A Review on Advancements and Characteristics of Cryogenic Propulsion Rocket Engine

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A Review on Advancements and Characteristics of Cryogenic Propulsion Rocket Engine

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Abstract: Future space exploration missions will require the synergistic integration of potentially lightweight, high thrust producing, and environmentally sustainable rocket engines. This article guides through one such capable rocket engine, the cryogenic propulsion rocket engine and some cutting-edge characteristics and novel engineering advancements affiliated with it. A typical cryogenic-propulsion rocket engine works similarly to all other LPRE's (Liquid Propellant Rocket Engines), in which the primary fluid (Cryogenic fuel 1) reacts chemically to get vaporized and get ignited by an oxidizer to provide extremely hot rocket thrust that escapes the engine nozzle and generates thrust from the combustion process. Considerable efforts have been made to optimize the engine's performance and reliability in order to utilize the most desirable output from it. Therefore, a brief overview of the different models and research approaches associated with it to provide predictions and results about the stability, dynamics, and cooling characteristics of the given engine configuration is presented.

Keywords: Propulsion, Cryogenic propellant, Liquid rockets, Cryocooler, Combustion, Regenerative cooling

1. Introduction

Effective human exploration of the solar system in the future will only be possible with engines capable of producing high thrust and specific impulse due to the ever-growing payload mass demands, and an engine that accommodates these requirements efficiently in the current industry is a cryogenic propulsion rocket engine. In 1877, Louis Paul Cailletet and Raoul Pictet experimented with liquefying oxygen gas[1–3], in which this liquefaction process prefigured the beginning of low-temperature science, the cryogenic technology. During World War II, however, this technology was further explored for propulsion applications with the development of the V2 rockets, which used cryo-fuels liquid oxygen/kerosene. Finally, with the deployment of the world's first cryogenic rocket engine, the RL-10 engine for NASA's upper-stage Centaur space launch vehicle in 1963[4], cryogenic rocket technology's possibilities in the aviation sector became more prevalent. As a result of the RL 10's remarkable range of spin-offs and phenomenal confidence level in the design, construction, and handling of cryogenic systems, as well as due to its feasibility in rocket technology, several space organizations and companies around the world became engaged and started building these systems indigenously for sustainable exploration beyond the Earth[5–7].

Cryogenic fluids are those fluids that are gaseous at room temperature but are preserved at low temperatures below their boiling point (below approximately -150ºc), and a conventional cryogenic-propellant rocket engine operates similar to LPRE's (Liquid Propellant Rocket Engine), but instead use at least one cryogenic fluid to propel. It consists of i) separate tanks for storing different cryo-propellant(s) and oxidizer, ii) an axisymmetric nozzle with iii) a combustion chamber, iv) a system for injecting propellants into the combustion chamber, v) a nozzle throat and vi) a convergent-divergent section[8]. These low-temperature power generating engines generally workon either one of thermodynamic cycles such as the expander cycle, gas-generator cycle, staged combustion cycle, and even in Rankine cycle [9] - Organic Rankine cycle[10,11] (same as Rankine Cycle (RC) in terms of its working principle, except fluids).The utilization of each cycle depends solely upon the mission complexity. The primary fluid (Cryofuel 1) is vaporized and get ignited by an oxidizer to provide typical hot rocket thrust, i.e., they (primary fuel and oxidizer) react chemically to produce a super-hot stream that escapes the engine nozzle and generates thrust from rapid expansion from this liquid to gaseous state.

The behaviour of cryogenic fluids gives rise to plenty of phenomena that take on a different significance when compared to the actual behaviour of fluids at room temperature. Therefore, several problems are likely to occur from an experimental perspective during the development of these engines until their successful launch. Due to the cryogenic quality and after-effects associated with these propellants, causes difficulty in operating it in multiphase conditions. Therefore, understanding the experimental setup and test conditions of this engine, in aligning with the selection of proper measuring approaches to extract quantitative facts about its properties is vital, so that it would be easy to devise strategy for avoiding the potential risks [12–14].

2. Propellant Combinations

The fuel and oxidizer used to produce the propellant in a LPRE like cryogenic engine are extremely cold, liquefied gases. These liquefied gases are actually super-cooled gases used as liquid fuels and the reason why it is referred to as super-cooled is because they remain in liquid phase, despite that they are below the boiling point. It is very critical to understand the characteristics and properties of these liquids (the non-reacted fuel and oxidizer liquids) and those of the hot gas mixture released by the combustion chamber reaction. The properties and characteristics however, depend on the chemical composition of the propellants, i.e. a high chemical energy content per unit of propellant mixture and a low molecular mass of resultant gases is preferred and ultimately has a significant impact on obtaining high engine performance. This resultant performance of the engine can be examined by analyzing and calculating the propellant density, the specific impulse, mixture ratio and certain other parameters under operating conditions with high degree of accuracy [15].

Table 1. Characteristic of Few Cryogenic Fluid Combinations[16]

Oxidizer	Fuel	Mixture ratios (r_{of})	Specific Impulse (I_{sp})	Density (in kg/m^3)
Liquid Oxygen	Kerosene	2,77	358	820
	LH_2	4,83	455	700
	LCH_4	3,45	369	430

Refer Table 1, this comparative analysis helps understand the properties of recurrently used cryogenic combinations such as their specific impulse properties, mixture ratios, and density variation. Out of these propellants, currently LOx (Liquid Oxygen) /LH2 (Liquid Hydrogen) combination is used in most cryogenic engines to utilize the relatively high thrust and delta velocity, especially in their upper stages. So here in this article this particular propellant combination is focused while compared to others.

2.1LOx - LH2 Propellant Combinations

The hydrogen gas and oxygen gas is super cooled to a temperature of -423 degrees Fahrenheit (-253 degrees Celsius) and -297 degrees Fahrenheit (-183 degrees Celsius) respectively into liquid states (LOX and LH2) to accommodate in a smaller, lighter tank[17,18]. The LH2 and LOX are fed into the combustion chambers of the engine once they are in the tanks as the launch countdown approaches zero. The hydrogen in the propellant interacts rapidly with oxygen to produce water when it is ignited. A tremendous amount of energy is produced along with superheated water (steam) in this "green" process. As a result, a great amount of heat is produced that significantly drives the water vapour to expand and flee through the nozzles at about 10,000 mph or more. Thereby the force that propel the rocket to rise off is generated by all of that fast-moving steam. Cryogenic LH2 - LOx however, isn't simply a great combination because of the ecologically friendly water reaction, whereas it's all about due its incomparable specific impulse (Isp) capability [19]. Behind the scenes,the specific impulse of an engine is swayed by propellant combination and their mixture ratio. When looking at the Fig 1, it is almost clear that LOx-LH2 when blend together results in producing peerless specific impulse effect.

Notardonato[20]has claimed that the LOX/LH2-based engine is the only engine in the industry so far that outperforms any practical chemical propellant mixture there-by operating at the highest efficiency. Apart from propulsion point of view, he also described that, long-term cryogenic storage will also be possible with these cryo-fluids, due to its advancements in active and passive temperature management, thus making these propellants nearly as “storable" in space as hypergols. The propellant combination analysis performed in NASA’s Titan Orbiter Polar Surveyor (TOPS) mission[21,22]set forth that a LOX/LH2 propelled missions saves 43% launched mass compared to Methyl hydrazine (MMH) and Nitrogen Tetroxide (NTO) hypergolic based missions (used in LPRE’s before cryo-propellants) due to their notable specific Impulse. Here, a twin circuit was used to regeneratively cool the chamber in which the throat would be cooled with LH2, while the nozzle would be cooled with LOx, so as to improve chamber life and thereby to increase the engine thrust. In addition to this, during the development stages of ISRO's in-house GSLV Mk 3 project[23,24], its LOX/LH2 based upper stage engine(CE20) was revolutionary at the time to operate in the gas generator cycle and was sufficient to attain a specific impulse of 443 seconds in a vacuum and operating thrust range between 180 kN to 220 kN, which was indeed a ground-breaking news to the aerospace community. All key elements like as atomization, vaporisation, reaction, mixing, thermal loads, nozzle performance, and engine stability were taken into consideration while designing the CE20's thrust chamber. Similarly, the advancement of this combination is even observable in commercial sea launch technologies and projects. For example, the medium-lift Chinese rocket CZ-8A/RH[25] was launched at sea and contained a second core or upper stage process operating with LOX/LH2 engines, resulted in the improved feasibility and commercial value of launching cryogenic liquid-fuelled rockets at sea.

These cryo-fuels (LOx and LH2) typically have a lower volumetric energy density than most other fuels, and being bulky, large volume tanks are necessary for accommodating these propellants, which significantly arises drag penalties. These penalties aren't however significant enough to surpass its high specific impulse and thrust generation capability [26].

2.2Substitutive Combinations

When comparing the various other existing combinations, based on performance and cost factors, the LOx/LCH4 (Liquid Methane) is also regarded as a prime candidate propellant for operating the cryo-engine with a pressure-fed system.

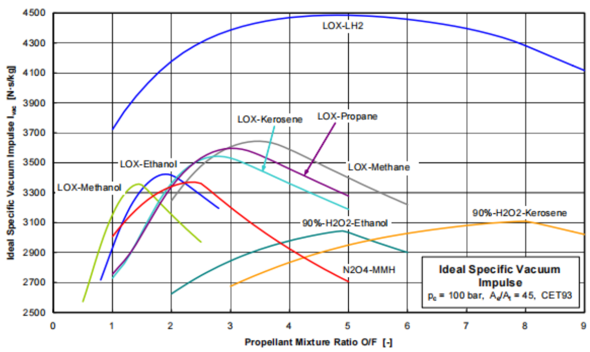

Fig 1. Variation of specific impulse properties due to the propellant combination and the mixture ratio [16]

Since it is highly-performing, non-toxic, relatively easy to handle during launch process, liquid methane propulsion adapts itself effectively to a broad spectrum of rocket applications. After inspecting the additional advantage of generating it from in-situ resources on Mars and the Moon (Presence of Methane (CH4) in the Martian atmosphere and Liquid Oxygen (LOx) in the Martian and Lunar soil), there has been some considerable progress made in studies linked to the LOx/LCH4 combination for future missions [27–29]. According to the Propulsion and Cryogenic Advanced Development (PCAD) Team,[30]LOx/LCH4 is a potential contendor for Lunar and Mars missions, due to the estimated 600- to 800-lbm mass reduction over more typical hypergolic systems. Concerns were raised at first that LOx/LCH4 ignition would be impossible to achieve, but a series of trials eventually led to the development of advanced high-performance cryogenic propulsion systems with decreased LOx/LCH4 ignition.

Likewise, a trade-off analysis between the conventional propellant kerosene and cryogenic fuels (particularly LH2 and LNG) is being conducted, gradually concluding that liquid hydrogen and LNG (mainly consisting of methane, CH4), when produced sustainably, can be a viable candidate for laying the foundations to carbon-free aviation and will be efficient at increasing the engine thrust. Incorporating LNG or LH_2 combination with appropriate CO_2 sequestration technique (Carbon dioxide sequestration is the method of preserving carbon dioxide in reservoirs for prolonged periods of time in order to minimize it from accumulating in the atmosphere[31]) seeks great attention in achieving the carbon-free propulsion. As conventional kerosene burnt, it releases CO_2 (Carbon Di-oxide) and NOx (Nitrogen Oxide), which interfere with the atmosphere and trigger pollutants around [32].

Contradicting to these various advantages offered by the above-mentioned substitute combinations (LCH4, LNG), the current TRL (Technology Readiness Level) of these 'going to be revolutionary' propellants isn't that impressive when compared to the dominant LOx/LH2 combination. However, we can't neglect the possibilities of these substitutes surpassing the LOx/LH2 in the near future too.

3. Combustion Dynamics & Instability

Combustion dynamics and control are already pressing priorities in energy and propulsion technology. Along with the origin of cryogenic rocket engines in the early 1950s, former Soviet Union and the US's fundamental efforts to analyse the combustion dynamic of these systems were evident. They were completely dependent on manual experimental data, trial and error procedures, and primitive analytical tools, because the optical imaging, computing power, numerical approaches[33] and other modern techniques were all in their infancy at the time [34]. In cryogenic engines such as the RL-10 and J2, using multitube concentric-orifice element injectors[35] completely eliminated the challenge of instabilities. Gradually, adequate changes were necessary to increase the engine's capability and thereby these updations brought the issues of combustion instability into the picture. Later on, there came a point when manual approaches like trial and error procedures, etc. became impractical and economically unfeasible, such that computational simulations[36] and other state of the art diagnostic techniques were necessary to evaluate the realistic conditions of the system undergoing combustion. Since then, a substantial deal of progress was achieved and combustion analysis methodologies of a cryogenic engine progressed from a basic science to a more complex art.

In a typical combustion chamber, the resultant flow due to chemical reaction is turbulent, reactive, and fluctuates between subsonic and supersonic speeds. As a result, combustion instabilities are likely to arise due to the system's combustion, resonant modes and fluid dynamics combination and have long been recognised as a major concern in cryogenic engine development. The types of instabilities usually found in a cryogenic rocket engine are illustrated in Table 2.

Among those (refer Table 2), the high-frequency (HF) - thermo-acoustic (chamber instability) instability that results from the interaction between the combustion process and the chamber acoustics are portrayed as the most detrimental[37–39]. These instabilities result in extremely unstable heat transfer rates, accelerates the combustion process by shortening the flame, leading to local burnout of the combustion chamber walls, injector plates, and severe damage to the propulsion system.The shortened flames are actually the visible outcome of accelerated mixing and evaporation of the reactant infused as liquid droplets, a particular phenomenon that is observed usually in tests and simulations done at trans-critical conditions[40–43].Indeed, the irregular heat emission during combustion may be seen as an acoustic source that transmits perturbations caused by soundalong the combustor. When pressure waves heading beyond the source strike the acoustic barrier, they begin to bounce off or reflect towards the flame, generating velocity irregularity and acoustic pressure in the proximity of injector plate. This results in modifying the incoming propellant flow and results in local fluctuations to the unbalanced heat release rate. If the burning rate is swayed by these acoustic oscillations, the severity of the instabilities inside the reaction slot increases, hence causes enhanced oscillation of flame. As a result of this unstable heat release fluctuations, increased amplitude acoustic disturbances are developed, accelerating the build-up of instability [44]. Considering all these complex phenomena inside the engine, adding baffles, resonators or cavities was initially thought to be viable enough to decrease the oscillation level and make the system stable. Using these devices however were just a partial fulfilment for a broad subject like this.

As per experimental studies in the field of HF thermo-acoustic instability Externally produced perturbations are inflicted under rocket-like injection scenarios, perhaps cold-flow or combusting, to evaluate injection and combustion dynamics under simulated instability conditions.Woschnak et al. [45] studied thermal transfer characteristics in a LOx/H_2 combustor containing longitudinal mode HF instability. During the study, it was discovered that raising the chamber pressure above critical affected the relative strength of particular transfer functions in the measured oscillation spectrum substantially. These findings were helpful in understanding that injection of fuel into a supercritical environment has a significant impact on the interaction of acoustic waves with the atomization and combustion processes.

In support to this, DLR facility[46] performed a comprehensive analysis of injection settings in a sub-scale combustor known as ‘Combustor C' (BKC). Here, thepressure due to hydrogen injection dropped below 20% of pressure inside the chamber enabled different degrees of unstable combustion to evolve at subcritical conditions. The first longitudinal (1L) acoustic (HF) mode within the chamber was observed along with an injection coupled Low Frequency (LF) mode. Whilefunctioning at or over the oxygen’s critical pressure, however, there was no evidence of instability. Later, a similar experiment [47] was conducted using the same BKC probe. This time LOx/CH4 combinations was used and OH* emission patterns with and without recess were contrasted within subcritical and supercritical chamber pressure conditions. Changes in the shape of the jet and intensity of emission, soon past the injection were noticed to be apparent during functioning with a recessed injector and were found to be sharper at supercritical pressure than for subcritical. Additionally, similarvariationweren’t detected when a non-recessed injector was used. More accurate and validated results were obtained when probe setups Combustor H and Combustor D were used to study the thermo-acoustic instability. These setups are considered as a more potential successor of Combustor C (BKC). Combustor H is a multipurposesubscale rocket thrust chamber that exhibits spontaneous acoustic resonance of an engine running on LOX/LH2 propellants, while Combustor D evaluated the resultant flame under forced acoustic interactions and perturbations (see [28] for detailed information).

Table 2. Types of Combustion Instabilities

Type of combustion instabilities	**Description**	**Example**
Chamber instabilities	Instabilities caused by combustion within a chamber	• Thermo-acoustic instabilities • Shock instabilities • Fluid-dynamic instabilities associated with the chamber, etc.
Intrinsic instabilities	Instabilities that arise as to if combustion occurs within or outside of a chamber	• Chemical-kinetic instabilities • Diffusive-thermal instabilities • Hydrodynamic instabilities, etc.

System instabilities	Instabilities caused by combustion process coupling in the chamber and other areas of the system	• Feed-system synergy • Exhaust-system synergy, etc.

A wide variety of theoretical and pragmatic methods, such as setting up a Lattice-Boltzmann Model(LBM), CFD simulations[48,49], Shadow-graphic Imaging, and Lumped parameter modeling, were used to visualize the instability pattern in these simulated probes and these approaches were convenient in evaluating the combustion instabilities and the behavior of the cryogenic propellant under realistic LPRE conditions (transient, injection, and ignition), thereby delivering better, sharper results.

In case of the LBM, McNamara and Zanetti[50] were the first to develop it and these equations have been extensively employed to simulate fluid flow conditions since then[51]. Over the last three decades, the LBM has matured into a viable alternative to the traditional Navier–Stokes equations for modelling turbulence and multiphase fluid systems of the cryogenic combustion[52]. It offers the benefits of handling with complicated boundaries, combining microscopic interactions during the burning process, and dynamic replication of the interface between different phases as compared to conventional CFD approaches[53–55]. Similarly, the multiple injector combustor (MIC), which utilizes five coaxial injectors to construct a thermo-acoustical environment and monitor flames at subcritical or trans-critical conditions, was regarded as a potential contender to investigate if contact between flames from adjacent injectors might be a key procedure for supporting instability in combustion. The propellant mixture LOx/H2 was first employed[56], but this was later replaced with LOx/CH_4[57] to utilize the advantage of obtaining lower injection velocities and hence flames that are more responsive to acoustic oscillation. The oscillation level, which reached roughly about 8% of the chamber pressure, however wasn't adequate to approximate the extremely high oscillation amplitudes found in engine thrust chambers. Therefore, a more advanced, very high amplitude modulator (VHAM) was integrated with the MIC and was used to stimulate transverse, thermo-acoustic modes and investigate their effects on flame dynamics under intense fire condition[41]. The Propulsion System Centre team of ISRO [58] conducted a thermo-dynamical analysis, thereby using one, two, and three-dimensional simulations that could reliably predict the thrust chamber's thermal characteristics. Those obtained results and simulation tools were validated and was advanced enough to diagnose the safe operation of the engine during hot test conditions.

In regard to the above-mentioned state of the art studies and approaches, a lot of vital experiments were/are being put into trying to learn and regulate the combustion dynamics of the engine's combustion chamber, so-as-to reduce the likelihood of combustion instability. After validating each of those methodologies, most of their experimental data and preliminary results were found to be ingood agreement. However, despite decades of study, the ability to forecast each mode of combustion instability empirically based on physio-chemical parameters, engine and its operating characteristics has yet to be achieved.

4. Cooling System

Usually during operational conditions, it is observed that the thrust chamber of a cryogenic rocket engine is subjected to severe conditions, with elevated pressures of up to 30 MPa and temperatures reaching 3500K, such that an increased heat transfer rates is resulted in the thrust chamber (as high as 100 MW/m2). i.e. the oxygen combustion produces extremely high temperatures and pressure in the thrust chamber and these high thermodynamic circumstances combined with diffusion flames burning near stoichiometric ratio can result in concentrations of burned gases exceeding this 3500 K range[59]. When such hot concentrations approach the combustion chamber walls, intense heat fluxes and extremely high temperatures occur, which may transcend the material's thermal resistance. Local heat flux values fluctuate throughout the thrust chamber wall depending on geometry and design factors, however the highest heat flux is seen proximal to the nozzle - throat area. Figure 2 illustrates a typical heat flow pattern along the thrust chamber wall.

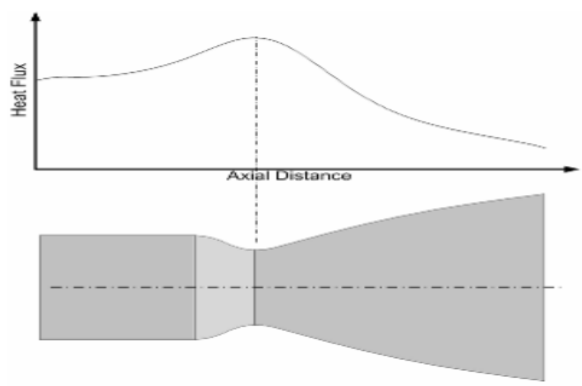

Fig.2: Heat flux variation at thrust chamber [60]

Meanwhile studying the post-launch conditions, the heat from the Sun and other celestial bodies in the proximity of the vehicle, as well as the conducted heat to the cryogenic storage tanks from other sources on the rocket, is predicted to influence the cryogens(fuel) to pressurize or boil off (i.e., liquid to gas phase change). Due to the boil-off conditions, the available energy can't be used efficiently, thereby deducing that increase inboil-off ratelead to a possibility of a great thermodynamic energy loss. As a function of these different venting process, the propellant quantity would be inadequate for running the engine during long-duration missions.

Considering these two significant scenarios that could cause the engine to be inefficient, or may be destructible, there has been a necessity of an effective cooling [61]techniques and systems for enhanced reliability and reusability of the engine. For heat management of cryo-rocket engines, a variety of cooling techniques such as regenerative cooling, film cooling, ablative cooling, and radiative cooling are employed in order to keep the wall temperature of engines within the material limit. However, regenerative cooling and film cooling are two of the most used methods.

4.1 Regenerative and Film Cooling System

Being a high thrust and extended burn engine such as the cryogenic engine, the regenerative cooling technology is widely employed to provide cooling due to its globally accepted high efficiency [62–64] Initially the coolant (fuel itself) is preheated and is then fed to flow along a counter-current direction through an annulus or channels of the thrust chamber wall and subsequently around the nozzle walls (see Figure 3).

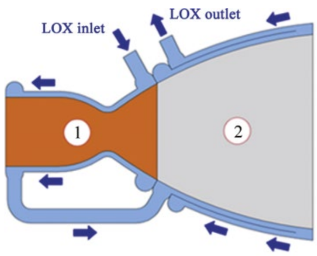

Fig.3: An illustration of regenerative cooling

Here, the amount of heat vented from the reactant gas is recovered ("regenerated") using the employed liquid such that there occurs very reduced possibility of heat getting escaped[65]. This technique necessitates both flow and heat transfer estimation, since the high-speed exhaust flow inside the nozzle is coupled with low-speed coolant flow surrounding the nozzle. As a result, convection is meant to transmit heat from the hot gas to the wall, then conduction through the wall, and lastly convection again, from the wall to the coolant. Since the propellants are preheated, regenerative cooling helps to improve combustion efficiency and therefore increasing the enthalpy. In support to this, Pizzarelli's[66] studied that preheating the fuel by heat energy absorption improves the exhaust velocity by around 1.5 percent. Eventhough this may appear as a slight change, but at the high exhaust velocities seen in rocket nozzles, it may be extremely beneficial. In regard to the Fig 2, utilizing the advantages of regenerative cooling at the throat, allows for significant temperature control without compromising performance.

When combining oxygen regenerative cooling technique with semi-expander cycles, reduction in the specific impulse losses of the engine were observed[67]. Regenerative cooling with oxygen allowed a considerable and feasible improvement in specific impulse and the associated semi-expander cycle was found to be efficient in offering additional advantages like roll control and propellant tank pressurization.

Correspondingly, the film cooling technique in cryo-engines is the phenomenon of introducing of a thin layer of coolant or cryo-propellant through orifices all over the injector perimeter or through manifolded orifices in the chamber wall at the injector/chamber throat area, thereby offering protection from excessive heat[68]. A richer fuel is delivered through the periphery injectors, because the rich fuel burns at a reduced temperature, resulting in a lower temperature on the surrounding wall than if the burning was near to stoichiometric. The film layer blends with the core flow and finally disappears as it goes downstream toward the nozzle and beyond. The efficacy of film cooling majorly depends upon the richness of the Peripheral Injector flow. i.e. when the injected film is highly rich, or if it's a pure fuel, maximum cooling is achieved. As the film layer's richness approaches the stoichiometric condition, cooling is far less efficacious. Film cooling is typically applied in conjunction with other cooling techniques such as regenerative cooling in high heat flux regions and is beneficial in increasing the chamber life of engines[69,70].

The origin of film cooling research may be traced all the way back to the late 19th century, to the days of Reynolds [71] who investigated the behaviour of vortex rings - that is strongly linked to film cooling jet modelling. However, Wieghardt[72] is credited with introducing the use of a fluid coating (a kind of film cooling) to protect surfaces in the aerospace industry. He used this technology to de-ice aircraft wings by pushing warm air across them. Later in the 1950's, film cooling for rocket combustion chambers was first studied and since then, various research investigations and approaches for predicting the efficacy of film cooling have been devised. Gradually the role of film cooling became significant in the advancement of reusable and booster rocket engines, as re-evaluated in[73]. This technique has been already implemented and was found efficient in reducing the thermal stress in systems like SSME (Aerojet Rocketdyne RS-25), F-1, J-2, RS-27, Vulcain 2, RD-171 and RD-180.

4.2SubstitutiveCooling Techniques

Using passive and active insulation systems seems to be a less complex technique to reduce heat flux. The passive insulation systems that meet these requirements includes multi-layer insulations and active heat removal systems such as Cryocoolers, Thermodynamic Venting System (TVS) can manage and reduce the fluid temperature and heat leaks respectively [74]. Since the early space programs (which began in the 1950s) and after the development of 80K Stirling long life coolers, used in the Improved Stratospheric and Mesospheric Sounder (ISAMS) and Along-Track Scanning Radiometer (ATSR-1) instruments [75,76], countless experiments have been performed to come up with a feasible state of the art technique. However, maintaining the temperature of the cryo-fuels as low as possible while still holding the Zero Boil Off (Zero Boil Off) point was extremely difficult. An efficient TVS can control the pressure in the propellant tank and at the same time reduce the thermal stratification and eliminate environmental heat leakage. By enabling indirect venting of vapor through heat transfer between the discharged fluid and the fluid stored in the tanks [21], this phenomenon of implementing TVS can be achieved. For example, the article [77] deals with the analytical modeling and the developments of ZBO systems to minimize the effects of zero gravity on fluid and thermodynamic activity by utilizing this TVS-Cryocooler techniques. In addition to that, the Cryogenic Boil Off Reduction System (CBRS)[78,79]and 90K -20K cryocooler setups [80] provided the scientific community with prolific test results in maintaining an exploration vehicle's propellant mass parameters by minimizing the thermal gradients and further allowed robust pressure control in the propellant tanks. Using Highly Effective Heat Insulation (HEHI) materials such as polyethylene terephthalate film and glass wool lining on the sides of the tanks, along with the cryo-pump designs using CaE-4B, Ca-H, carbon fabric adsorbents to limit boil off in reservoirs was suggested by Gorbaskii et al. [81]. A new system that avoids clogging of the mixing chamber was a result of their experiments. Therefore, the issue of storing the propellants for an extended period could be effectively solved. In order to achieve similargoal of maximum cryo-fuel storage and cooling efficiency,[82] conducted numerical analysis and simulations to track the boil off rate and obtained a feasibleexergetic efficiency[83,84] (storage efficiency of a system without energyloss) among different cryogenic LNG ISO-tanks using *COMSOL* tool.

Similarly, the strategy by using a recirculation chill-down mechanism for cooling the turbopump for long-duration space explorations have been addressed in [85].In regard to the recirculation chill mechanism, the enthalpy of the propellant is expected to rise considerably to chill down the turbopump, when the propellant from the tank is extracted into the engine using a cryogenic pump via feedlines. Then this extracted propellant is recirculated vice versa without getting vented elsewhere to recover the radiant energy vented from the engine. This recovered heat can be substituted to heat the inert fluid for pressurizing one or more propellant tanks and is advantageous in limiting the use of additional devices (electro-thermal systems) required to boil the inert fluid, thereby minimizing the onboard weight of the launcher.

5. Conclusion and Future Outlook

Since the beginning of this low temperature technology, it has been apparent that the theoretical and practical study of cryogenic characteristic engine is highly challenging and often falls short during each development process. This review has examined the characteristics and research activities associated with the cryogenic rocket engine and have summarized the potential of using this engine for fulfilling the ever-growing payload mass-thrust demands, with appropriate methodologies

The thrust produced in the combustion chamber of a cryogenic engine is due to rapid exothermal reaction and expansion of super-cooled liquids to the gaseous state and is relatively high. Using this engine with a LOX/LH2 propellant mixture yields impressive test results, including a high specific impulse of 443s and a 43% reduction in launched mass, well outperforming any rocket propulsion technology currently in use. There are substitutes like LCH4, LNG propellants which have the capability to operate efficiently and sustainably without triggering atmospheric pollution[86], however, the current TRL of these propellant combinations isn't that impressive when compared to the dominant LOx/LH2 combination. Although, the possibilities of these substitutes surpassing the LOx/LH2 in the near future can't be ignored.

Furthermore, a strong fundamental knowledge on the combustion dynamic analyses of a typical cryogenic rocket engine using various in-situ modeling and computations has been handed down since the beginning of the space programs. In respect to this, a lot of vital experiments were/are being put into endeavour to study and regulate the combustion dynamics of the engine, thereby to reduce the likelihood of combustion instability. Despite decades of research, the potential to precisely predict and plot each form of combustion instability based on physio-chemical factors, the engine, and its operational characteristics is still being developed.

The cooling techniques/systems such as regenerative and film cooling, cryocoolers and multilayer insulations, directly helped to reduce the heat flux generated as a result of high temperature combustion and to achieve significant ZBO characteristics respectively. In summary, when a suitable, state-of-the-art analyses and techniques comes into place, the engine is expected to rise off incredibly with reduced drag penalties and desired performance and efficiency. Therefore, a need for constant improvement in the efficiency and durability of current LPRE's, such as a cryogenic engine and the development of a new propulsion technology; but without jeopardizing the environment's sustainability is vital.Numerous nations, space organisations, and enterprises have already centered their efforts on harnessing this most effective propulsion technology throughout the years. Exploring novel cryogenic liquid propellants and inductive approach to existing cryogenic technology constraints may play a vital role in constructing improved rockets for prospective space missions. As a result, unless and until innovative-speculative propulsion technologies develop and prove realistic, it is undeniable that future space travel will be heavily reliant on cryogenic technology.

References

1) F. Papanelopoulou, "Louis paul cailletet: the liquefaction of oxygen and the emergence of low-temperature research," *Notes Rec. R. Soc. Lond.*, **67** (*4*) 355 (2013). doi:10.1098/RSNR.2013.0047.
2) K. Chowdhury, "CRYOGENICS: ITS PRODUCTION, PROPERTIES AND INDUSTRIAL APPLICATIONS," in: 4th Int. Conf. Mech. Eng., Dhaka, Bangladesh, 2001: pp. 135–154. http://me.buet.ac.bd/icme/icme2001/cdfiles/Papers/Keynote/13_Kanchan_2_final(135-154).pdf (accessed April 29, 2022).
3) J. Wisniak, "Louis paul cailletet-the liquefaction of the permanent gases," *Int. J. Chem. Technol.*, **10** 223–236 (2003). http://nopr.niscair.res.in/bitstream/123456789/22723/1/IJCT 10%282%29 223-236.pdf (accessed April 29, 2022).
4) J.R. Brown, "CRYOGENIC UPPER STAGE PROPULSION RL1O and Derivative Engines," 1990. https://ntrs.nasa.gov/api/citations/19910018888/downloads/19910018888.pdf (accessed April 29, 2022).
5) N.. Mohite, B.. Kale, and V.. Patil, "Cryogenics-Birth of an Era," in: Proc. Natl. Conf. Innov. Paradig. Eng. Technol. (NCIPET 2012), International Journal of Computer Applications, 2012: pp. 24–26. https://www.ijcaonline.org/proceedings/ncipet/number9/5259-1071 (accessed April 29, 2022).
6) B. Thakur, and I.J. Pegu, "A review on cryogenic rocket engine," *Int. Res. J. Eng. Technol.*, **4** (*8*) 2248–2252 (2017).
7) P. Soni, G. Sahu, P.K. Sen, and R. Sharma, "A review on cryogenic rocket engine," *Int. J. Res. Appl. Sci. Eng.*, **3** (*11*) 412–414 (2015).
8) Dobek. Olivier, and D. Le Dortz, "ROCKET ENGINE WITH CRYOGENIC PROPELLANTS - Patent application," 20120144797, 2012.
9) J.E. McKeathen, R.F. Reidy, S.K.S. Boetcher, and M.J. Traum, "A cryogenic rankine cycle for space power generation," *41st AIAA Thermophys. Conf.*, (2012). doi:10.2514/6.2009-4247.
10) M. Sharma, and R. Dev, "Review and preliminary analysis of organic rankine cycle based on turbine inlet temperature," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **5** (*3*) 22–33 (2018). doi:10.5109/1957497.
11) E.L. Tsougranis, and D. Wu, "A feasibility study of organic rankine cycle (orc) power generation using thermal and cryogenic waste energy on board an lng passenger vessel," *Int. J. Energy Res.*, **42** (*9*) 3121–3142 (2018). doi:10.1002/ER.4047.
12) R.G. Scurlock, "A matter of degrees: a brief history of cryogenics," *Cryogenics (Guildf).*, **30** (*6*) 483–500 (1990). doi:10.1016/0011-2275(90) 90048-H.
13) C. Esposito, "Study of cryogenic transient flows. the impact of the fluid thermosensitivity on cavitation," (2020). https://lirias.kuleuven.be/3041084?limo=0 (accessed April 29, 2022).
14) H. Elserafy, "Assessment of demo reactors for fusion power utilization," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **05** (*04*) 18–25 (2018). doi:10.5109/2174854.
15) G.P. Sutton, and O. Biblarz, "Liquid Propellants ," in: Rocket Propuls. Elem., 7th ed., A Wiley-lnterscience Publication, JOHN WILEY & SONS, INC., 2001: pp. 242–250. http://mae-nas.eng.usu.edu/MAE_5540_Web/propulsion_systems/subpages/Rocket_Propulsion_Elements.pdf (accessed April 29, 2022).
16) O.J. Haidn, "Advanced rocket engines," *Haidn, O. J. (2008). Adv. Rocket Engines. Adv. Propuls. Technol. High-Speed Aircr.*, 6–1 (2008). https://www.kimerius.com/app/download/5783787868/Advanced+rocket+engines.pdf (accessed April 29, 2022).
17) M.J. Casiano, J.R. Hulka, and V. Yang, "Liquid-propellant rocket engine throttling: a comprehensive review," *J. Propuls. Power*, **26** (*5*) 897–923 (2012). doi:10.2514/1.49791.
18) J. Verma, and D. Sharma, "A comprehensive review of propellants used in cryogenic rocket engine," *Vidyabharati Int. Interdiscip. Res. J.*, **11** (*2*) 8–17 (2021). doi:10.13140/RG.2.2.13241.08809.
19) J. Harbaugh, "Rocketology: nasa's space launch system," (2016). https://blogs.nasa.gov/Rocketology/author/jharbaug/ (accessed April 29, 2022).
20) W. Notardonato, "Active control of cryogenic propellants in space," *Cryogenics (Guildf).*, **52** (*4–6*) 236–242 (2012). doi:10.1016/j.cryogenics.2012.01.003.
21) S. Mustafi, C. Delee, J. Francis, X. Li, D. McGuinness, C.A. Nixon, L. Purves, W. Willis, S. Riall, M. Devine, and A. Hedayat, "Cryogenic propulsion for the titan orbiter polar surveyor (tops) mission," *Cryogenics (Guildf).*, **74** 81–87 (2016). doi:10.1016/J.CRYOGENICS.2015.11.009.
22) S. Mustafi, H. Delee, J. Francis, X. Li, L. Purves, D. Willis, C. Nixon, D. Mcguinness, S. Riall, M. Devine, and A. Hedayat, "Cryogenic propulsion for the titan orbiter polar surveyor," *Semant. Sch.*, (2019).https://pdfs.semanticscholar.org/8a26/e07c9634a02d7836ae1b31d42e75090944d9.pdf (accessed

April 30, 2022).
23) R.S. Praveen, N. Jayan, K.S. Bijukumar, J. Jayaprakash, V. Narayanan, and G. Ayyappan, "Development of cryogenic engine for gslv mkiii: technological challenges," *IOP Conf. Ser. Mater. Sci. Eng.*, **171** (*1*) 012059 (2017). doi:10.1088/1757-899X/171/1/012059.
24) N.K. Gupta, "Cryogenics in space with particular reference to isro programs," *Indian J. Cryog.*, **44**(*1*) 1 (2019). doi:10.5958/2349-2120.2019.00001.3.
25) Z. SONG, Z. XIE, L. QIU, D. XIANG, and J. LI, "Prospects of sea launches for chinese cryogenic liquid-fueled medium-lift launch vehicles," *Chinese J. Aeronaut.*, **34** (*1*) 424–437 (2021). doi:10.1016/J.CJA.2020.06.018.
26) S.K. Mital, J.Z. Gyekenyesi, S.M. Arnold, R.M. Sullivan, J.M. Manderscheid, and P.L.N. Murthy, "Review of Current State of the Art and Key Design Issues With Potential Solutions for Liquid Hydrogen Cryogenic Storage Tank Structures for Aircraft Applications," 2006. https://ntrs.nasa.gov/api/citations/20060056194/downloads/20060056194.pdf (accessed April 29, 2022).
27) M.D. Klem, T.D. Smith, M.F. Wadel, M.L. Meyer, J.M. Free, and H.A.C. Iii, "LIQUID OXYGEN/LIQUID METHANE PROPULSION AND CRYOGENIC ADVANCED DEVELOPMENT," in: Int. Astronaut. Conf. , n.d.: pp. 1–12. https://ntrs.nasa.gov/api/citations/20110016509/downloads/20110016509.pdf (accessed April 29, 2022).
28) J.S. Hardi, T. Traudt, C. Bombardieri, M. Börner, S.K. Beinke, W. Armbruster, P. Nicolas Blanco, F. Tonti, D. Suslov, B. Dally, and M. Oschwald, "Combustion dynamics in cryogenic rocket engines: research programme at dlr lampoldshausen," *Acta Astronaut.*, **147** 251–258 (2018). doi:10.1016/J.ACTAASTRO.2018.04.002.
29) T. Neill, D. Judd, E. Veith, and D. Rousar, "Practical uses of liquid methane in rocket engine applications," *Acta Astronaut.*, **65** (*5–6*) 696–705 (2009). doi:10.1016/J.ACTAASTRO.2009.01.052.
30) T.D. Smith, M.D. Klem, and K. Fisher, "Propulsion risk reduction activities for non-toxic cryogenic propulsion," *AIAA Sp. Conf. Expo. 2010*, (2010). doi:10.2514/6.2010-8680.
31) A.M. Saiful, A. Tri Wijayanta, K. Nakaso, and J. Fukai, "Predictions of o 2 /n 2 and o 2 /co 2 mixture effects during coal combustion using probability density function," *J. Nov. Carbon Resour. Sci.*, **2** 12–16 (2010).
32) A.G. Rao, F. Yin, and H.G.C. Werij, "Energy transition in aviation: the role of cryogenic fuels," *Aerospace*, **7** (*12*) 181 (2020). doi:10.3390/AEROSPACE7120181.
33) A.T. Raheem, A. Rashid, A. Aziz, S.A. Zulkifli, A.T. Rahem, and W.B. Ayandotun, "Development, validation, and performance evaluation of an air-driven free-piston linear expander numerical model," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **09** 72–85 (2022). doi:10.5109/4774218.
34) O.J. Haidn, and M. Habiballah, "Research on high pressure cryogenic combustion," *Aerosp. Sci. Technol.*, (2000). https://www.researchgate.net/publication/224789748_Research_on_High_Pressure_Cryogenic_Combustion (accessed April 29, 2022).
35) J. Hulka, and J.J. Hutt, "Instability phenomenology and case studies: instability phenomena in liquid oxygen/hydrogen propellant rocket engines," *Liq. Rocket Engine Combust. Instab.*, 39–71 (1995). doi:10.2514/5.9781600866371.0039.0071.
36) N. Kumar Maurya, V. Rastogi, and P. Singh, "Experimental and computational investigation on mechanical properties of reinforced additive manufactured component," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **6** (*3*) 207–214 (2019). doi:10.5109/2349296.
37) M. Gonzalez-Flesca, P. Scouflaire, T. Schmitt, S. Ducruix, S. Candel, and Y. Méry, "Reduced order modeling approach to combustion instabilities of liquid rocket engines," *AIAA J.*, **56** (*12*) 4845–4857 (2018). doi:10.2514/1.J057098.
38) I.Y. Moon, S.H. Kang, S.Y. Lee, and S. Se, "Study on combustion dynamic characteristics of oxygen-rich preburners," *J. Propuls. Power*, **30** (*4*) 917–924 (2014). doi:10.2514/1.B35140.
39) M.A. Mazlan, M.F. Mohd Yasin, M.A. Wahid, A. Saat, A. Dairobi Ghazali, and M.N. Rahman, "Initiation characteristics of rotating supersonic combustion engine," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **08** (*01*) 177–181 (2021). doi:10.5109/4372275.
40) L. Hakim, T. Schmitt, S. Ducruix, and S. Candel, "Dynamics of a transcritical coaxial flame under a high-frequency transverse acoustic forcing: influence of the modulation frequency on the flame response," *Combust. Flame*, **162** (*10*) 3482–3502 (2015). doi:10.1016/J.COMBUSTFLAME.2015.05.022.
41) Y. Méry, L. Hakim, P. Scouflaire, L. Vingert, S. Ducruix, and S. Candel, "Experimental investigation of cryogenic flame dynamics under transverse acoustic modulations," *Comptes Rendus Mécanique*, **341** (*1–2*) 100–109 (2013). doi:10.1016/J.CRME.2012.10.013.
42) S.K. Beinke, J.S. Hardi, D.T. Banuti, S. Karl, B.B. Dally, and M. Oschwald, "Experimental and numerical study of transcritical oxygen-hydrogen rocket flame response to transverse acoustic excitation," *Proc. Combust. Inst.*, **38** (*4*) 5979–5986 (2021). doi:10.1016/J.PROCI.2020.05.027.
43) A. K, and M.A. Wahid, "On the effects of tangential air inlets distribution configurations to the

combustion characteristics of a direct injection liquid fueled swirl flameless combustor (sfc). ," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **8** (*1*) 117–122 (2021). doi:10.5109/ 4372267.

44) J.W. Bennewitz, and R.A. Frederick, "Overview of combustion instabilities in liquid rocket engines-coupling mechanisms & control techniques," *49th AIAA/ASME/SAE/ASEE Jt. Propuls. Conf.*, 1–24 (2013). doi:10.2514/6.2013-4106.
45) A. Woschnak, D. Suslov, and M. Oschwald, "Experimental and numerical investigations of thermal stratification effects," *39th AIAA/ASME/ SAE/ASEE Jt. Propuls. Conf. Exhib.*, (2003). doi:10.2514/6.2003-4615.
46) J. Smith, D. Suslov, M. Oschwald, O. Haidn, and M. Bechle, "High Pressure LOx/H2 Combustion and Flame Dynamics," in: 40th AIAA/ASME/SAE/ ASEE Jt. Propuls. Conf. Exhib., American Institute of Aeronautics and Astronautics (AIAA), 2004. doi:10.2514/6.2004-3376.
47) J. Lux, and O. Haidn, "Flame stabilization in high-pressure liquid oxygen/methane rocket engine combustion," *J. Propuls. Power*, **25** (*1*) 15–23 (2012). doi:10.2514/1.36852.
48) A. Reno Andi Bahar, A. Saad Yatim, and E. Pramudya Wijaya, "CFD analysis of universitas indonesia psychrometric chamber air loop system," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **09** 465–469 (2022). doi:10.5109/4794173.
49) S. Darmawan, K. Raynaldo, and A. Halim, "Investigation of thruster design to obtain the optimum thrust for rov (remotely operated vehicle) using cfd," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **9** (*1*) 115–125 (2022). https://catalog.lib.kyushu-u.ac.jp/opac_download_md/4774224/115-125.pdf (accessed August 5, 2022).
50) G.R. McNamara, and G. Zanetti, "Use of the boltzmann equation to simulate lattice-gas automata," *Phys. Rev. Lett.*, **61** (*20*) (1988). doi:10.1103/ PhysRevLett.61.2332.
51) S. Succi, "The lattice Boltzmann equation for fluid dynamics and beyond," Oxford Science Publications, 2001.
52) K.J. Petersen, and J.R. Brinkerhoff, "On the lattice boltzmann method and its application to turbulent, multiphase flows of various fluids including cryogens: a review," *Phys. Fluids*, **33** (*4*) (2021). doi:10.1063/5.0046938.
53) N. Mohd, M.M. Kamra, M. Sueyoshi, and C. Hu, "Lattice boltzmann method for free surface impacting on vertical cylinder : a comparison with experimental data lattice boltzmann method for free surface impacting on vertical cylinder: a comparison with experimental data," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **04** 28–37 (2017). doi:10.5109/1929662.
54) A.K. Gunstensen, D.H. Rothman, S. Zaleski, and G. Zanetti, "Lattice boltzmann model of immiscible fluids," *Phys. Rev. A*, **43** (*8*) (1991). doi:10.1103/PhysRevA.43.4320.
55) N. Mohd, M.M. Kamra, M. Sueyoshi, and C. Hu, "Three-dimensional free surface flows modeled by lattice boltzmann method : a comparison with experimental data three-dimensional free surface flows modeled by lattice boltzmann method: a comparison with experimental data," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **04** (*1*) 29–35 (2017). doi:10.5109/1808450.
56) C. Rey, S. Ducruix, P. Scouflaire, L. LastNameVingert¡, and S. Candel, "Collective interactions in high frequency combustion instabilities," (n.d.). http://www.icders.org/ ICDERS2003/abstracts/ICDERS2003-123.pdf (accessed April 29, 2022).
57) F. Richecoeur, P. Scouflaire, S. Ducruix, and S. Candel, "High-frequency transverse acoustic coupling in a multiple-injector cryogenic combustor," *J. Propuls. Power*, **22** (*4*) 790–799 (2012). doi:10.2514/1.18539.
58) B.T. Kuzhiveli, S.C. Ghosh, G.K. Kuruvila, and V.G. Gandhi, "Thermal analysis of cryogenic rocket engine with one, two and three dimensional approaches," *Proc. Twent. Int. Cryog. Eng. Conf. ICEC 20*, 441–444 (2005). doi:10.1016/B978-008044559-5/50103-4.
59) P. Grenard, N. Fdida, L. Vingert, L.H. Dorey, L. Selle, and J. Pichillou, "Experimental investigation of heat transfer in a subscale liquid rocket engine," *J. Propuls. Power*, **35** (*3*) 544–551 (2019). doi:10.2514 /1.B36928.
60) T. Vinitha, S. Senthilkumar, and K. Manikandan, "Thermal design and analysis of regeneratively cooled thrust chamber of cryogenic rocket engine," *Int. J. Eng. Res. Technol.*, **2** (*6*) 662–669 (2013). https://www.ijert.org/research/thermal-design-and-analysis-of-regeneratively-cooled-thrust-chamber-of-cryogenic-rocket-engine-IJERTV2IS60264.pdf (accessed April 29, 2022).
61) Safril, Mustofa, M. Zen, F. Sumasto, and M. Wirandi, "Design of cooling system on brushless dc motor to improve heat transfers efficiency," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **09** 584–593 (2022). doi:10.5109/4794206.
62) D.H. Huang, and D.K. Huzel, "Introduction to Liquid-Propellant Rocket Engines," in: Mod. Eng. Des. Liq. Rocket Engines, American Institute of Aeronautics and Astronautics, 1992: pp. 1–22. doi:10.2514/5.9781600866197.0001.0022.
63) D.H. Huang, and D.K. Huzel, "Design of Liquid-Propellant Space Engines," in: Mod. Eng. Des. Liq. Rocket Engines, American Institute of Aeronautics and Astronautics, 1992: pp. 373–388. doi:10.2514/5.9781600866197.0373.0388.

64) M. Rajagopal, "Numerical modeling of regenerative cooling system for large expansion ratio rocket engines," *J. Therm. Sci. Eng. Appl.*, **7** (*1*) (2015). doi:10.1115/1.4028979/379323.
65) J. Song, T. Liang, Q. Li, P. Cheng, D. Zhang, P. Cui, and J. Sun, "Study on the heat transfer characteristics of regenerative cooling for lox/lch4 variable thrust rocket engine," *Case Stud. Therm. Eng.*, **28** 101664 (2021). doi:10.1016/J.CSITE.2021.101664.
66) M. Pizzarelli, "Regenerative cooling of liquid rocket engine thrust chambers," 2017. https://www.researchgate.net/publication/321314974_Regenerative_cooling_of_liquid_rocket_engine_thrust_chambers?channel=doi&linkId=5a1c1aaf0f7e9be37f9c2f9e&showFulltext=true (accessed April 29, 2022).
67) I.N. Nikischenko, R.D. Wright, and R.A. Marchan, "Improving the performance of lox/kerosene upper stage rocket engines," *Propuls. Power Res.*, **6** (*3*) 157–176 (2017). doi:10.1016/J.JPPR.2017.07.008.
68) A. Miranda, and M. Naraghi, "Analysis of film cooling and heat transfer in rocket thrust chamber and nozzle," (2011). doi:10.2514/6.2011-712.
69) A.N. Pavlenko, and D. V. Kuznetsov, "Experimental study of the effect of structured capillary-porous coating on rewetting dynamics and heat transfer at film cooling by liquid nitrogen," *J. Phys. Conf. Ser.*, **1105** (*1*) (2018). doi:10.1088/1742-6596/1105/1/012053.
70) R. Arnold, D.I. Suslov, and O.J. Haidn, "Film cooling in a high-pressure subscale combustion chamber," *J. Propuls. Power*, **26** (*3*) 428–438 (2012). doi:10.2514/1.47148.
71) O. Reynolds, "On the resistance encountered by vortex rings, and the relation between the vortex rings and streamlines of a disk | cinii research," *Nature*, **14** 477–479 (1876).
72) K. Wieghardt, "On the Blowing of Warm Air for De-icing-devices," Ministry of Aircraft Production, 1946.
73) S.R. Shine, and S.S. Nidhi, "Review on film cooling of liquid rocket engines," *Propuls. Power Res.*, **7** (*1*) 1–18 (2018). doi:10.1016/J.JPPR.2018.01.004.
74) B.D. Taylor, J. Caffrey, A. Hedayat, J. Stephens, and R. Polsgrove, "Cryogenic Fluid Management Technology Development for Nuclear Thermal Propulsion," in: AIAA/SAE/ASEE Jt. Propuls. Conf. (AIAA Propuls. Energy Forum 2015), American Institute of Aeronautics and Astronautics, 2015. https://ntrs.nasa.gov/api/citations/20150016543/downloads/20150016543.pdf (accessed April 30, 2022).
75) R.G. Ross, and R.F. Boyle, "An Overview of NASA Space Cryocooler Programs-2006," in: Int. Cryocooler Conf., Annapolis, 2006. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.492.1757&rep=rep1&type=pdf (accessed April 30, 2022).
76) R.G. Ross, "Cryocoolers for space applications," (2015). https://www.jlab.org/IR/Cryocooler_Fundamentals_Course_Notes/CEC-RGR_1_200dpi-final.pdf (accessed April 30, 2022).
77) L.J. Hastings, D.W. Plachta, L. Salerno, and P. Kittel, "An overview of nasa efforts on zero boiloff storage of cryogenic propellants," *Cryogenics (Guildf).*, **41** (*11–12*) 833–839 (2001). doi:10.1016/S0011-2275(01)00176-X.
78) T. Nast, D. Frank, and K. Burns, "Cryogenic Propellant Boil-Off Reduction Approaches," in: 49th AIAA Aerosp. Sci. Meet. Incl. New Horizons Forum Aerosp. Expo., American Institute of Aeronautics and Astronautics (AIAA), Orlando, Florida, 2011. doi:10.2514/6.2011-806.
79) D.W. Plachta, R.J. Christie, E. Carlberg, and J.R. Feller, "CRYOGENIC propellant boil-off reduction system," *AIP Conf. Proc.*, **985** (*1*) (2008). doi:10.1063/1.2908506.
80) D. Plachta, J. Stephens, W. Johnson, and M. Zagarola, "NASA cryocooler technology developments and goals to achieve zero boil-off and to liquefy cryogenic propellants for space exploration," *Cryogenics (Guildf).*, **94** 95–102 (2018). doi:10.1016/J.CRYOGENICS.2018.07.005.
81) Y. V Gorbatskii, A.M. Domashenko, and V.N. Krishtal, "Stages of development of cryogenic systems for space rocket technology," *Chem. Pet. Eng. 2002 389*, **38** (*9*) 594–598 (2002). doi:10.1023/A:1022024923524.
82) A. Sunjarianto Pamitran, R. Dandy Yusuf, and M. Arif Budiyanto, "Analysis of iso-tank wall physical exergy characteristic – case study of lng boil-off rate from retrofitted dual fuel engine conversion," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **06** (*2*) 134–142 (2019). doi:10.5109/2321007.
83) Harinaldi, M. Denni Kesuma, R. Irwansyah, J. Julian, and A. Satyadharma, "Flow control with multi-dbd plasma actuator on a delta wing," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **07** 602–608 (2020). doi:10.5109/4150513.
84) R.A. Rouf, M.A.H. Khan, K.M.A. Kabir, and B.B. Saha, "Energy management and heat storage for solar adsorption cooling," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **3** (*2*) 1–10 (2016). doi:10.5109/1800866.
85) K. Kinefuchi, H. Kawashima, D. Sugimori, K. Okita, and H. Kobayashi, "Cryogenic propellant recirculation for orbital propulsion systems," *Cryogenics (Guildf).*, **105** (2020). doi:10.1016/J.CRYOGENICS.2019.102996.
86) M.I. Sabtu, H. Hishamuddin, N. Saibani, M. Nizam, and A. Rahman, "A review of environmental assessment and carbon management for integrated supply chain models," *Evergr. Jt. J. Nov. Carbon Resour. Sci. Green Asia Strateg.*, **8** (*3*) 628–641 (2021). doi:10.5109/4491655.