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Low-temperature heat transfer mediums for cryogenic applications

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ABSTRACT

Background: Researchers and industrialists have grown interested in cryogenic technologies over the years. Cryogenic heat transfer has enabled new applications due to material properties and behaviour at very low temperatures. This domain is still underdeveloped and unfamiliar in various applications.
Methods: This work discusses the recent progress on cryogenic mediums and their respective use in different heat transfer applications. After identifying what is commonly designated as a cryogenic medium, i.e., those with a boiling point below -150 °C, the different characteristics and features of such mediums are critically discussed.
Significant findings: Liquid He and N2 were found to be the most used cryogenic mediums, mainly due to the very low temperature attained by liquid He, as the closest to the absolute zero, along with the low cost and high availability of liquid N_2. The use of liquid-phase cryogenic in a single-phase state was found to be the most common application method. Two-phase applications of the cryogenic medium are mainly for use in a heat pipe, in which both latent and sensible heat is utilized. Cryogenic mediums are essential for critical and niche applications such as in aerospace, superconductivity, advanced machining and manufacturing methods, and more critically in many healthcare applications and advanced scientific research.

1. Introduction

The interest in cryogenic technologies has kept growing over the past years for both researchers and industrialists [1,2]. Due to the significant changes in material properties and behaviour at very low temperatures, cryogenic heat transfer has opened new horizons and provided opportunities for various applications [3]. Yet, this domain still needs to be further developed and remains unfamiliar to many. As an example, the notion of cryogenics is not strictly defined in the literature and can be confusing. Indeed, it is largely adopted that cryogenics designates low-temperature phenomena but the temperature level at which the cryogenic region is not well defined [4,5]. According to cryogenic experts [5–7], the cryogenic range is suggested to start below −150 °C as many fluids commonly used by the cryogenic industry, such as helium He, hydrogen H_2, nitrogen N_2, oxygen O_2, and air, have a boiling point lower than this temperature. Several other institutions such as the National Institute of Standards and Technology (NIST) and the Cryogenic Society of America consider the cryogenic range to start below −153 °C or −180 °C, respectively. With this in mind, the first definition of the cryogenic range is considered and only cryogenic mediums where the boiling point temperature at an ambient pressure is lower than −150 °C are studied.

The potential of cryogenic mediums in heat transfer is evident as the temperature ranges of these mediums are much lower than most of the ambient temperature processes. Even if the high gradients of temperature are promising for higher heat transfer rates in comparison to ambient temperature ones, cryogenic heat transfer presents peculiarities of its own [4]. To start with, material properties significantly change in the cryogenic temperature range and the evolution of these properties with temperature can be significantly different in comparison with common material at an ambient temperature. According to the chemical composition of elements and their molecular structures, materials can react differently. For instance, metals with face-centered-cubic (FCC) structures, such as copper and stainless steel, are much more ductile than metals with other structures, such as carbon steel, whilst undergoing a decrease in temperature to the cryogenic temperature range [8]. In the cryogenic temperature range, heat transfer to these materials

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Nomenclature

Symbol	explaination units
Cp	specific heat of vapour (KJ/kg.K)
h1-2	latent heat of phase change (J/kg)
I	current (amp)
k	thermal conductivity (W/m. K)
L	liquid form
n	exponent
P	pressure (kg/m^3)
P	pressure N/mn^2)
T	temperature (°C)
T	temperature (K)
V	voltage (V)
v	specific volume (m3/kg)

Greek symbols

μ	dynamic viscosity (kg/m.s)
ρ	density (kg/m^3)

Subscripts

1	phase 1
2	phase 2
c	critical
Phase change	phase change
Sat	saturation

Abbreviation

ATM	atmospheric pressure
BCC	body centred cubic
CERN	European Organization for Nuclear Research
CFD	computational fluid dynamics
CGS	crystal growth system
CHMFL	High Magnetic Field Laboratory of the Chinese Academy of Sciences
COBE	cosmic background explorer
CPMU	cryogenic permanent magnets
EAST	experimental advanced superconducting tokamak
ESR	electron spin resonance spectrometer
FCC	face centred cubic
FTIR	fourier transform infrared spectroscopy
HCC	high capacity cooler
HCP	hexagonal closed packed
HEC	high efficiency cooler
HP	heat pipe
HPC	hematopoietic progenitor cells
ITER	international thermonuclear experimental reactor
ITP	institute for technical physics
LHC	large hadron collider particle accelerator
LHP	loop heat pipe
LNG	liquified natural gas
MIRI	mid InfraRed Instrument
MPMS	magnetic property measurement system
MRI	magnetic resonance imaging
NASA	National Aeronautics and Space Administration
NGAS	Northrop Grumman Aerospace Systems
NIST	National Institute of Standards and Technology
NMR	nuclear magnetic resonance
OMS	optical magnetic system
POLO	poloidal field model coil
SCU	superconducting undulators
SM_TECH	superconducting magnet technology research
SMA	STM-MFM-AFM combo system
STEP	satellite test of the equivalence principle
SWIP	Southwestern Institute of Physics
TFMC	ITER toroidal field model coil
TOSKA	Toroidal Spulentestanlage Karlsruhe
ULTES	ultra low temperature experiment system

Elements

Ag	silver
Ar	argon
Au	gold
CH_4	methane
CO_2	carbon dioxide
F_2	fluorine
H_2	hydrogen
He	helium
Kr	krypton
Mg	magnesium
N_2	nitrogen
NbTi	niobium-titanium
Ne	neon
O_2	oxygen
PrFeB	praseodymium iron boron
X	additional elements (Ta, Ti)

could lead to increased brittleness and in the worst-case scenarios, cause its rupture. Similarly materials containing zinc, tin and lead risk randomised crystallisations which makes the material unworkable. This is particularly troublesome for low temperature circuitry in electronics.

As for the cryogenic medium itself, its properties within the cryogenic range can ease the heat transfer or, on the contrary, limit it. Typically, cryogenic fluids can present extremely low surface tensions which are favourable to filmwise condensation between the surface and the liquid, and can show significant improvement in the heat transfer rate compared to condensation of liquids with higher surface tension [9]. Working with cryogenic mediums can be more difficult due to the relatively small domain of existence for some mediums. As will be demonstrated later, the phase transitions of cryogenic mediums can be extremely close. Hence, in a cryogenic heat transfer process, the working conditions of a given medium are generally close to a phase transition or critical/supercritical conditions and must be controlled more carefully to prevent any undesired phase change of a medium that could lead to hazardous consequences. Moreover, the phase change process of cryogenic mediums is also eased as the latent heat of vaporization of many cryogenic fluids is much lower than other conventional heat transfer fluids. The capacity of cryogenic mediums to change phase can be profitable and allow large amounts of thermal energy transport, but cryogenic mediums can also be difficult to contain and store. With this purpose, high-performance insulations have been developed to limit high heat transfer between the cryogenic medium and the ambient atmosphere. Similarly, mediums that are difficult to store are being researched to develop stable energy storage systems.

Some metallurgical applications of cryogenic cooling involve machining to process challenging materials [10]. For instance, titanium alloys present low thermal conductivities which can convey high tensile loads in local shear zones if not cooled by special processes such as cryogenic cooling [5]. Cryogenic cooling can also be used to make some materials more brittle and thus improve their machining.

In aerospace, cryogenic mediums are used to cool down instruments and other equipment. In this application, the main obstacle to overcome is to guarantee effective cooling over long periods. The absence of gravity and ambient air, in addition to the weight reduction objective, made cryogenic mediums particularly attractive for space applications.

Among others, utilizing the phase change characteristics of cryogenic fluids has permitted the development of low-temperature accumulators that act as a thermal energy sink, and allow cryogenic liquid propellants such as oxygen, hydrogen, or methane to be gasified and used as Low-Thrust Cryogenic Propulsion, along with their use as fuel [11,12].

Cryogenic heat transfer is also used to develop superconductors and superconducting magnet energy storage systems. The phenomenon of superconductivity was discovered by Kamerlingh Onnes in 1911, who reported that, when cooling down a conductor below its critical point, the electrical resistance becomes zero [13]. Thus, cryogenic cooling can be used to develop superconducting transmission lines [14], even though the technology still has some challenges to be economically feasible More recently, high-temperature superconductors have shown new horizons for this technology by presenting materials that can achieve superconductivity at higher temperatures in the range of 70–90 K. This is a promising opportunity to reduce the costs, as less costly liquid nitrogen can be used to reach this range of temperature instead of liquid helium for previous superconductors. The superconductivity effect was applied to develop superconducting magnet energy storage systems. By cryogenic cooling of a magnet, the superconductivity of the material allows the current injected in the magnet to circulate after disconnecting the power source. Hence, electricity is stored by maintaining the magnetic field around the magnet. By re-opening the circuit, a large quantity of stored electrical energy can be used. Similar applications have also been applied to trains [15] and magnetic resonance imaging (MRI).

Cryogenic heat transfer has enabled the development of cryogenic refrigeration and cooling systems using cryocoolers. Cryocoolers can be classified into two main categories: the recuperative type including heat exchangers, where the cold and hot fluids are separated, whereas the regenerative type consists of single channel filled with a matrix which is in contact with both hot and cold fluids, alternatively [16]. The most notable application of large-scale cryocoolers have been used in major scientific programs such as the Large Hadron Collider Particle Accelerator (LHC) at the European Organization for Nuclear Research (CERN), the experimental advanced superconducting tokamak magnetic fusion reactor in Hefei, China, and the nuclear fusion research project of International Thermonuclear Experimental Reactor (ITER) [17,18].

Cryogenic freezing systems are to preserve cell cultures while allowing efficient storage of the product. In this case, the objective is to freeze the sample with minimal changes in the biological composition of the product and keep its properties [19]. Indeed, depending on the freezing process, the quality of the product, such as its dehydration, thiobara bituric acid rate, salt-soluble protein rate, percentage of freezing loss, thawing loss and cutting loss can vary [20,21].Other medical applications include: Cryogenic mediums are also used in cryosurgery to destroy abnormal tissues and is particularly useful when the diseased tissue overlies bones [22,23].

Based on this brief overview on cryogenic heat transfer applications, it is evident that there is a high number of technologies reliant on cryogenic mediums. Until now, the cryogenic mediums according to the application have not been focused and reviewed. With this objective, this work reports the recent progress on cryogenic mediums and their most common applications. The review first discusses the different cryogenic mediums along with their unique features and characteristics. Then the work critically and briefly discusses the different applications when cryogenic mediums as cooling fluid, i.e., for cryogenic cooling. The scheme follows to discuss applications where single phase of cryogenic medium is involved, i.e., liquid or gas. Followed by applications where two-phases of cryogenic medium, i.e., solid-gas and liquid-gas are involved. The final section discusses applications involving cryogenic medium in three-phase state, i.e., solid-liquid-vapor involved are discussed.

2. Cryogenic mediums

According to the cryogenic domain definition given in the introduction, cryogenic mediums are defined to have a boiling point at ambient pressure is lower than −150 °C. In this work, the applications of: hydrogen (H_2), helium (He), nitrogen (N_2), oxygen (O_2), air, fluorine (F_2), neon (Ne), argon (Ar), krypton (Kr), and methane (CH_4) are considered. Before moving on to the applications of cryogenic mediums, this section focuses on discussing the cryogenic mediums and their unique features. To start with, cryogenic mediums exist in three main phases which are solid, liquid, and gas. The state or phase of pure matter are defined according to pressure and temperature, as per the phase rule, and shown Pressure-Temperature P-T phase diagram as schematized in Fig. 1. The triple point is the temperature and pressure at which the three phases coexist. At the critical point, the states of the liquid and vapour phases become identical. The triple and critical points of cryogenic mediums are important limits that govern the design of heat transfer systems as uncontrolled phase changes should be avoided not to damage the system. The triple and critical points of the cryogenic fluids studied, in addition to their boiling point at ambient pressure (1 atm) are presented in Table 1 [4,24–31]. The domain of existence of the cryogenic mediums and more particularly the temperature at which transitions occur are a first indicator on the potential suitability of a cryogenic medium for a given application.

From Table 1, one could observe that the two isotopes of helium, namely He-3 (rare) and He-4 (common), present special characteristics. At low temperatures, under certain pressure conditions, these isotopes do not freeze to form a solid state. Instead, a liquid-liquid transition, known as the lambda point, takes place. At temperatures below the lambda point, liquid He-4 behaves as a superfluid. In the superfluid state, the liquid presents a zero entropy and zero viscosity which means that the fluid can flow continuously without loss of energy [4]. On the other hand, if further cooled, Helium-3 can form two types of superfluid phases named phase A and B [32]. He-3 and He-4 are found in high quantity in the earth's mantle but it seems that the He-3 isotope was formed during planetary accretion while He-4 mainly appeared by radiogenic growth [33]. Today, He is mainly extracted from natural gas by low-temperature fractional distillation. An important characteristic of He is its short liquid existence domain, which makes it more sensitive to changes in temperature and pressure.

Hydrogen (H_2) is the most common element in the universe and represents about 75% of the baryonic mass [34]. Even if H_2 is mainly present as water or hydrocarbons, natural sources of pure hydrogen also exist [35]. Most of the H_2 produced is obtained by steam reforming of natural gases [36]. Neon (Ne) is a noble gas, which is scarce on earth due to its high volatility and because it does not co-exist with other elements in a solid form. The main source of Ne on earth is air, and was first discovered after drying air and was part of the residuals. Therefore, the only commercial production of neon is made by fractional distillation of

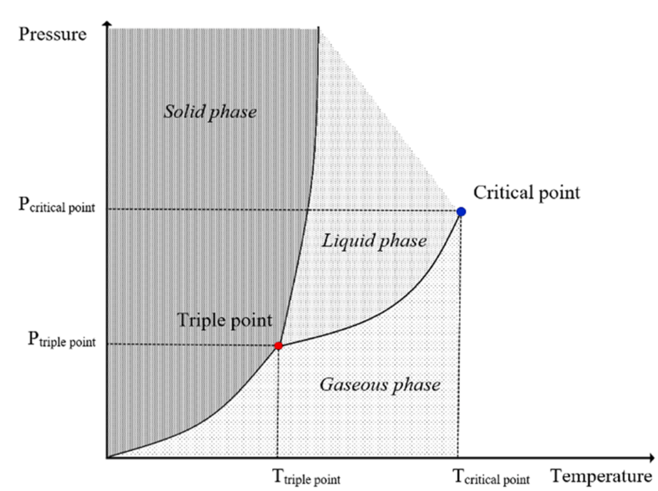

Fig. 1. Schematized Pressure-temperature phase diagram.

Table 1
Triple point, boiling point and critical point of studied cryogenic mediums.

Cryogenic medium	Triple point temperature, °C	Triple point Pressure, MPa	Boiling point (at 1 atm), °C	Critical temperature, °C	Critical pressure, MPa
Helium-3	−273.15	2.94*	−269.96	−269.85	0.311
Helium-4	−270.98	2.53*	−268.93	−267.95	0.227
Hydrogen	−259.34	0.00721	−252.78	−239.85	1.315
Neon	−248.59	0.0433	−246.04	−228.75	2.654
Nitrogen	−210.01	0.01253	−195.79	−146.95	3.396
Air	−213.40	0.005265	−194.25	−140.55	3.77
Fluorine	−219.67	0.000239	−187.95	−129.15	5.32
Argon	−189.37	0.0689	−185.85	−122.35	4.870
Oxygen	−218.82	0.0001503	−182.96	−118.55	5.043
Methane	−182.48	0.01169	−161.65	−82.65	4.640
Krypton	−157.2	0.07315	−153.2	−63.8	5.502

* For liquid helium, these are the minimum melting pressure.

liquid air, which makes neon a costly product [37]. Even if Ne is gaseous above its boiling point at relatively low pressures, a superfluid phase of Ne exists at extremely high pressures.

Nitrogen (N_2), and in particular liquid nitrogen LN_2, is the most commonly used cryogenic medium. As air is made up of about 78% N_2, its availability and abundance make it the easiest and most accessible cryogenic medium to be used, and at relatively low costs compared to other cryogenic mediums [38]. The abundance of N_2 in air can be explained by the strong interaction between the two nitrogen atoms that form the N_2 molecule. Breaking this bond requires a significant amount of energy. Pure N_2 is commercially produced by separation from air by the cryogenic distillation process.

Fluorine (F_2) is a halogen which is extremely reactive and this has made its study and applications difficult in the past. It can be found naturally in some minerals containing fluoride, such as fluorite [39]. Pure fluorine is produced in the laboratory by treatment of fluorite with sulfuric acid to obtain hydrogen fluoride HF and further thermal degradation or electrolysis of the HF [40]. Argon (Ar) is a noble gas at ambient temperature and an inert component [41]. Ar is obtained by fractional distillation of liquid air in cryogenic air separation units. Oxygen (O_2)is the third most common element in the universe after H_2 and He [42]. In its pure state, O_2 is reactive and strong oxidizer. Its abundance makes it accessible and suitable for commercial application and is supported by its natural renewal by photosynthesis. Methane (CH_4), is gaseous at ambient conditions and flammable, hence controlled conditions are required. Finally, krypton (Kr), is a noble and inert gas present in air, and was discovered simultaneously with Ne by evaporation of the main components of air. Kr has magnetic properties that make it useful for radiology and particle physics applications.

The properties and characteristics of cryogenic mediums vary with the temperature, pressure, and phase. The liquid phase properties of the studied cryogenic mediums at their standard boiling point under an ambient pressure of 1 atm are presented in Table 2 [4,43]. With a change in the pressure and temperature, cryogenic mediums can be subjected to significant change in their properties. For instance, between approximately 5 and 150 K, the gaseous helium phase thermal conductivity is ten times, hence it should be well considered in applications where a high gradient of temperature or pressure occur [4].

An important characteristic for heat transfer fluids, is the energy required or released during a phase change, i.e., latent heat and has the dimension of an enthalpy. During phase change the temperature remains constant, and energy received or released is used to drive phase change. Therefore, the phase change process of elements has a significant potential to store and release high amounts of energy and thus achieve heat transfer rates much higher than that for sensible heat transfer, where temperature is changed. This introduction of phase change mechanism is schematized in Fig. 2.

The three main phases studied in this manuscript are solid, liquid, and gas phases. The plasma phase is not discussed. Three types of latent heat are considered according to the phase transition taking place: latent heat of fusion, latent heat of sublimation, and latent heat of vaporization. The latent heat to achieve phase change from phase 1 to phase 2 is given by the Clausius-Clapeyron relationship:

$$h_{1\rightarrow 2} = T_{phase\ change}(v_2 - v_1)\left(\frac{dp}{dT}\right)_{sat} \quad (1)$$

Where, h is the latent heat for phase change from phase 1 to phase 2 (energy/mole or energy/mass), $T_{phase\ change}$ is temperature at which the phase change takes place (K), v are the specific volumes (volume/mole or volume/mass), and $(dp/dT)_{sat}$ is the slope of the P-T curve (pressure/temperature). In comparison to common mediums used at ambient temperature, the latent heats of fusion, vaporization, and sublimation of cryogenic mediums are relatively low. As an example, the enthalpy of vaporization of all the cryogenic elements studied except CH_4 and H_2, more than ten times lower than the latent heat of vaporization of liquid water under ambient conditions (2254 kJ/kg). The latent heat of fusion, vaporization, and sublimation of different cryogenic mediums are shown in Table 3 based on the data from [4,24,44]. It is clear that some cryogenic mediums are more suitable for phase-change heat transfer due to the high latent heat released.

During the start-up of employing cryogenic mediums, the piping

Table 2
Cryogenic liquid properties at their standard boiling point (1 atm).

Cryogenic liquid	Density (ρ), kg/m^3	Specific heat (C_p), kJ/kg.K	Viscosity (μ), mPa.s	Thermal conductivity (k) W/m.K
Helium-3	58.9	4.61	0.00162	0.0171
Helium-4	124.9	5.263	0.00317	0.0186
Hydrogen	70.85	9.772	0.0126	0.1005
Neon	1205	1.867	0.127	0.123
Nitrogen	806.1	2.042	0.161	0.145
Air	875.1	1.933	0.270	0.140
Fluorine	1494	1.511	0.257	0.70
Argon	1395	1.237	0.260	0.129
Oxygen	1142	1.697	0.195	0.151
Methane	422.3	3.481	0.117	0.189
Krypton	2416.7	0.520	0.407	0.0094

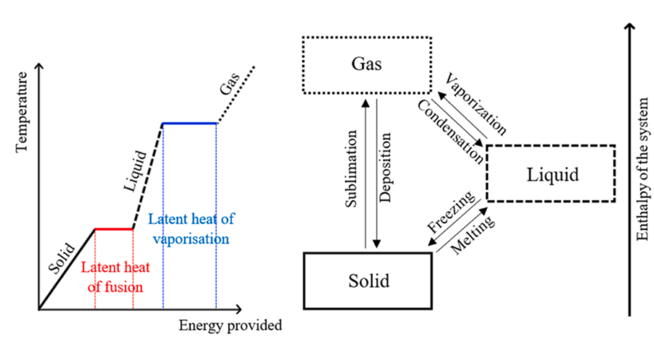

Fig. 2. Schematized phase change routes.

Table 3
Latent heat of phase change [4,24,44,45].

Cryogenic liquid	Latent heat of fusion, kJ/kg	Latent heat of fusion, kJ/kg	Latent heat of fusion, kJ/kg
Helium-3	0*	8.49	0*
Helium-4	5.23	20.7	0*
Hydrogen	59.5	448.7	452
Neon	16.8	85.8	105.1
Nitrogen	25.6	199.2	252
Air	0*	202.8	0*
Fluorine	6.72	174.4	0*
Argon	27.8	169.3	190.2
Oxygen	13.8	213.2	207
Methane	58.6	510.8	615
Krypton	19.6	107.5	128.8

* A zero value indicates that no data is available or that the transition does not exist.

equipment at ambient temperature needs to cool down to the operating cryogenic temperatures before reaching the desired heat transfer conditions. If a liquid cryogen is used, boiling can occur in the system due to the high temperature gradient. Boiling is also widely used as a two-phase mechanism to transmit large amounts of energy by successive boiling and condensation phenomena [26,46–48]. Therefore, the study of boiling including flow boiling, pool boiling and quenching of liquid cryogens has been widely investigated by many researchers [23,49–56]. Yet, the amount of energy applied is lower than for mediums commonly used at ambient temperature and the two-phase heat transfer is lower. To illustrate this fact, the pool boiling curve of LN_2 is compared to that of water in Fig. 3.

In Fig. 3, the boiling heat flux is represented in terms of excess temperature between the saturation temperature of the fluid and the wall. The boiling heat flux is closely linked to the heat transfer coefficient which presents a similar evolution. At the end of the nucleate pool boiling regime, a maximum heat flux is reached and a further increase in the wall temperature reduces the pool boiling heat transfer coefficient due to the appearance of a vapor film that blankets the hot wall surface and prevents the energy from the hot surface spreading to the liquid [26, 46]. It can be noted that the pool boiling range of LN_2 is much shorter than for water. Thus, the transition from nucleate boiling to film boiling takes place at excess temperatures much lower. In the transitional regime and film boiling regime, the boiling heat flux and heat transfer coefficient of LN_2 pool boiling are greatly reduced. Hence, it is shown that the suitable two-phase heat transfer temperature range of some cryogenic mediums such as LN_2 is much shorter than usual. In addition, the maximum boiling heat flux and heat transfer coefficient are much lower: for LN_2, the maximum boiling heat flux and heat transfer coefficients are about 145 kW/m^2 and 10 kW/m.K, respectively, whereas they reach 1020 kW/m^2 and 34 kW/m^2.K for water, respectively. Thus, in some applications, single phase heat transfer of cryogenic mediums is preferred. Once the liquid phase of cryogenic mediums has turned to gas, heat transfer can still occur. However, an increase in the temperature of the gas leads to an increase of the pressure in the system. Therefore, for cryogenic applications using the gaseous phase of cryogenic mediums, pressure calculations need to be cross-checked with simultaneous heat transfer calculations as a significant increase in the gas temperature can lead to a large increase in the pressure of cryogenic gas [57].

3. Single-phase applications

In this section, the applications of cryogenic medium in a single phase, i.e., without phase change, namely liquid and gaseous phases, is thoroughly discussed. In practice, the solid phase of cryogenic mediums is not used for heat transfer purposes as it is harder to handle and achievable only for a limited number of cryogenic medium, with alternative cryogenic liquid medium present at the same conditions. For example, Table 1 shows that boiling point of Kr is −153.2 °C, at which many other cryogenic mediums such as O_2, Air, N_2, Ne are already in liquid phase, which is much easier to handle.

3.1. Application of liquid cryogenic mediums

3.1.1. Machining and manufacturing

In machining operations, cryogens are used as a coolant to alter the material properties, as well as to dissipate the heat generated. Another advantage of using cryogenic cooling is the possibility of dry machining which makes the manufacturing process more environmental friendly and safer [5]. Cryogenic manufacturing is a large domain that has been largely reviewed by authors such as Jawahir et al. [5], Shokrani et al. [58], Yildiz and Nalbant [38] and Gill et al. [59]. As reported by Jawahir et al. [5], at low temperature, the properties of some metallic materials

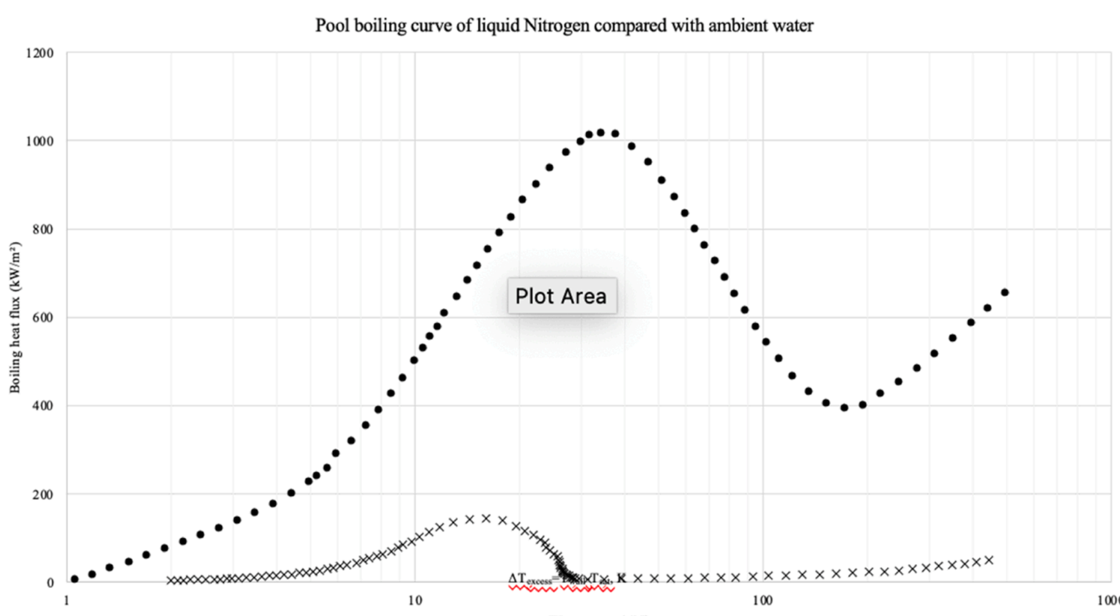

Fig. 3. Pool boiling curve of liquid nitrogen LN_2 compared to ambient liquid water.

evolve. For instance, by applying cryogenic cooling, the tensile strength, fatigue resistance, and hardness of some metals are enhanced which makes them easier to process. In particular, at cryogenic temperatures, materials with a face-centred cubic (FCC) structure maintain their ductility whereas hexagonal-closed packed (HCP) and body-centred cubic (BCC) structures become more brittle [5,8].

Daborn and Derry [8] reported that increasing the brittleness of some materials can facilitate crushing or grinding processes. In particular, this is used for comminution processes to recycle scrap materials. On the other hand, cryogenic cooling can also improve the properties. Bensely et al. [60] studied the wear resistance of carburized steel using deep cryogenic treatment, in which the wear resistance was improved by 372%. The improved hardness and wear resistance of material was explained by the conversion of austenite into martensite. Fredj and Sidhom [61] studied the impact of cryogenics on AISI 304 stainless steel ground components. It was observed that, by using cryogens instead of oil during the grinding, the generated surface presented a lower roughness, higher hardening, fewer defects and less tensile residual stress. In addition, the fatigue cracks in the cryogenic cooled surface were significantly smaller (30–50 μm) than the fatigue cracks in the oil generated surface (150–200 μm). Fig. 4 shows the relation between the stress corrosion cracking network and the stress distribution inside the material for both conventional cooling and cryogenic cooling. Cryogenic cooling was found to result in short and shallow cracks in comparison to long and deep cracks for wet cooling, along with higher surface residual stress.

Similarly, an increase of bearing steel hardness of 14% and 18% was reported by Harish et al. [62] and Sri Siva et al. [63], respectively. Bensely et al. [64]. also noted a decrease in the residual stress of carburized steel up to −235 MPa. Thornton et al. [65] used cryogenic treatment on H13A tungsten carbide and followed the wear evolution. After subjecting the material to a cryogenic treatment, the hardness was increased by 9.2%. Pu et al. [66] studied the surface integrity of magnesium alloy after cryogenic machining. It was found that the cryogenic treatment led to a better integrity. Indeed, the study observed a better surface finish, a refinement of the grain, and larger compressive areas in residual stress profiles. In relation to the hardening of materials, the use of cryogenic cooling can significantly increase the component's lifetime during turning, drilling and grinding. Firouzdor et al. [67] used a deep cryogenic treatment on drills for carbon steel manufacturing. A single cryogenic treatment increased the life of the drill by about 77%, whereas a cryogenic and tempered drill can last about 126% longer.

The work by Lal et al. [68] highlights that the use of cryogenic treatment on steel tools can be beneficial but needs to be done according to a well-defined protocol. In their study, steel tools were cryogenically treated at 133 K and 93 K. It was discovered that, at 133 K, the effects conveyed by the cryogenic cooling were negative. However, when cooled further down to 93 K, the material maximum life was expanded by 20%. Gill et al. [59] conducted a review on the use of cryogenic cooling for cutting tool materials. The study reported the use of LN_2 as a coolant to reach temperatures down to −196 °C. The use of LN_2 makes the process rather inexpensive and expands the life span of the cutting tools. Some examples of the use of liquid nitrogen in manufacturing are illustrated in Fig. 5 [69,70,71]. Pereira et al. [72] compared the machining of stainless steel 304 without cooling, with LN_2 cooling, and with CO_2 cooling. It was concluded that using cryogenic cooling improved the tool life by 50% and the cutting speed by 30%. In addition, the use of LN_2 cooling on the environment was evaluated and proved to be much better than common cutting processes in terms of eutrophication, ozone depletion, ecotoxicity and global warming.

Reddy and Ghosh [74] have been more critical on the use of LN_2 for high speed machining. The drawbacks of LN_2 use have been focused during the grinding of hardened AISI 52100 steel with a vitrified bonded wheel. It was reported that LN_2 did not reach the equivalent finishing that was obtained with oil. According to the authors, LN_2 strengthened the bonds which led to a deterioration of the wearing grits. Wu et al. [75] balanced this statement and reported that cryogenic LN_2 jetting is a very promising method to improve drilling processes by inducing stress in the material by thermal treatment. The authors compared the performances of LN_2 cooling and supercritical N_2 cooling during manufacturing. It was discovered that, under a similar jet pressure, the supercritical N_2 achieved better heat transfer results compared to LN_2. Hence, the drilling process reached better performances while using supercritical N_2.

Xia et al. [70] showed that cryogenic cooling also has application in the manufacturing of composite materials. The authors investigated the impact of cryogenic cooling on the drilling performance and on the composite surface integrity of a carbon fibre-reinforced plastic. It was discovered that using cryogenic cooling had the disadvantage of increasing the delamination but also reduced outer corner wear and the cutting edge rounding of the drill bit.

Cryogenic heat transfer is also used for recycling purposes. For

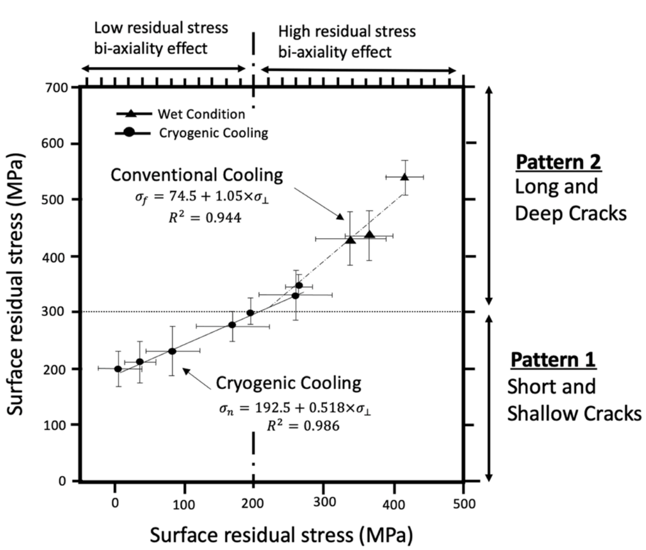

Fig. 4. Correlation between the stress corrosion cracking network and the residual stress distribution under cryogenic and conventional grinding [61].

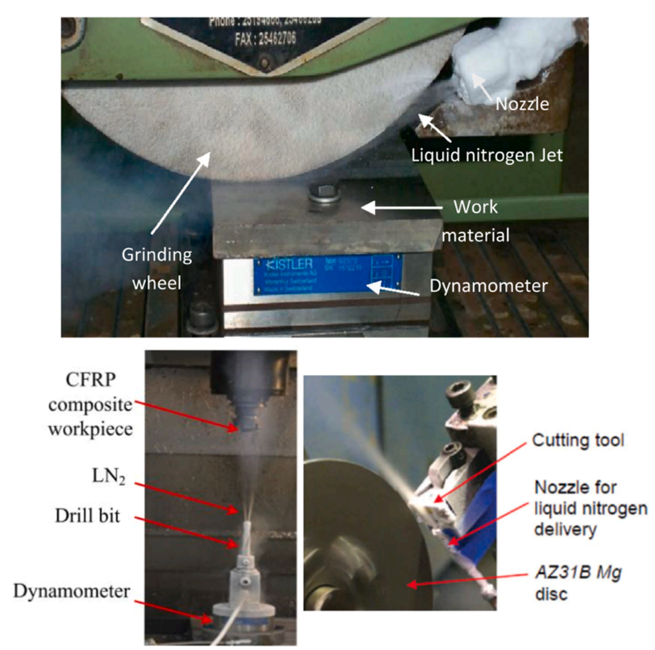

Fig. 5. Examples of liquid nitrogen use for manufacturing applications [66,70,73].

instance, at the end of a product life, milling is often used to transform objects or materials into particles that are easy to store and can be reused. However, due to the presence of heterogeneous materials and chemical differences in the scrap materials, the milling process can become challenging. One of the options developed to tackle this issue is cryogenic milling. In particular, cryogens help in the milling of plastic-rich materials. For instance, Bruyère et al. [76] compared different techniques with cryogenic milling in the waste management of end-of-life vehicles. The grinding jar was continuously cooled by liquid nitrogen. The results were different but the final particle size was acceptable. Manimaran et al. [71]. applied LN_2 to the grinding process of stainless steel 316. It was observed that the cryo-cooling reduced the grinding zone temperature of about 500 K and the grinding force by 37%. Paul and Chattopadhyay [77–79] published several works attesting the benefits of using LN_2 in the grinding process. During the grinding of steel, it was reported that the LN_2 cooling successfully reduced the surface temperature and assured its integrity, along with reduction of grinding force requirements.

3.1.2. Aerospace

In aerospace applications, the liquid cryogen preferred is helium due to the extremely low temperature that can be reached. Liquid He (LHe) is typically used to cool down earth-orbiting telescopes and satellites [23]. Volz and DiPirro [80] have detailed the importance of LHe cooling and the challenges faced during the National Aeronautics and Space Administration (NASA) cryogenic operation Cosmic Background Explorer (COBE). The performance of the dewar containing LHe, in addition to the temperature and pressure oscillation, were analysed. The X-ray astronomy satellite ASTRO-H was built to study the universe evolution and was based on a Soft X-ray Spectrometer as a main instrument. The detectors of the spectrometer needed to be demagnetized and thus were cooled to 0.05 K using a multistage adiabatic demagnetization refrigerator using LHe [81]. The satellite comprised a LHe tank for cooling purposes which was sufficient to maintain the detector fully functional for more than three years.

Yoshida et al. [81] fully described the hybrid cryogenic system of ASTRO-H including the He management and control to fuel the cryocoolers of the satellite. Cryocoolers are largely used for aerospace applications to cool down equipment and surfaces. Many cryocoolers are based on LHe. Shen et al. [82] studied the characteristics of a Joule-Thomson cryocooler using LHe for space applications. This type of cryocoolers has been commonly adopted due to its constant cooling temperature, long lifespan and reduced level of electromagnetic interference and vibration. Under certain conditions, Shen et al. [82] stated that the cryocooler can become unstable which limits the cooling temperature. Raad and Tward [83] conducted a review of the Northrop Grumman Aerospace Systems (NGAS) cryocoolers for space applications. The applications of these cryocoolers includes detectors for astronomy, cryogenic propellant management and missile warning purposes. Many types of cryocooler have been listed and detailed such as 10 K pulse tube cooler, Mid InfraRed Instrument (MIRI) hybrid cooler, high capacity cooler (HCC), high efficiency (HEC) cooler, mini and micro cooler, which all use He-3.

Orlowska et al. [84] developed a closed-cycle cooler for aerospace applications to obtain temperatures in the range of 2.5 K – 4 K, which is reachable only using LHe. Around temperatures of 4 K, He-4 was chosen as a working fluid whereas He-3 was used below 3 K. The cryocooler was able to maintain a temperature of 2.5 K for 72 h. Similarly, Jones and Ramsay [85] characterized a long life 4 K mechanical cooler. The cooler included a precooling section of LHe to 20 K before its injection. The operating cryocooler was capable of reaching and maintaining a temperature of 4 K. Sugita et al. [86] reported the use of LHe-based cryocoolers for the infrared telescope of the SPICA spacecraft. Cryogenic cooling has been used to protect the 3.5 m diameter primary mirror from radiation, the cryocoolers have successfully met the cooling requirements at temperatures of 1.7 K, 4.5 K, and 20 K.

Liquid oxygen LO_2 is mainly used as a propellant due to its reactive characteristics. In cryogenic rockets, the mechanical seals of high rotational speed LO_2 turbopumps must be cooled to control the rising temperature caused by friction. Turbopumps are made of two main components which are a rotodynamic pump and a gas turbine and are typically used to pressurize the propellant of rockets. The cooling working fluid used to control the temperature of the turbopump is generally in direct exposure to hot surface but Xie et al. [87,88] developed a new cooling approach driven by radial centrifugal force. The principle of this new cooling technique is to allow a portion of the LO_2 to reach the back of the impeller to cool down the assembly by itself. To investigate this principle, Xie et al. [87,88] used 3D computational fluid dynamics (CFD) including fluid-solid coupled heat transfer, cavitation and mixture models. The LO_2 used as a coolant had an inlet temperature between 82 and 90 K. Authors concluded that this new cooling technique was feasible and permits the maintenance of the solid material temperature within an acceptable range.

In many cases, it is important to maintain a certain flow phase and regime of the cryogenic medium to maintain optimum conditions. Shapiro and Hamm [89] wrote a report for NASA about the impact of the seal technology on LO_2 turbopumps. A spiral-groove seal aiming at sealing the high-pressure LO_2 at the turbopump impeller was investigated, in addition to a floating-ring buffered seal type whose function was to prevent the LO_2 injection into the turbine side. It was reported that an undesired vaporization of the cryogenic liquid can damage the seal by overheating. The seal was also affected by changes in the flow regime of the cryogenic liquid and pressure drop. This may result in turbulence and thicker fluid films which reduces the cooling performance in comparison to thin films. Oike et al. [90,91] also carried out an experimental study on high pressure gas seals intended for the LO_2 turbopump of the LE-7 rocket engine of Japan. Seals are also used to link the turbopump to an He purge for safety purposes. In this work, the floating-ring seal was resistant to a H_2 gas pressure of 15 MPa.

3.1.3. Superconductivity

Solids at cryogenic temperatures are the core of superconductivity where selected solid materials are cooled down to cryogenic temperatures. The first solid coil used for superconductivity that was stable with cryogenic cooling was Niobium-titanium (NbTi) [92]. The material was first cooled by cryogenic forced convection using LHe to provide a better dielectric insulation [93]. In the objective of having a magnetic field as strong as possible, Nb_3Sn and Nb_3Al have later been introduced. Yet, these materials are more brittle and required new manufacturing methods to avoid the degradation of the conductor. Later, materials in the form $(NbX)_3Sn$ with X an additional component that can be Ta or Ti have been introduced to reach frequencies in the range 700–1000 MHz. High temperature superconductors such as the Bi-2212/Bi-2223 tapes with critical temperatures of 110 K have later appeared and allow the use of LN_2 instead of LHe for superconductive purposes. The superconductors developed are commonly compared according to the law [93]:

$$V(I) = V_c(I/I_c)^n \quad (2)$$

Where, V the voltage, I the current, V_c the critical voltage, I_c the critical current, and n the exponent. The *V-I* characteristics of some superconducting solids at cryogenic temperatures are presented in Fig. 6 [93].

At the beginning of the 2000's, new manufacturing methods of elements have permitted the improvement of the recrystallisation process and texture quality of superconductors such as MgB_2, BSCCO 2223 with AgMg/AgAu sheathed conductors, YBCO coated conductors, and composite conductors [93]. In addition to the electric and magnetic characteristics of superconductors at cryogenic temperatures, another challenge in the choice of superconductors is the choice of structural solid elements chosen for cryogenic application is to limit the transverse stresses induced with the cryogenic cooling.

Over the years, it is observed that the demand of LHe for cryogenic

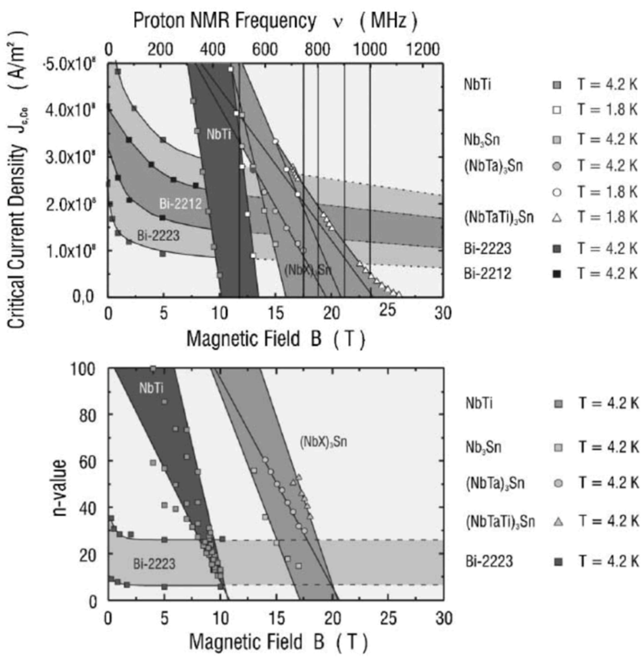

Fig. 6. V-I characteristics of several superconducting solids at cryogenic temperatures [93].

application is rising [94]. The main reason for this is that LHe is the only cryogenic medium available that can reach temperatures closest to absolute zero. In particular, LHe is used to extract heat of the order of tens of kWs in coils, solenoid structures, to maintain the superconductive state of magnets and must handle the pulsating heat load from the magnets [18]. To face this increasing demand for LHe, new LHe plants such as the High Magnetic Field Laboratory of the Chinese Academy of Sciences (CHMFL) LHE plant are developed to supply LHe for superconducting magnets. Each year, the CHMFL lab supplies more than 40, 000 litres of liquid helium to twelve major experimental facilities [94]. The twelve experimental facilities are: Optical Magnetic System (OMS), Crystal Growth System (CGS), Fourier Transform Infrared Spectroscopy (FTIR), STM-MFM-AFM Combo System (SMA), Electron Spin Resonance Spectrometer (ESR), RAMAN Spectroscopy, JANIS_9T Magnet, Magnetic Property Measurement System (MPMS), Physical Property Measurement System (PPMS), Magnetic Resonance Imaging (MRI), Superconducting Magnet Technology Research (SM_TECH) and Ultra Low Temperature Experiment System (ULTES). This clearly shows the wide range of critical applications in which cryogenic LHe is being essentially used.

The main use of the cryogenic LHe is to develop superconducting magnets [4,15,93,95] that themselves have different applications and open new opportunities in domains such as nuclear fusion, particle science, magnetic resonance spectrometers etc. Since the 1970s, the Institute for Technical Physics (ITP) of the Research Centre Karlsruhe has hosted many national and international collaborative projects based on superconductivity and cryogenic engineering [93]. The cryogenic infrastructure of the institute is equipped with two large refrigerators to achieve a cooling capacity between 4.5 and 1.8 K. The institute has largely contributed to the progress in superconductivity employing cryogenic LHe cooling. Among others, ITP has developed nuclear fusion superconducting magnets with the Toroidal Spulentestanlage Karlsruhe (TOSKA) facilities to test the super magnets and developed the EURATOM LCT coil, Wendelstein 7-X demonstration coil (W7-X DEMO coil), poloidal field model coil (POLO), and the ITER toroidal field model coil (TFMC) [93]. In collaboration with industry, the ITP institute has made the superconducting magnet technology accessible to commercial uses. Even if LN_2 is commonly used for pre-cooling, all the superconducting magnets utilize LHe. Among others, the JUMBO facility uses a liquid helium bath for superconducting NbTi and Nb3Sn [93]. To compensate for the rise of pool temperature, rotating LHe pools are used [96].

Cryogenic cooling is also used to develop superconducting cables. In 1975, Erb et al. [97] conducted a comparison of advanced high power underground cables and studied the economic side of forced convection cooled cables by water or oil, polyethylene cables, SF_6 cables, cryoresistive and superconducting cables. The authors concluded that the use of superconductivity for transmission cables is not viable economically. However, the appearance of high temperature superconductors allowing LN_2 to be used instead of LHe [4] can make superconductivity more accessible to a larger public [98,99]. The layout of a high temperature superconducting cable is presented in Fig. 7 [14].

Yapicioglu and Dincer [14], investigated high temperature superconducting cable thermal behaviour using cryogenic vacuum cooling. LN_2 was selected as a working fluid and the vacuum chamber was used to decrease the boiling point of LN_2 and maintain the liquid state of LN_2 at temperatures lower than −196 °C. The chamber was maintained at −209 °C which is below the superconducting temperature of the cable of −200 °C. The authors studied the impact of the ground depth of the superconducting cable, the wire diameter, and the ambient temperature of the system. It was shown that the mass flow rate and thus the pump work required increases with a decrease of ground depth, increase of the wire diameter and increase in the system temperature. As reported by Zuo et al. [98], the position and configuration of the high temperature superconducting cable in annular pipes and helically corrugated pipes is of importance for design and heat transfer purposes for superconducting cables. Therefore, many researchers such as in references [100–107] have oriented their research work to characterizing the liquid flow pattern and heat transfer of fluids such as LH_2 and LN_2 in a given pipe configuration. Among them, Das and Rao [108] conducted a flow analysis of subcooled LN_2 injected between the cable core and nine different corrugated pipes. High temperature superconductivity also has the advantage of being safer and less challenging on the avoidance of heat leakage.

Bahrdt and Gluskin [95] conducted a state of the art on cryogenic permanent magnets (CPMUs) and superconducting undulators (SCUs). They reported many CPMUs using LN_2 for cryocoolers such as in references [109–118]. Among them, Huang et al. [119] developed a hybrid-type CPMU using a PrFeB permanent magnet. The magnet was cooled down to 77 K using LN_2 based cryocoolers. To face the rising demand of high temperature superconducting cables and improve their performance, other fluids than LN_2 are being proposed. Dondapati et al. [120] studied the applicability of supercritical N_2 as a cooling fluid for future power transmission cables. By first detailing the properties of supercritical N_2, the authors estimated the pumping power and difference of temperature generated in the cable by supercritical N_2 and compared it with the subcooled LN_2. It was concluded that using supercritical N_2 led to a reduced pumping power requirement and higher temperature differences in the cable compared to LN_2. Vysotsky et al. [121] reported a novel superconducting MgB_2 cable using a hybrid heat transfer line with LH_2, LN_2 shield, and vacuum super-insulation. Three types of thermal insulation were tested, and the new system was concluded to be successful. Kalsia et al. [122] proposed supercritical Ar to be used as futuristic high temperature superconducting cable coolant. Correlations for supercritical Ar properties have been reported. Even if no practical tests have been conducted to prove the feasibility of supercritical Ar cooling, the authors concluded that the use of Ar would decrease the pumping power required and increase heat transfer rates.

Another application of superconductivity and thus of cryogenic cooling is the development of superconductive magnets for magnetic resonance imaging (MRI). MRI is a radiology technique that uses magnetic field gradients to visualize organs. MRI has been mainly used for anatomical imaging of organs in a centimetre-scale resolution but the progress in this area and the new technologies developed are now allowing microscopic details to be visualized. According to Mercado et al. [23] superconducting magnets typically use LHe as a cryogenic

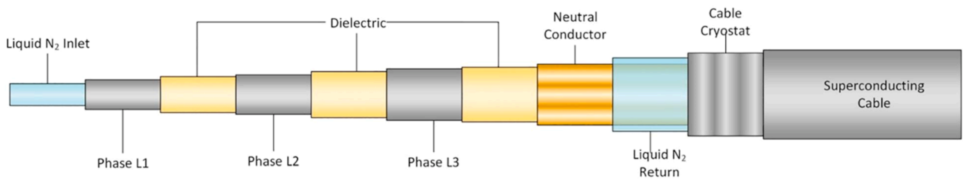

Fig. 7. High temperature superconducting cable [14].

heat transfer medium. However, with progress in this area and the appearance of commercial high temperature superconducting materials, new fluids such as LH_2 and LN_2 may become a viable solution for the future. High temperature superconducting magnets are also being implemented in tokamaks such as the Golem tokamak in Prague that uses LN_2 for superconducting magnets [123].

3.1.4. Healthcare

In the healthcare industry, the freezing of samples must be accurately controlled to preserve the cells and guarantee the quality of biological samples, hence LN_2 is largely used for the storage of samples [23]. Many works have thoroughly studied cryogenic cooling for healthcare applications using LN_2 for freezing/cooling process or storage purposes [124–128]. According to Clarke et al. [129], controlled rate freezing and LN_2 storage are the most common cell cryopreservation techniques. Rowe [130] conducted a state of the art work on blood cryopreservation, where cooling is usually achieved by LN_2 at −196 °C. Using LN_2, the current red cell cryopreservation techniques indicate more than 90% of clinically acceptable cells after thawing [130]. Donnenberg et al. [131] studied the viability of cryopreserved BM progenitor cells after storage for more than ten years. The samples analysed were placed in LN_2 for long-term storage of 9 to 14 years. It was concluded that the cryopreserved cells can still be used after such a time and that LN_2 immersion allowed the successful preservation of cells. This was also defended by Veraputhiran et al. [132] who stored dimethyl sulfoxide concentrations for up to 17.8 years in LN_2 and observed no difference in the viability of the product with the cryostorage period.

Fountain et al. raised the concern of hepatitis B transmission between putative stem cell components and hematopoietic progenitor stored in LN_2 [133]. In the study, five LN_2-based freezers have been surveyed to follow the microbial contamination. 1.2% of the samples have presented some contamination. Therefore, according to the authors, LN_2 can be a significant source of microbial contamination and its sterility must be measured and indicated to prevent the microbial transmission between samples and the cryogenic cooling medium. In addition, the cryoprotectant used during the freezing process can also pose a risk of contamination. Sputtek et al. [134] investigated the use of dimethyl sulfoxide as a cryoprotectant for the preservation of peripheral blood progenitors. Different cryoprotectant rates and cooling rates have been tested. The freezing process of the samples implied the submersion of the products into LN_2. Akkok et al. [135] carried out similar work on the use of dimethyl sulfoxide as a cryoprotectant and tested the impact of the cryoprotectant quantity on the blood cell preservation. The optimisation and research around cryoprotectants to implement LN_2-based cryogenic freezing process is of interest for many researchers [136,137].

In addition to cryoprotectants, the bags containing the samples can also be a source of contamination during the freezing process. Khuu et al. [138], described the causes and consequences of freezing bag failures during the storage of cellular therapy products. The test bags were stored for two years in LN_2. To overcome the risk of bag failures, authors proposed the use of overwrapping bags for the LN_2 immersion. In case of contact between products and LN_2, both sides can be contaminated. Indeed, the presence of particles in LN_2 can create ice in the storing dewars. Among others, Morris [139], studied the origin of sediments potentially accumulating in LN_2 storage vessels. Therefore, it is deduced that the direct contact between LN_2 and samples is an important potential source of contamination. In this regard, some innovative techniques are currently tested to achieve an effective cooling without direct contact between the product and LN_2.

In cooperation with the industry, Chauhan et al. [19,20] investigated the freezing process and performance of a batch freezer using LN_2 sprays. The LN_2 was directly injected into the fan which distributed the LN_2 mixed with air inside the chamber. The freezing process was investigated using numerical and experimental approaches. In particular, attention was focused on the optimal blood bag positioning. It was concluded that LN_2 injectors allowed short freezing times without a sudden variation of blood bag temperature. Moreover, the bag placement in addition to the LN_2 injector's position are of importance to assure optimum cooling and limit local rises of temperatures in the samples.

Another application of cryogenic mediums for healthcare purposes is cryotherapy [140]. Cryotherapy is the treatment of tissue lesions by heat transfer. This process is particularly attractive in the treatment of damaged cells which cannot be removed by surgery. The cryotherapy process usually implies the local projection of LN_2. Kachaamy et al. [141] have reported the treatment of inoperable esophageal cancer by LN_2 endoscopic spray cryotherapy. The LN_2 was sprayed at −196 °C on the tumour tissue, as illustrated in Fig. 8 [141].

After several cryotherapy treatments, the cancer cells significantly reduce. The tests were carried out on 49 inoperable esophageal cancer patients and it was concluded by Kachaamy et al. [141] that the cryotherapy technique may be a safe and effective procedure. De Jesus Azevedo et al. [142] reported the use of cryotherapy in the treatment of an odontogenic tumour. The LN_2 cryotherapy was associated with surgery to limit the risk of recurrence, which after a year, no tumour recurrence has been observed. Singh and Neema [143] compared cryotherapy by the LN_2 spray technique with electrosurgery by electrodessication, with the objective to treat plantar warts. A total of 48 patients were treated by electrosurgery whereas 60 were treated by cryotherapy. The overall clearance rate for both techniques is similar and around 75%. Nevertheless, the pain felt by the patients and wound healing was improved when using cryotherapy. Fraunfelder [144] considered the use of LN_2 cryotherapy on superior limbic keratoconjunctivitis. A double freeze-thaw technique was used with LN_2 spray. As a result, seven eyes were treated with zero symptoms after two weeks. Zawar and Pawar [145] treated chronic, unresponsive nodular scabies using LN_2 therapy, using freezing-thawing cycles, the persistent nodules have been removed.

3.1.5. Advanced research

When applications imply extremely low temperatures, LHe is commonly used. Some of these applications requiring an extreme cooling close to the absolute zero temperature are often the most demanding but also represent major scientific progress. Therefore, LHe is used in many high-level research applications such as fusion reactors, particle accelerators, gravitational wave detectors and tokamaks. A tokamak is an installation using the magnetic fields of super-magnets to control thermonuclear fusion power and confine extremely hot plasma. Here, cryogenic mediums are not only used for the superconductivity of the magnets but also for cooling or thermal shielding purposes.

The Experimental Advanced Superconducting Tokamak (EAST) at Hefei, China, is a superconducting tokamak magnetic fusion reactor, and

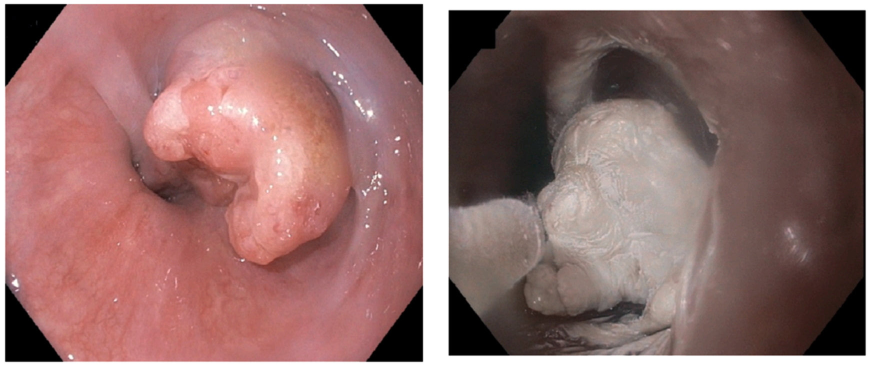

Fig. 8. Esophageal cancer treatment with cryotherapy [141].

is the first tokamak that uses superconducting poloidal and toroidal magnets. Chen et al. [146], described the design and manufacturing of the superconducting toroidal field magnets used for the EAST tokamak The toroidal field magnet system comprising sixteen superconducting coils has been cooled down from ambient temperature to 4.5 K using supercritical He. Chen et al. [147], reported the design and construction states of the cryogenic system of the HL-2A tokamak at the Southwestern Institute of Physics (SWIP), China. To cool down the cryopumps and thermal shield of the tokamak, in addition to maintaining the superconducting state of the magnets, a He refrigerator was installed. The LHe cryogenic system designed enables the cryopumps and superconducting magnets to cool down to 4.5 K whereas the thermal shields are maintained at around 80 K. The 500 W cryogenic system mainly uses LHe, but the supercritical form of He is also used for the cryopumps. In addition, LN_2 was used before He for pre-cooling purposes and two-layers of LN_2 protect the pumping surface and act as thermal shields [148]. Finally, gaseous He was used to pre-cool the cryogenic line and avoid sudden gradients of temperature in the system.

The International Thermonuclear Experimental Reactor (ITER) nuclear fusion research is a cooperative international project building the world's largest tokamak in Saint-Paus-les-Durance, France. Its construction started in 2013 and it is expected to be completed by 2025. The ITER reactor uses toroidal and poloidal superconducting field coils maintained at cryogenic temperatures by supercritical He [149]. The world's most powerful and largest particle accelerator named Large Hadron Collider (LHC), situated in Geneva, Switzerland, is fully relying on cryogenic cooling. The particle accelerator uses 26.7 Km of superconducting magnets whose magnetic field is used to increase the energy of the particle. To maintain the superconductivity state of the magnets, the only suitable cryogenic element available is LHe. Magnet cooling by pressurized static LHe baths permits the magnet temperatures to be maintained at about 1.85 K and therefore allows the feasibility of LHC operation [150].

The Satellite Test of the Equivalence Principle (STEP) mission aimed at verifying Einstein's theory of relativity and gravity by performing an earth-orbital experiment in a satellite using superconducting elements. To maintain the temperature of the four gravimeters used at around 1.8 K, superfluid LHe was used [151]. The superfluid phase of LHe was of interest due to the extreme precision of measurements required and to limit the gravitational disturbances induced by the coolant motion. Cryogenic cooling is also used for very sophisticated applications such as gravitational-wave detectors. These detectors aim at measuring gravitational waves which are small distortions in the curvature of spacetime generated by the acceleration of masses and were first mentioned by Poincaré and later introduced by Einstein. Achieving very low cooling temperatures close to absolute zero for tons of metallic large cylinders leads to improved sensitivity of the gravitational wave detector [152]. The highest sensitivity reached up to today was achieved in the gravitational wave observatory called NAUTILUS where LHe cooling allowed a cylinder temperature of 0.1 K to be reached [152]. Yet, this cooling is not efficient enough to detect the largest gravitational waves. To do so, the cryogenic cooling must be improved to reach temperatures around 0.01 K [152].

3.2. Gaseous mediums

3.2.1. Machining and manufacturing

In agreement with the sustainable development concerns, green manufacturing methods are of interest where cryogenic mediums have a role to play [71,153]. Zhang et al. [153] reported the use of cryogenic air gas and a minimum nanofluid quantity to achieve a more environmentally friendly grinding process. The cryogenic air combined with the nanofluids minimum lubrication gave the best results in terms of lubricant viscosity, contact angle, stability and grinding energy required. The use of cryogenic air reduced the grinding temperature by 60 °C. Cryogenic heat transfer is also used for cryogenic comminution as a waste management technology. The principle of comminution in scrap recycling is to allow some components of a material to be separated from a mixture to be reused or retransformed [8]. In this application, cryogenic mediums are used to facilitate the comminution process and also limit the accumulation of thermal energy in the scrap, thus preventing the components from being degraded.

According to Daborn and Derry [8] and Allen and Biddulph [154], cryogenic comminution processes usually operate using LN_2 which is volatilised on the material. For instance, the Connecticut Metal Industries in Monroe use LN_2 in their cryogenic comminution process to separate plastic bottle caps and aluminium [8]. Before the comminution process, particles such as crumbs from scrap rubber can be pre-cooled before proceeding to the comminution process. To do so, Wang et al. [155] utilised a vibrated fluidised bed to investigate the heat transfer between vaporised LN_2 mixed with air and rubber particles from discarded tyres, using the experimental setup shown in Fig. 9 [155].

In their experimental procedure, LN_2 is vaporized, and the N_2 gas is mixed with air which is injected to the vibrated fluidised bed containing the rubber particles. The theoretical analysis indicated that the heat

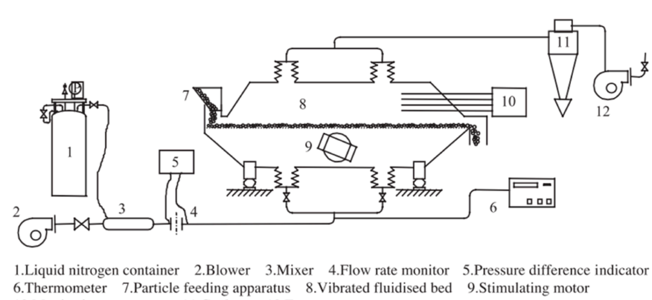

Fig. 9. Cryogenic cooling between vaporized liquid nitrogen and scrap rubber particles in a vibrated fluidised bed [155].

transfer coefficient was improved using a vibrated fluidised bed instead of a fixed bed. By investigating the bed layer thickness and cryogenic gas flow rate impact on the heat transfer, Wang et al. [155] developed a new heat transfer correlation relating the forced convective gas-solid heat transfer coefficient to the gas flow Reynolds number, strength of vibration, and bed layer thickness A similar applicability of cryogens in the same domain is the thermal treatment of rock or particles for thermal shock [156]. When a solid element is suddenly confronted with a very low temperature, an induced thermal stress appears, which reduces the strength of the element and can lower the power consumption needed in the crushing or grinding process (Fig. 10).

3.2.2. Superconductivity

Cryogenic mediums are also used in the gaseous phase for superconducting applications. As attested by Pamidi et al. [158], He gas can be used for the cryogenic cooling of high-temperature superconducting power cables. Even for superconducting materials for which the critical point cannot be reached with inexpensive LN_2, LHe remains costly and the use of a high quantity of liquid phase is more onerous than using the gaseous phase. Therefore, Naumov et al. [159] studied the feasibility of using gaseous He of LHe for superconducting coil cryocoolers. Gaseous He based cryocooler was developed, tested and validated, and it was found that quench current at a temperature of 4.2 K was equal to the quench current while using LHe. Pamidi et al. [160] have studied cryogenic He gas circulation system for high temperature superconductors operating in the range of 50–80 K. It was found that the use of gaseous He is more costly efficient for the application where the compactness and weight are of importance. A thermal model for design purposes has been developed and it highlights the importance of the He gas mass flow rate on heat transfer. According to the flow circulation facilities used, the use of He gas can be limiting if very high flow rates are needed for large superconducting devices.

Flitzpatrick et al. [161] reported the use of a fifty meters of gaseous helium based high temperature superconductor for a Navy ship. For naval applications, to face the increased signature and safety requirements, cryogenic gas is preferred over liquid. Especially, a leak of LN_2 into the ship environment would be dangerous. The superconductor was maintained at 55 K and was proved to be a viable solution for high temperature superconductors. Kephart et al. [162], similarly highlighted the degaussing potential of high temperature superconducting cables using gaseous He. This is of interest in reducing the ship's magnetic signature. The He gas flow system was mounted and tested. Despite a failure during the first attempt due to an inadequate He flow rate; the system has been fully operational from June 2009 to February 2010. A similar work was conducted by Ferrara et al. [163] to use gaseous He superconductors for shore power connectivity in naval ships. The use of superconductors can decrease the number of copper cables used and therefore decrease the weight of the installation. The decrease in weight of power transmission devices using gaseous He high temperature superconductors is also greatly interesting for airborne applications [164].

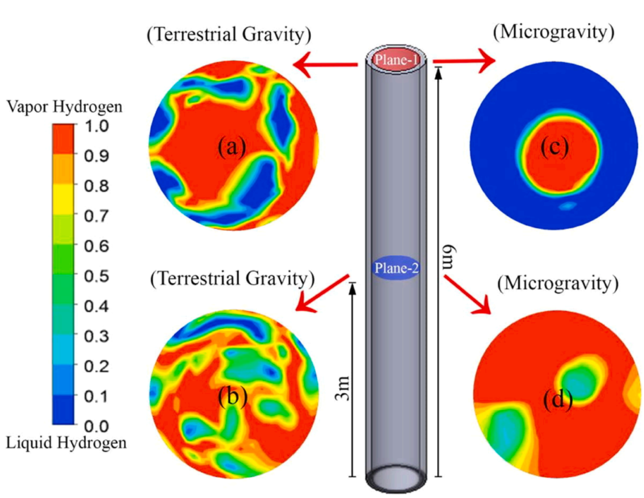

Fig. 10. Influence of gravity on hydrogen phases distribution of a two-phase flow in a pipe [157].

Suttell et al. [165] numerically investigated the injection of gaseous He for high temperature superconducting cables. The pressure drops of He gas in the channels, temperature gradient and channel geometry were investigated and the authors proposed a new gas channel geometry to decrease the required pumping power. Kim et al. [166] focused their work on the termination design for testing gaseous H_2-Ar cooled superconducting cables. To prevent the oxidation of the superconducting cable, gaseous H_2 is used as an absorbent to protect the superconducting solid [167]. Maeda et al. [167] focused their research on studying the impact of the presence of Ar in gaseous H_2 on the superconductor's properties. It was found that the presence of gaseous Ar in the hydrogen drastically decreases the magnetic properties of the cable.

In relation to superconductivity, a generic but promising technique of MRI is the use of hyperpolarized He-3 gas to improve the visualization. Under current conditions, MRI on the magnetisation of hydrogen protons H^+. In the case where the substance has a significant amount of water, the visualization is of good quality. However, for biological objects such as human organs, i.e., lungs that contain fewer protons, classical MRI has difficulties in producing accurate results. In this regard, to enhance the imaging, Elbert et al. [168] introduced in 1996 Hyperpolarized He-3 MRI. Before the process, the patient inhaled He-3 hyperpolarized gas which provides an extensive improvement in the polarization of protons. Altes et al. [169], Zha et al. [170], Shreiber et al. [171] all assessed the capacity of the hyperpolarized He-3 based technology.

3.2.3. Healthcare

In order to limit the degradation of samples due to the direct contact between LN_2 and cells, gaseous N_2 has been considered for freezing purposes. According to Skowron et al. [172], some human cells such as red blood cells, bone marrow, lymphocytes or spermatozoae need to be preserved at temperatures close to the N_2 boiling point. To reach −140 °C and preserve biological cells, Skowron et al. [172] used cryotubes placed in the N_2 gas. Baudot et al. [173] used the vitrification process to assure the long term cryopreservation of organs and ease transportation. The vitrification was made using N_2 vapour and a temperature regulation system controlled the mechanism to limit the constraints induced in the material during vitrification. Sputtek et al. [174] investigated the cryopreservation of hematopoietic progenitor cells (HPC). To preserve the cells, sterile, cryogenically stable plastic bags are commonly used. In their work, Sputtek et al. [174] compared the cell quality after freezing, thawing and refreezing of the biological sample using partial immersion of the bags in gaseous N_2. Two cryogenic freezing bags, namely the CryoMACS freezing bag 200-074-402 and the Cryocyte freezing container R4R9955, were compared and found to be equivalent in terms of cell preservation.

The use of gaseous N_2 is also common for sperm cryopreservation. Wayman et al. [175] investigated the preservation of sperm from pallid sturgeon. Methanol was used as a cryoprotectant at concentrations of 5–15%v. The samples were then placed in aluminium cans and introduced into a N_2 vapor dewar. After 1 year of storage, the samples successfully produced eggs. Similar works on fish sperm preservation were conducted by Wayman et al. [176], Tiersch and Green [177] and Cloud et al. [178] with the use of N_2 vapour for freezing purposes. Anel et al. [179] compared four different freezing protocols for the preservation of sperm from ram. The results showed that the sample had a better quality when the cooling was conducted under controlled conditions such as bio-freezers in comparison to uncontrolled exposure to N_2 vapor. Ziegler and Chapitis [180] used N_2 vapor freezing of human sperm before submersion in LN_2. The objective of using N_2 vapor instead of a direct plunge into LN_2 was to protect the samples. It was found that direct submerging in LN_2 led to a reduction of sperm recovery by 65%, whereas using N_2 vapour prior to submerging the samples led to a reduction of sperm recovery by 32% only. Therefore, the use of N_2 vapor is advised to improve the recovery of motile sperm and improve pregnancy rates. Bielanski [181] studied the bacterial transmission from the vapour phase of LN_2 to embryos. The embryos were stored in short-term storage dewars to allow the transportation of biological specimens. The embryos were stored for 7 days in gaseous N_2 before analysis and it was found that this cell preservation technique was reliable for a short-term storage of 7 days.

4. Two-phase applications

Cryogenic mediums are involved in some applications where phase change is taking place, hence transfer of latent heat as well as sensible heat is involved. In this case the two-phase equilibrium between involved phases such as solid-liquid, solid-gas, and liquid-gas has to be carefully considered [182]. Accordingly, the systems are thermodynamically studied as the thermodynamics of the system defines its state and characteristics [183]. The characterisation of two-phase flows is typically determining the interphase relation between the two phases. Tan et al. [184], investigated the solid-liquid, solid-vapor, and solid-liquid-vapor interfaces under cryogenic conditions. The aim of the study was to investigate the equation of state between the phases based on the framework of the thermodynamic perturbation. The research applies a theoretical approach due to the limitation of numerical simulation on a molecular level. The theoretical model was applied to predict the thermodynamic process of Kr, Ar and CH_4 with an applied binary phase interaction. The results from the investigation indicate a satisfactory prediction of thermodynamic profiles. The research suggests a numerical instability to predict the immiscibility of the solid phase during the phase change process due to the difference in crystalline structures.

4.1. Solid-Liquid mediums

For heat transfer purposes, the use of solid cryogens is limited. Nevertheless, for the use of natural gases as fossil fuel, the separation between the methane CH_4 and contaminants such as carbon dioxide CO_2 is essential. Liquification of natural gas, i.e., to liquified natural gas (LNG) is one of the main means of easing the transportation of natural gas from producing countries to consumers worldwide. LNG is obtained by cooling natural gas to a temperature of -160 to -162 °C and pressure of 1 atm by cryogenic means. One of the main challenges for cryogenic cooling to obtain LNG is the solidification of CO_2 (sublimation point of -78.5 °C and 1 atm), hence it has to be efficiently removed. Additionally, to avoid pipeline corrosion and environmental issues, the acceptable standard of CO_2 in natural gas should be $<2\%$ [185,186]. Therefore, technologies for CO_2 separation are required. Among them, cryogenic CO_2 separation has recently become more attractive due to 30% lower energy requirements in comparison to conventional methods, sorption and membrane separation processes [187]. For an optimized CO_2 separation from natural gases with cryogenic heat transfer, an accurate thermodynamic phase study is required. In this regard, researchers have particularly focused their efforts on describing the phase interactions between CH_4 and CO_2. The interaction of the two phases at cryogenic conditions has been investigated by Shafiq et al. [188]. The study investigates the two-phase flow between solidified CO_2 and CH_4 in a cryogenic distillation column [189]. The results from the study indicate a change in solidification rate in relation to the CO_2 phase.

The numerical prediction using software to predict and analyse the relationship between CH_4 and the solidification of CO_2 in a two-phase flow has been widely investigated. Although numerical solvers exist, the key question is whether to include or disregard the thermal equilibria between phases. Baker et al. [190], discussed the numerical validation tools available to model the solidification within CO_2 and CH_4 under cryogenic conditions. The study highlights a preferential treatment for theoretical modelling over numerical solvers due to the ability to predict the temperatures where hydrocarbons will begin to solidify. The investigation defines the benefits of theoretical modelling in relation to the domain, showing accurate predication of liquid and solid phases even during weak or limited phase interactions. A comparative study was conducted on CH_4/benzene, CH_4/hexane, CH_4/toluene and CH_4/CO_2 mixtures. The results show a level of variation between the numerical model and the thermodynamic cycle for each solution, due to the unaccounted crystallisation changes during the solidification process. Another study was conducted by Spitoni et al. [191], where the phase interaction between CO_2 and CH_4 was investigated under cryogenic conditions. As previously mentioned, studies have investigated the varying effects of CO_2, and it is evident the relationship between CO_2 and CH_4 is increasingly complex with the increase in CO_2. The resultant two-phase diagram indicates a change in the triple point, which is not ideal for the cryogenic application. The proposed solution to maintain the thermal equilibria involves a set of two heat exchangers to cool down the CO_2 within the flow stream. The rate of solidification between the phases is significantly changed as frost will form on the heat exchanger rather than solidifying within the flow stream. The results from the study indicate the potential to manipulate the thermodynamic cycle to improve cryogenic two-phase flow streams.

Babar et al. [192] investigated the two-phase flow of CO_2 within CH_4 and hydrocarbon flow stream for the processing of natural gas under cryogenic conditions. The study shows two potential routes: a numerical model and a theoretical analysis. The analysis using equation of state allowed an appropriate definition of the solid-liquid interface but also the analysis of the triple point. When the equation of state analysis was implemented, the model allowed the definition of molar fraction between the phases, which was previously unknown in other numerical models. Similarly, Guido et al. [193] investigated the solubility of solid CO_2 phase fractions in an array of hydrocarbon phase fractions using the equation of state approach. Among other alkanes, a CO_2—CH_4 mixture was studied. The outcome of the study showed a successful implementation of the model with the accurate prediction of the solubility of the carbon dioxide solid phase within the hydrocarbon liquid phase.

4.2. Liquid-gas mediums

The interaction between liquid and gas is highly investigated in many industries including in the development of cryogenic heat pipes. The heat pipe (HP) consists of a hermetically closed tube with a small amount of cryogen as the working fluid [194]. HP can be characterised in three sections: the evaporator, condenser and an adiabatic region between the evaporator and the condenser. The evaporator section of a HP is placed within a hot stream[195] .As the working fluid inside the HP is at saturation conditions, the hot evaporator stream forces the working fluid to boil [48,196,197]. The vapour produced from the boiling phenomena will travel to the condenser section, at which condensation of the working fluid takes place. Finally, the condensate returns to the evaporator section via a wick or by gravity. HP can operate in a wide range of conditions ranging from low absolute temperatures to 1000 °C hence making it very efficiently utilized in many applications such as in industrial waste heat recovery [198–202].

Typically, the development of cryogenic HP involves the application of elemental gases such as: N_2, Ne, Kr, Ar etc. Elemental fluids have been applied in non-gravity applications, from the cooling of satellites and telescopes to the cooling of particle detectors. The implementation of cryogenic HP has been investigated and applied in a cooling system at the CERN research facility. The study presented by Pereira et al. [203] highlights the utilisation of loop heat pipes (LHP) to effectively cool particle detectors in an initial lab scale scenario. The LHP was investigated with both Kr and Ar working fluids with a copper shell material.

During the operation, the LHP effectively transfers heat allowing for a considerable temperature difference between the condenser and the evaporator sections, without the risk of dry out—previously observed in other LHPs. The comparison between Kr and Ar was performed with a change of inclination angles ranging from 0° to 90° from an initial vertical position. The overall results highlighted the decline in performance as the system reached 90°, with saturation of wicks and the condensation chamber and a significant decline in performance at 75° The operational difference between both working fluids highlighted the superior performance of Kr of 25 W at 75°, with Ar only providing 10 W.

The application of cryogenic working fluids within LHP has experienced a level of dry out which is a significant performance-limiting factor. The physical operation of cryogenic LHP often features auxiliary loops due to the failure to start during initial conditions. The characterisation of failure has been widely researched, Guo et al. [204] investigated the operational failure of a Ne-based LHP. The experimental set up highlights a simplistic LHP design connected to a cryocooler acting as a heat sink and a primary evaporator acting as the heat source. The overall results highlighted a successful start-up with a dramatic temperature decline in the condenser temperature once the minimum wettability requirement of the wick was achieved. The successful operation was hindered once a heat load was applied, showing a failure to start up due to several reasons, ranging from irregularity in condenser temperature leading to the solidification of the working fluid within the condenser, which blocks the operation of the HP. Similarly, the failure could be due to the limited liquid fraction to the evaporator, allowing for a significantly reduced operation and incapability to handle the thermal load. The studies highlighted the potential for cryogenic fluids, but the operation is highly dependent on the heat load requirements which can lead to the failure of the system.

The application of cryogenic fluids is not limited to the use of HPs. Agarwal et al. [157] investigated the two-phase flow of liquid H_2 through cryogenic feed lines, subsequently modelled through ANSYS Fluent. The premise of the study was to investigate the flow properties between liquid and gaseous phases. The basis of the test shows a development of a slug flow throughout the feed line. The indicated results show the influence of gravity, as the liquid and vapour phases begin to separate causing a slug flow, as illustrated in Low mediums. The change in gravitational effects indicates a higher level of formation of vapour slugs which break under increased gravitational effects. The study highlights the change in phase interaction between liquid and vapour in relation to the phase distribution and the subsequent change in flow structure. The relationship between the phases and gravitational effects allowed the progression into an annular flow, where the liquid phase is only present between the wall and the vapour. The compounding effects of this significantly increase shear stresses in a pipe flow and increase the resistance in a feed line. The relation between the phases was further validated through ANSYS Fluent, which confirmed the hydrodynamic forces and change in two phase flow dynamics as a result of different gravity levels.

A comparative flow study was conducted by Barber et al. [205] who investigated the cooling of fusion magnets using H_2, He and Ne. The aim of the study was the cooling of high-temperature superconductors, where the cooling capacity of H_2, He and Ne were tested independently through a cooling loop. Traditionally, the cooling of fusion magnets was limited to the use of LHe. With the increase in thermal load and the development of superconducting materials, the available cooling range is wider allowing for a range of cryogenic mediums. The cooling schematic allows an annular flow surrounded by a super conductor. As expected, the operation with LHe shows the optimum heat transfer rate, but H_2 and Ne both performed comparatively with high thermal loads. The two-phase interaction between LHe and gaseous He has been widely noted due to the favourable temperature range, and ability to perform within high pressure applications. The identical test with gaseous and liquid Ne proved to be a hinderance with an associated pressure drop as a result of the liquid-gas interaction.

4.3. Solid-gas mediums

The investigation of solid-gas two phase flows is commonly seen in the application of cryogenic fluidised beds. A study between solid and gas phases was investigated by Guo et al. [206], who investigated the characterisation of phases on a cryogenic moving fluidised bed. The interaction between the solid particles and the fluid was noted, alongside the displacement of particles as the fluid phase flow rate increases. The interaction defines the heat transfer process between the gas and solid phase. The phenomenon was investigated by Wang et al. [155], who studied a cryogenic vibrating fluidised bed with solid particles. A numerical model was developed and validated versus the experiments conducted. The initial observations from the study indicate an increased heat transfer rate as a result of the vibration in comparison to a fixed or moving bed. As the vibration through the fluidised beds is constant, the suspension of the solid phase was sustained with minimal separation from the gas phase.

The interaction between solid and liquid phases has been investigated in refrigeration cycles. Yamaguchi et al. [207] investigated solid-liquid phases of CO_2 in a refrigeration loop. The investigation was based on a cryogenic retrofitted refrigeration loop. The refrigeration is achieved by expanding the liquid CO_2 into a two-phase flow of a solid-gas flow. The characterisation of the flow was further validated through a one-dimensional model to investigate the feasibility of a solid-gas CO_2 refrigeration loop. The initial outcomes with a traditional refrigerant showed a surrounding temperature of −50 °C. The implementation of an expanded two-phase flow indicates a surrounding temperature of −90 °C. A key observation from the study was the phase fraction between the solid and gas mediums. One of the key relations noted is the concentricity of the solid in relation to the gas. The observations from the study indicate the solid particles of CO_2 will eventually sediment when the gas velocity is minimal. The increase in gas flow rate saw the suspension of the solid phase throughout the refrigeration system.

The addition of cryogenic fluids has been investigated using a hybrid refrigeration loop consisting of solidified Ne and LN_2. Higashikawa et al. [208], developed a hybrid refrigerant for the cooling of high temperature superconductors for the application of nuclear magnetic resonance (NMR). The refrigeration cycle was used to cool a chamber to 25 K. The performance of the hybrid refrigerant was investigated by varying the concentricity of Ne and N_2. The basis of the study assumes solid phases of Ne. The concoction of the refrigerant was produced in a mixing chamber, where a Ne stream was fed into the chamber. The outcomes from the study highlight the improved cooling performance with the addition of Ne, with an increased cooling performance with an increase of concentricity. The interaction between both phases leads to two observations. The first observation is that the Ne added during the operation as a cryocooler soon liquifies but does not hinder the cooling performance, which was recommended as a development of a hybrid cryogenic fluid. The second observation indicates the liquification of N_2, with the optimum concentricity of Ne particles to be a beneficial hybrid refrigerant.

5. Three-phase applications

The investigation of three-phase flows can be determined by the interaction of homogenous and non-homogenous species. Typically, the definition of three-phase flows can be split into three characterisations: Gas-Solid-Liquid, Gas-Liquid-Liquid and Solid-Liquid-Liquid. The interaction of these phases depends on several interphase characteristics. For instance, the relationship between two or more liquid phases is highly dependent on the immiscibility of each phase in relation to wettability of each phase. This can play a key indicator in characterisation of the flow or indicate separation between the phases. Similarly, the introduction of gaseous phases introduces bubbles into the flow stream. The size of the bubbles needs to be considered as the size of the bubble affects the surface tension between each phase. The addition of solid particles follows similar principles, where the solid particles require a minimal mass flow rate to be suspended. The application and study of three-phase flows has been widely investigated in several applications ranging from microfluidic chips to fluidised beds. Although these areas are widely researched at ambient to high temperatures, the application within the cryogenic field remains sparse both experimentally and numerically.

6. Conclusion

The manuscript reported a state-of-the-art on cryogenic mediums and their applications for heat transfer purposes. After introducing the studied cryogenic mediums which present a boiling point below −150 °C, the study identified the cryogenic mediums used for a given application. For heat transfer implying a single phase of cryogen, N_2 is largely used due to its low cost, availability and inert behaviour. Among other applications, N_2 is mainly used as a liquid or gas in the food and healthcare industry for storage purposes. N_2 is also a promising solution for the improvement of manufacturing processes with cryogenic cooling assistance. As nitrogen is one of the largest applications due to its thermal properties and highlights one of the largest areas of growth related to healthcare and food, several on-going studies discussed in this paper highlight the need to optimise liquid nitrogen systems.

The second largely used cryogen is He. Due to the existence of its liquid phase at very low temperatures, He is used for demanding applications where cooling temperatures near absolute zero are required. Typically, He is used for aerospace and superconductivity applications. Due to the challenging nature of liquid helium, several studies involve optimising helium from a processing perspective to optimise storage potentials and develop helium based energy storage solutions.

Yet, with the progress of superconductivity and the appearance of high-temperature superconductors, the use of H_2 and N_2 for superconductivity applications is opening new opportunities as these cryogens are more cost efficient. Due its reactivity and instability, O_2 is rarely used as a heat transfer medium, but is mainly used as a propellant for engines. The use of hydrogen as a fuel has also been widely researched this past decade from both a domestic and industrial perspective.

For low temperature cooling, cryocoolers using H_2, N_2, air and He have been reported. Cryogenic mediums are also used in two-phase status. To separate CO_2 from natural gas under cryogenic conditions. With the objective of transferring large amounts of heat and limiting the risk of contamination, heat pipes are a promising solution which involve the phase change of a working fluid from liquid to vapour. Heat pipes can be used for cryogenic heat transfer and working fluids such as Kr, Ar, Ne and N_2 have been investigated and found to be very efficient. It was also identified that the use of solid cryogens and the three-phase applications of cryogenic heat transfer is scarce up to the present day.

The previous sections show the most recent developments within the cryogenic temperature spectrum. One of the main topics for research is to understand the mechanisms behind cryogenic mediums from both a heat transfer and materials point of view. For instance, several new models and correlations are being developed to understand their heat transfer and boiling mechanisms. The development of new numerical models also allows an increased amount of research into cryogenic heat pipes where characterising the boiling phenomena is of great importance and imperative to the technology's performance. With the ongoing research into cryogenic mediums, this will also push the development for cryogenic technologies but also the processing to obtain these mediums. Several studies are emerging to develop more efficient storage tanks to cryocoolers, especially for challenging mediums such as liquid helium. The development of more efficient processing equipment also means that innovative energy storage methods can be developed such as cryogenic hydrogen fuel cells.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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