossil fuels which include CO, CO_2 and unburned hydrocarbons. Recent research on hybrid buoyant (HB) aircraft [2,3] may offer a good solution for the overall reduction in CO_2 and other harmful emission by the aviation industry. In case of aircraft, half of the fuel is used just to keep it aloft [4]. Whereas, the use of aerostatic lift in hybrid buoyant (HB) aircraft has the potential to cancel out such requirement. Such aircraft combine the aerodynamic (similar to aircraft) as well as aerostatic lift (similar to airship) and is considered as "*best of the both worlds*" [5]. Requirement of less infrastructure, shorter runways and less fuel consumption as compared with short takeoff and landing (STOL) aircraft are some of the characteristics of HB aircraft.

Design and development of airships and aircraft took place in almost similar time span. If we look back in the history of aviation, Zeppelin LZ-1 took its first flight on 2nd July, 1900 and Wright brothers had flown the aircraft in 1903 [6]. The first wind tunnel was established for airship but later during world war-II, more interest was shifted towards aircraft and more research was then focused on aircraft. Even to date, much of the latest research work available is more focused on aircraft such as liquid hydrogen as an alternative power source for future aircraft [7] or towards drag reduction and flow control to improve aircraft performance [8].

Airship is found to be competitive with cruises for distances between 200 and 1000 km [9] and HB aircraft which are disguised as airship will be more suitable for sight-seeing and comfortable travel for tourists at low speed. These aircrafts have the characteristics to take off, land and fly as any other aircraft but unlike the others, have a buoyant gas inside the hull. Moreover, the agricultural products such as pepper, palm oil, fresh vegetables and fresh meat do not have a low-priced as well as fast freight mode available as compared with aircraft and ships, respectively [10]. Therefore, by taking advantage of huge volume of hull, export products can also be transported from remote areas having insufficient ground transportation network.

As far as the environmental effects are concerned, liquid hydrogen can be used as an alternative fuel for buoyant aircraft in which voluminous tanks of LH_2 can be accommodated inside the hull. This is the basis for the considerations which led to the volumetric sizing of hull and physical location of the tanks for the LH_2 fueled buoyant aircraft. Usage of liquid hydrogen is ideal for reduction in atmospheric pollution [11] as combustion of hydrogen produces water vapors and it may influence contrail and cirrus cloud formation. Hence no ozone layer depleting chemicals are generated. Moreover, similar to conventional airships [12], water vapors can be collected to compensate the decrease in weight due to burning of fuel to some extent.

In order to prove this concept, there is a requirement to design and develop HB aircraft such that the performance