Liquid Hydrogen in THRUST Architecture

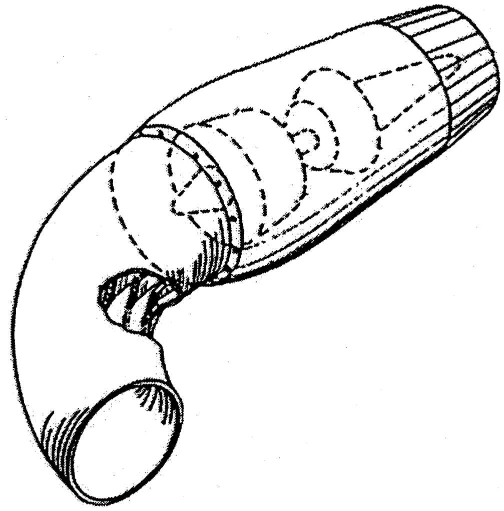

Figure 1: Curved air intake extender with engine.

Figure 1 shows a preferred embodiment of a generic reaction engine(s).The engine(s) are preferably turbojets, having a compression stage, a combustion stage, and a turbine stage to drive the compressor stage. Power is provided by the thrust of the expanded gas as it leaves the exhaust stage.

The air conduit bends from a longitudinal to a transverse posture from the air inlet disc to the reaction engine. Internal vanes are mounted within the conduit in order to facilitate a generally uniform flow stream around the curved portions of the conduit. The reaction engine may be releasably connected to the extremity for a support arm by the provision of a mounting saddle having thrust mounting blocks and a plurality of circumferential mounting collars.

Liquid Hydrogen: For Fuel Cooled Thermal Management System

ABSTARACT: This paper explores the possibility of using liquid hydrogen as cooling for a gas turbine engine in such a fashion so that major design changes could be avoided. We would not be looking into those aspects of regenerative cooling those change the engine cycle itself, for example diverting the bleed air and use of a heat exchanger. Cycle change would be a new research area in itself and therefore it is more pertinent to suggest changes only for the combustor chamber walls, intake, and exhaust.

1 INTRODUCTION

Fuel-cooled thermal management (popularly known as regenerative cooling) is an enabling technology that offers potential for cycle improvements and pollutant emissions control for a gas turbine engine. A fuel can absorb energy from various engine components (viz. combustor, nozzle, or inlet regions) and help to vaporize high-density fuel before entering the combustion chamber[1] [2] [3] [4] [5]. The heat is rejected to the environment by thermal radiation from adjacent external surfaces. This process of cooling would be a complementary cooling technique along with the existing cooling options in the engine. Various thermal management design studies have shown that fuel based cooling systems require high pressures, heavy and potentially hazardous fuel/air heat exchangers and fuel reactors, and elaborate pumping and distribution passages[6] [7] [8]. The use of such fuel cooling systems strongly impacts the engine system design and increases the cost of on-ground fuel handling infrastructures[9]. But in this study we would like to explore the possibility of using fuel based regenerative cooling with minimal design changes to an existing engine as well as keep thermal management system as simple as possible to keep the cost of infrastructure involved minimal.

Limited availability of fossil energy sources and the effect greenhouse gases on the climate of our planet have forced us to search for hydrogen as a clean fuel (Ammonia also has got immense potential as the fuel of the future). Use of hydrogen to generate energy is also in sync with the President Bush's “Hydrogen Initiative” that was launched in the year 2003.

If we look at the gas turbine fuel panel, hydrogen looks quite promising. It contains mere about 10MJ/l energy on volume basis but it has got about 120MJ/kg energy stored in it on mass basis (see Fig.1). Studies show that because of its high-BTU character and because of its nature of exhaust gases, a hydrogen-powered plant at base load generates about 4 % more power when compared with a natural gas powered plant[10]. That is 1.5MWe for 40MW gas turbine and about 2% relative increase in efficiency could be achieved. Now, that means, at a constant power output, there is 2.5MWe less heat consumption for a 40MW gas turbine. That is a whopping 2 million cubic meter savings of natural gas in a year if a power plant generates 350GWh at base load.

This paper deals with the study of using liquid hydrogen as coolant for a conventional gas turbine engine and therefore a new engine cycle or an unconventional engine system will not be studied. To keep the design changes minimum and cost effective, this paper looks for the possibilities where hardware changes could be kept minimum.

2 HYDROGEN COMBUSTION

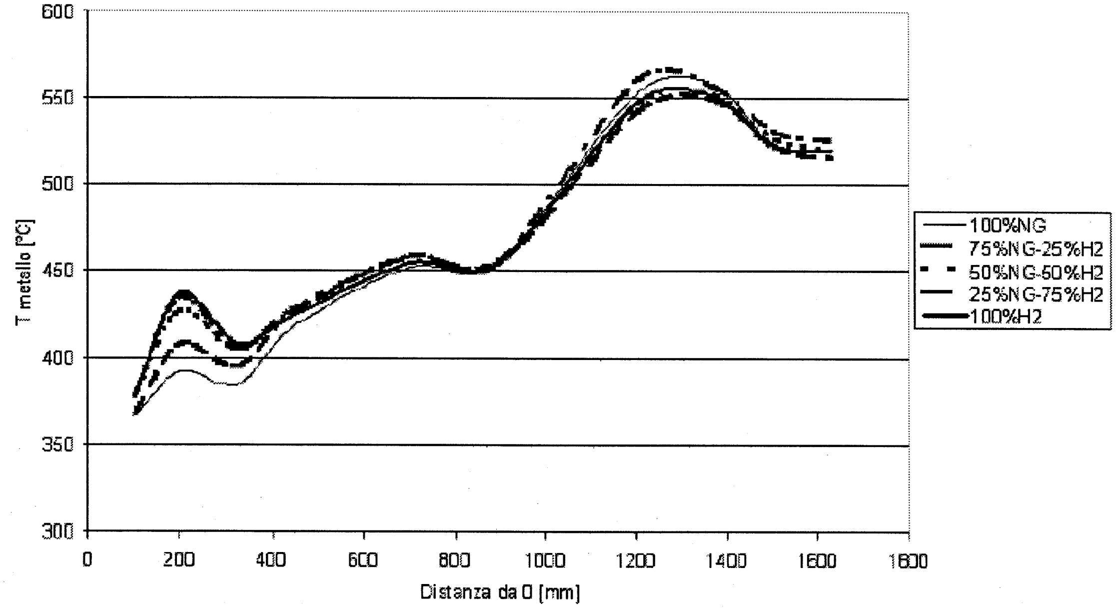

Fig.1: Temperature variation in a gas turbine combustor.

Before going in to the thermal management using liquid hydrogen, one needs to understand the liquid hydrogen combustion and in what manner it is different from other existing turbine fuel combustion. The Fig. 2 shows the temperature variation inside a combustor for methane and hydrogen. There seems to be not much difference in the temperature distribution except in the primary zones where temperature of hydrogen is high. This difference could be attributed to the way hydrogen combusts. The hydrogen combustion is different from the combustion of hydrocarbon fuel mainly in two ways, one, very fast combustion kinetics and two, lower and upper flammability range between 4% to 75%. During combustion, hydrogen develops a short and robust diffusion flames as it cannot be burnt within premixed flame combustion owing to very low ignition energy and its propensity to experience deflagration to detonation transitions. When burnt in a diffusion flame, hydrogen produces high NOx. To make the matter more complicated, steam in the exhaust leads to overheating of the HPT nozzle[11] [12].

This is where routing of liquid hydrogen becomes quite important; only if this could be achieved by minimum design changes.

Compared to the hydrocarbon fuels, hydrogen would certainly improve the fuel combustion characteristics, as the molecular weight of hydrogen is quite less. Assuming that the engine is equipped to handle high hydrogen combustion efficiency[$], a thermal management designer's task would be to ensure effective regenerative cooling

- to maintain engine structural integrity and
- to make sure that hydrogen reaches at right temperature and pressure in the combustion chamber.

And both of these challenges must be met in various power plant operating conditions.

One can obtain the combustor exit enthalpy (i.e. the enthalpy of the product, h_p) from the energy equation with the assumption that the combustion takes place under adiabatic conditions.

$$h_p = \frac{h_{in} + FAR\, h_{fuel}}{1 + FAR} \tag{1}$$

where h_{in} is the enthalpy at combustor entrance, FAR is the fuel-to-air ratio and h_{fuel} is the fuel enthalpy at the fuel injection temperature. With the aid of the definition of lower heating value (LHV; 120MJ/kg), we can write following expression for the fuel enthalpy-

$$h_{fuel} = \frac{1 + FAR_{stoich}}{FAR_{stoich}} h_{p,25^\circ C} + LHV - \frac{h_{air,25^\circ C}}{FAR_{stoich}} + \Delta h_{fuel}\Big|_{25^\circ C}^{T} \tag{2}$$

where FAR_{stoich} is fuel to air ratio for a stoichiometric mixture, $h_{air,25^\circ C}$ is the enthalpy of air and $h_{p,25^\circ C}$ is the enthalpy of products for stoichiometric mixtures of fuel and air at 25 degrees Celsius and steam. These expressions would allow one to calculate enthalpy at the combustion chamber exit and, also, provide the influence of fuel temperature at injection conditions as well as of LHV on engine performance. The effect of fuel injection temperature could be manifested in the TSFC. For a given thrust production, studies[13] show that specific fuel consumption is increased if hydrogen is injected in gaseous phase. Injection of gaseous hydrogen also causes a slight increase in the turbine entry temperature[§]. For a given condition, hydrogen powered, with gaseous hydrogen injection, has following advantages –

[$] This assumption seems to be quite reasonable as the TET would be fixed and there would be no major changes in the engine design.

[§] An increase in TET of 10K represents a thrust increase of the order of 2%, and a decrease on turbine life in 25%.

- The engine would run at a considerable lower TET when compared with a kerosene-powered engine, and
- TSFC would be much lower.

As the fuel is changed and (and hence combustion product too), for a given operating conditions, the effective minimum cross-section nozzle area is expected to reduce to allow for an effective engine matching[14]. Since a turbine nozzle is assumed to function under choked conditions, the area is given by the following formula

$$A=\sqrt{\frac{R}{\gamma}}\left(\frac{\gamma+1}{2}\right)^{\gamma+1/2(\gamma-1)}\frac{W\sqrt{T_0}}{P_0}$$

(3)

With a change in the fuel properties and exhaust gas composition, the exhaust nozzle throat area also would need modifications and it is quite easy to implement

3 LIQUID HYDROGEN AS A COOLANT

The heat sink capacity of hydrogen is due to its sensible heat (i.e., $c_p \Delta T$) and is therefore proportional to the maximum temperature the fuel can achieve and the magnitude of its specific heat. Gaseous hydrogen has a much higher specific heat (14.3kJ/kg-K at room temperature vs 1.0kJ/kg-K for air) than hydrocarbon fuels, and assuming that ΔT is the same, is considered to have a higher heat capacity than hydrocarbon fuels; however, as the energy content of hydrogen is quite high (see Fig. 2), less hydrogen mass is required to achieve a given amount of heat release. Hydrogen flow rate would be lower than that of a

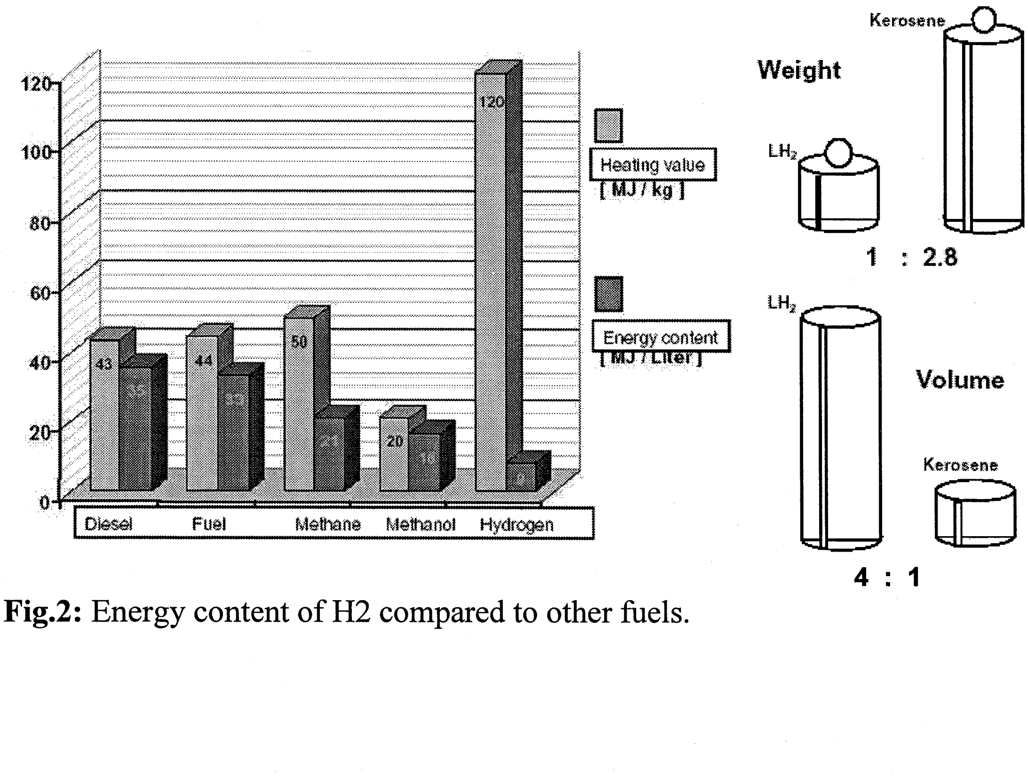

Fig.2: Energy content of H2 compared to other fuels.

hydrocarbon fuel. A more relevant measure of heat sink potential is the ratio of specific heat to the heat of combustion, which brings hydrocarbon fuels more in line with hydrogen in terms of heat capacity (within a factor of 2 or 3). Thus, it is not so much the specific heat of hydrogen that gives it better heat capacity than hydrocarbon fuels but rather its ability to sustain higher temperatures and thus increase the ΔT part of its heat capacity.

The regenerative cooling technology has been in use for quite a long time in liquid hydrogen powered rockets and these days with the use endothermic hydrocarbon fuels, it is also being used in modern aircraft engines. Such fuels can absorb energy from an engine and help to vaporize high-density fuel or change the chemical composition of the fuel before it enters the combustion chamber. In case of liquid hydrogen, the expansion of liquid hydrogen to lower injection pressure creates an endothermic (heat-sink) expansion reaction where the liquid hydrogen absorbs heat as it expands from a higher to a lower pressure. When the hydrogen is injected as a gas, it increases the temperature and also it does not need additional heat to change phase from a liquid.

4 REGENERATIVE THERMANL MANAGEMENT

Implementation of thermal management for liquid hydrogen powered gas turbine engine has two objectives and these objectives are to be met without major changes in the existing engine –

- To inject hydrogen in gaseous state (liquid hydrogen needs to be heated to about 200K prior to injection) and
- To improve the TSFC

If one thinks of routing liquid hydrogen through various hot spots across the engine, one can think of cooling combustor walls, exhaust nozzle, and nozzle guide vanes. Of course, for all of these options, necessary modifications need to be carried out. Although, modifications would be minimum for the case where exhaust nozzle is being cooled but maximum benefit could be obtained from the third option. Cooling of nozzle guide vanes would allow significant increase in the turbine entry temperature (TET). But from the sec. 2, it is clear that no such cooling arrangement would be required.

As far as a combustor is concerned, it absorbs energy form the combustion products by convection and from the flame by radiation. The absorption of radiation follows the same laws as those of emission. However, a highly reflective surface on the inside wall of the chamber would reduce absorption and lead to lower wall temperature. The amount of heat transferred by conduction from the combustion products to the combustor walls would be negligible. The combustor, would loose energy to the outer casing by radiation and to the cooler air along the outer surface. But this loss is not sufficient enough to keep the temperature below the critical limits. A common practice is to employ the technique of film cooling where a film of cooling air is swept along the inner surface that not only insulates the surface from the hot gases, also removes energy absorbed by radiation. Although empirical relations for predicting heat transfer rates through film cooling are available[15], but because of the complex nature of heat transfer process and its dependence on combustion products, it is not possible to predict the wall temperatures through energy balance equations alone.

In modern aircraft engines high TET insures that fuel rich mixture is used for combustion. That means the flow of air inside the combustor is controlled and the amount of air for film cooling would be limited. Another factor, along with the higher TET, is higher cycle pressure ratio for an optimum cycle performance. This in turn indicates that the air leaving the HPC would be quite hot. For TET 1500K and beyond, film cooling looses its advantage[16]. But as long as an existing engine is used with the fuel it is designed for, one need not to look into all these issues. But when an engine that is designed to burn a hydrocarbon fuels, would be running on hydrogen, these issues becomes critical, specially where maintenance cycle of the system have to be kept large.

4.1 OPTIONS

One can go for regenerative cooling using various possibilities. One of them would be to use heat exchanger and other would be route the liquid hydrogen through various hot spots (preferably exhaust nozzle) and use low temperature hydrogen too cool compressed air just after the HPC. But as stated, changes in the existing engine have to be minimum. We will these options one by one. With heat exchanger option there could be following possibilities-

- The heat exchanger is in the mainstream where all gases flow through it – the heat exchanger could be placed just after the LPT. But since thrust concept is going to produce thrust, which depends on temperature available after LPT so heat exchanger at LPT exit would reduce thrust output. Better bet will be to put heat exchanger at nozzle exhaust.
- A part of the mainstream flow is bled through the heat exchanger that later on merges with the mainstream flow. Following alternatives could proposed –
    i. The air is bled after the LPC and mixes with the jet stream just after the LPT - This will lead to huge losses in the mixer plane.
    ii. The air is bled from the HPC and mixes with the jet stream after LPT - This will also lead to huge losses in the mixer plane. Also this will lead to choking in the mixer plane destabilizing the whole compressor.

In the second option (see Fig. 3), as indicated above, liquid hydrogen could be routed over the exhaust nozzle (combustor and nozzle guide vanes seems to be not in any need of any extra cooling) through heat pipes. A heat pipe that caries liquid hydrogen receives heat from exhaust nozzle through convection, conduction and radiation. Material compatibility would be a crucial factor in the design of these heat pipes as different feed system metals will have different effect on the phase change (or gasification) of liquid hydrogen[17]. A liquid hydrogen pump is required to pump the liquid hydrogen to pump the hydrogen through heat pipes. After that, gaseous hydrogen that is still below 200K is passed through an intercooler that is kept between LPC and HPC. Hydrogen is injected in the combustion chamber at a temperature of about 200K. The completely untapped exhaust heat, then, would be used to heat a boiler for a steam turbine.

The advantage of putting an intercooler would be to reduce the temperature of the air entering the HPC and hence lower □T for the same cycle pressure ratio. That also means effective film cooling at the combustor walls as the temperature is reduced due to hydrogen intercooler. To make sure that the hydrogen, that reaches to the combustor chamber, is at right pressure and temperature, a fuel flow control software would be required. Second point that is to be kept in mind, that the pressure of hydrogen in the heat pipe should always be above the critical pressure so that the boiling of hydrogen could be avoided during the phase change[14].

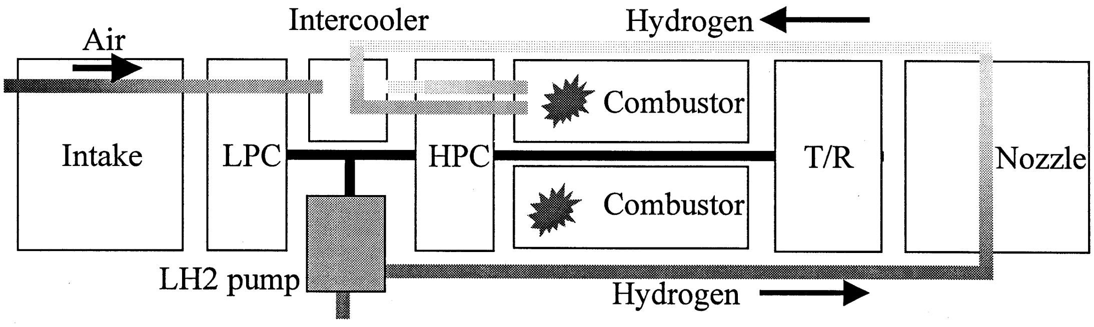

Fig. 3: Schematic of regenerative cooling flow path.

4.2 Heat Transfer Calculations

In almost all designs and operations of a gas turbine engine, considerable heat is transferred, and the phenomena of heat transmission often control the proper functioning of the units. A simple heat transfer analysis of regenerative cooling would consist of studying the steady heat transfer from hot gas through a solid wall to a cool liquid.

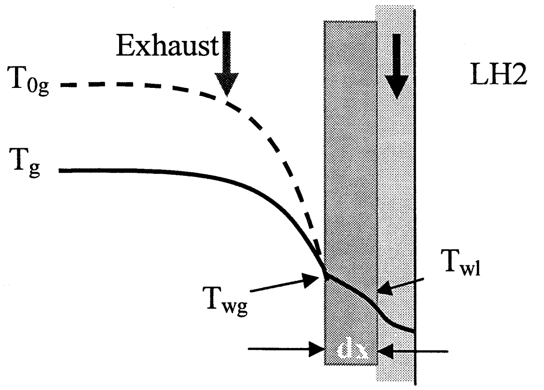

Fig. 4: Schematic of regenerative cooling.

Conductive Heat Transfer through the solid wall is given by

$$q=\frac{Q}{A_w}=-k_w\frac{dT}{dx} \tag{4}$$

where q is the heat flux [W/m2], Q is the heat transfer rate [W], A is equivalent surface area [m2], k is thermal conductivity [W/m-K]. The convective heat transfer from the hot exhaust gases to the nozzle wall and from nozzle wall to the liquid hydrogen is given by

$$q=\frac{Q}{A}=h\,dT \tag{5}$$

where h is the heat transfer coefficient [W/m2K].

Therefore

$$Q=h_g\,A_g\,(T_{0g}-T_{wg})=k_w\,A_w\,(T_{wg}-T_{wl})/dx=h_l\,A_l\,(T_{wl}-T_l)=\dot{m}C_p(T_{injection}-T_{entry}) \tag{6}$$

or

$$q=\frac{(T_{0g}-T_l)+q_r/h_g}{\left(1/h_g+dx/k_w+1/h_l\right)} \tag{7}$$

or

$$q=\frac{(T_{0g}-T_l)+q_r/h_g}{\left(1/h_g+A_g\,dx/A_w\,k_w+A_g/A_l\,h_l\right)}$$

where T_{entry} is the liquid hydrogen temperature at the beginning of the regenerative cooling, $T_{injection}$ is the hydrogen temperature at the combustion entry, T_{0g} is the combustion temperature, A_g is the gas side area, A_w is the effective wall area, A_l is the effective liquid side area, and q_r is the radiation heat transfer and this could be neglected. We need to provide conductivity data for hydrogen as a liquid as well as vapor at varying temperatures. If exact values are not available, empirical relation could also be used. In case empirical values, one needs to reverse engineering and do backward calculations from assumed values of the heat transfer coefficients till the necessary temperatures are obtained. Also the shape and size of the heat pipe is also going to play a major role in the regenerative cooling process.

4.3 Losses in cooling passage

The passage through which liquid hydrogen would flow, should be designed in such a manner so that it absorbs all the energy transferred across the walls, wherever this cooling is employed, while keeping the pressure drop in passage minimal. For better cooling performance, high fuel velocities are required, but incidentally, high pressure losses are associated with those high velocities which in turn would require powerful feed system. A typical pressure loss could be calculated as follows-

$$\Delta p = f\left(\frac{L}{D}\right)\rho\frac{\overline{v}^2}{2}$$

(8)

where f is the friction factor, L is the cooling passage length in [m], D is the hydraulic diameter [m], $\overline{v}$ is the mean flow velocity [m/s] and ρ is liquid hydrogen density [kg/m3]. Once the liquid hydrogen injection rate and the passage area are known, pressure drop could be calculated. If one can estimate the areas where the energy transfer from the hot combustion gases would be maximum, the rate of transfer could be increased by increasing the liquid hydrogen velocity.

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