

Use of cryogenic fluids for zero toxic emission hybrid engines

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ABSTRACT

In this paper we present the basic concepts of operations of a hybrid liquid nitrogen and internal combustion engine currently under development by Ricardo Innovations, Dolphin N2 and the University of Brighton, the CryoPower recuperated split cycle engine (RSCE). The engine is based on a new split-cycle combustion concept utilising isothermal compression via cryogenic injection to maximise the efficiency of the engine, while also providing near zero polluting emissions from the dilution effects. Combined experimental and numerical findings will be presented and the effect of evaporation dynamics of the LN₂ are explored. This study aims to improve the understanding of the spray process evolution in order to achieve optimal isothermal compression.

1 INTRODUCTION

Cryogenic liquids are gases which have been converted to liquids by cooling them to very low temperatures. It is generally agreed that a liquid is cryogenic if it exists in its liquid state at temperatures below 122K. Common cryogenic liquids which have found applications in several technologies are Liquid Helium (LHe), Liquid Oxygen (LOX), Liquid Hydrogen (LH₂) and Liquid Nitrogen (LN₂). LHe is used to achieve very low temperatures and is used in Magnetic Resonance Imaging (MRI) scanners and other superconductor applications. LO_x and LH₂ are used as oxidizer and fuel combinations respectively in cryogenic rocket engines. LN₂ is currently mostly used for refrigeration and cryo-preservation due to its cheap and abundant availability.

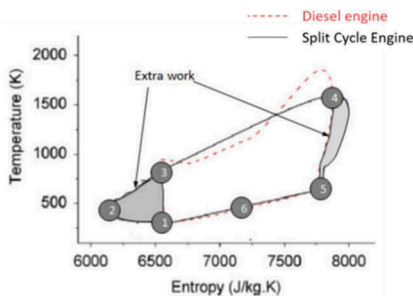
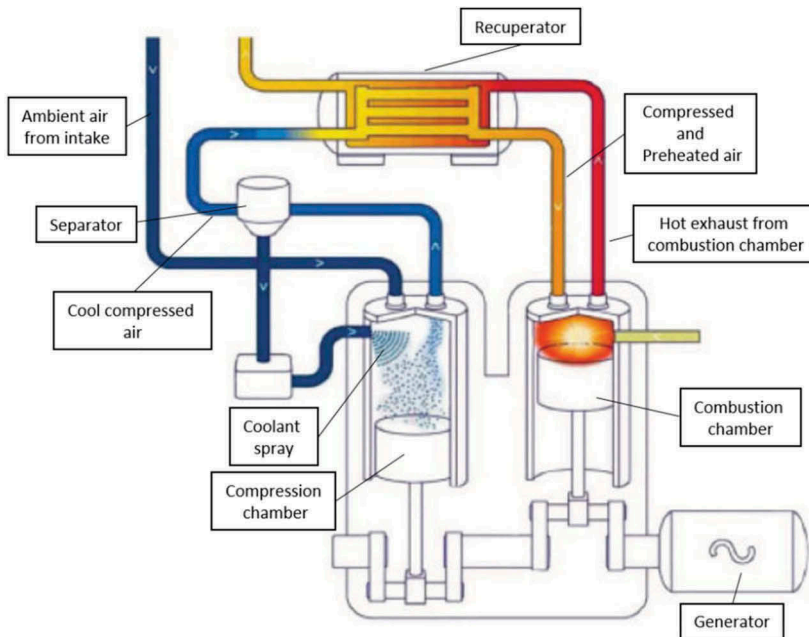
Recently there has been an increase in interest for research relevant to the use of cryogenic fluids in transportation applications. Examples of such systems are the Dearman engine, which is a zero-emission engine featuring no combustion, and the CryoPower RSCE, a hybrid high efficiency engine aimed at heavy duty applications. If the production of the cryogenic fluid is obtained from renewable energy resources, or wasted heat such as wasted cold during regasification of LNG, these engines have the potential to be game changing energy systems in terms of environmental impact. Nitrogen is already a by-product of industrial oxygen production which can be readily re-liquefied for use in transport. Many industrial cryogenic production facilities are operated intermittently using off peak (currently overnight) energy. In the future, surplus renewable energy could be used for cryogenic fluid production, offering a way of absorbing and effectively storing renewable energy. There is already an extensive distribution infrastructure for liquid nitrogen fluids (unlike hydrogen) and refuelling technologies developed for CNG can be readily utilised.

The Dearman engine works on the principle that cryogenic liquids expand around 700 times in volume when they undergo the transition from liquid to an atmospheric gaseous state. This expansion is used to drive a reciprocating engine, relying on the increase in pressure to drive a piston to create torque in a same way as an Internal Combustion Engine (ICE), but without emitting polluting gases since no chemical reaction takes place inside the engine. On the other hand, the CryoPower engine is a split cycle engine where compression and expansion (though combustion) happen in separate chambers. This allows the compression and expansion cylinder processes to be individually optimised, which is not possible in conventional ICE architectures. In the RSCE a further increase in efficiency is achieved by injecting small amounts of coolant liquid during the compression process, in order to maintain isothermal conditions. This significantly reduces the compression work and enables the recovery of waste heat from the engine exhaust heat to the working fluid before combustion. Several variations of the RSCE are underdevelopment, Dry ThermoPower, Wet ThermoPower and CryoPower. The Dry ThermoPower RSCE does not have any coolant injection during the compression process while wet ThermoPower uses water. The CryoPower RSCE represents the largest technological challenge due to the unique process of using LN₂ injection as a coolant during compression. However, this concept shows the most promise with research to date suggesting that the CryoPower concept has the potential to achieve up to and possibly over 60% efficiency and a significant reduction in emissions.

In the following sections, the basic principles of the operation of the RSCE will initially be presented, which is currently under development by the University of Brighton (UoB) in collaboration with Dolphin N2 and Ricardo. The focus will then be turned to the examination of the thermodynamic processes taking place in the compression chamber. After which experimental evidences for the dynamics of cryogenic liquids based on extensive review of existent experiments as well as new ones currently under development at the UoB will be presented. Next a comprehensive analysis of cryogens from thermodynamic point of view will be performed along with an investigation of the challenges of moving from water to LN₂ as coolant. Finally, the complications in numerical modelling of cryogenic liquid properties are presented.

2 RECOVERED SPLIT CYCLE ENGINE

The idea of a split cycle engine was first proposed by George Brayton in 1876 but the first commercial split cycle engine was the Dolphin engine by Sir Harry Ricardo in 1908. Interest has renewed in split cycle concepts over the last couple of decades with the pressing need to primarily (a) increase engine efficiency (b) decrease CO₂ emissions and (b) reduce toxic emissions. Figure 1 presents a schematic of a RSCE. It can be seen that the compression chamber ingests ambient air from atmosphere, which is then compressed and simultaneously cooled by the induction of a coolant such as water or liquid nitrogen. This coolant should maintain a near constant temperature during compression, towards isothermal compression conditions. This cool compressed air is then passed through a recuperator which absorbs some of the otherwise wasted heat from the exhaust. The preheated air is then passed into the combustion chamber where combustion with fuel takes place. Some of the wasted heat from exhaust is re-utilised in the recuperator to heat the cool compressed air.



- 1-2 : Ingestion of air and isothermal compression in the compression cylinder.
- 2-3 : Heat transfer from recuperator to the compressed air at constant pressure.
- 3-4: Injection of air into the combustion cylinder, Fuel addition and combustion.
- 4-5: Expansion inside the combustion cylinder.
- 5-6: Exhaust and recovery of some heat from exhaust in the recuperator and passing it to the pre combustion air.

Figure 1. Schematic of a Split Cycle Engine by Ricardo[6] with T-S diagram of a RCSE compared to a diesel engine by Morgan[1]. The numbers referring the positions in the cycle are described on the right.

One important characteristic of this engine is that although 55 % efficiency is the max upper limit for conventional diesel engines with large 2 stroke low speed engines approaching this, the efficiency of RCSE at its limit is calculated to be over 55 % and up to 60% [1]. The factors upon which primarily the higher efficiency is dependent are, optimisation of compression and expansion cylinder processes, achieving near isothermal compression and the recuperation efficiency of the wasted heat [2]. In order to explain this further, the thermodynamic cycle of a RCSE compared to a Diesel engine by Morgan et al [1] is shown in Figure 1 (graph on the bottom). This clearly shows the additional work extracted by the cycle and thereby increasing the efficiency, due to the above mentioned factors.

Quasi-isothermal compression alone can achieve 5% thermal efficiency in the RSCE as calculated by Dong et al [3]. Maintaining quasi-isothermal compression is linked to the way the coolant will atomise. The rate at which the air will heat up because of the compression should be balanced by the rate by which the coolant is capable of absorbing heat and vaporises. Past experiments used water as a coolant and have achieved predicted overall efficiencies of 60% [4] in 2004, but due to the technological constraints of that time, stable, efficient combustion could not be achieved in the combustion chamber. Nevertheless, the isothermal compression concept and overall cycle were demonstrated [5]. Recent R&D developments were focused on using liquid nitrogen as the coolant for the isothermal compression. Unlike in the previous work by Coney et al [4], stable efficient combustion was achieved at remarkably low levels of NO_x emissions. This was attributed to a combination of improved mixing, low temperature retarded combustion phasing and dilution of the charge air with nitrogen from the isothermal compression process.

3 EXPERIMENTS

3.1 Previous experiments

If cryogenic fluids are to be used extensively in future energy and transport applications, their thermofluids behaviour must be understood. One of the challenges is that the fundamental properties and dynamics of cryogenic fluids have not been extensively studied at the conditions present in an engine or compressor. After performing a critical review on the existent available data, Figure 2 has been produced and shows an overview of the existing experimental data of cryogenic liquids compared to the operational regime of the compression chamber of a current RSCE prototype on a phase diagram chart of nitrogen. For reference, a split cycle engine is expected to operate at a maximum of 17 MPa compression chamber pressure [4]. The current experimental work on the CryoPower engine is expected to operate at 7 MPa. Two of the important conclusions of the figure are: a) Existent experiments are not representative of the operating conditions of the RSCE and b) The maximum pressure in the compression chamber of all the demonstrator prototypes are above nitrogen's critical pressure of 3.39 MPa (see also Table 1 and Figure 3), which means the cryogenic fluid will transition from sub to super-critical conditions in the compression cylinder. The behaviour even of common fluids, let alone cryogenics, is not well understood under these conditions.

Experiments done by Mayer [7]–[9], Chehroudi [10] and Oswald [11] provide valuable information in the quest to understand cryogenic jets in their supercritical state. The observation from these experiments can be summarised as:

1. Starting from a sub-critical pressure, with increase in pressure the cryogenic fluids reach a trans-critical state where surface tension reduces considerably, and the fluids lose their capability to produce observable droplets. This is not specific to cryogenic fluids, but it also happens in any fluid that reaches these conditions. What is particular for cryogenics is that the super-critical state is reached at conditions much closer to atmospheric than other fluids/fuels.
2. As a result of the reduced surface tension, with increase in super-critical pressure the mixing of cryogenic fluid with ambient fluid becomes more rapid.
3. The pressure at which the transition of the fluid properties from liquid to gas happens, does not depend only on the critical pressure of the injected fluid but on the ambient fluid as well.

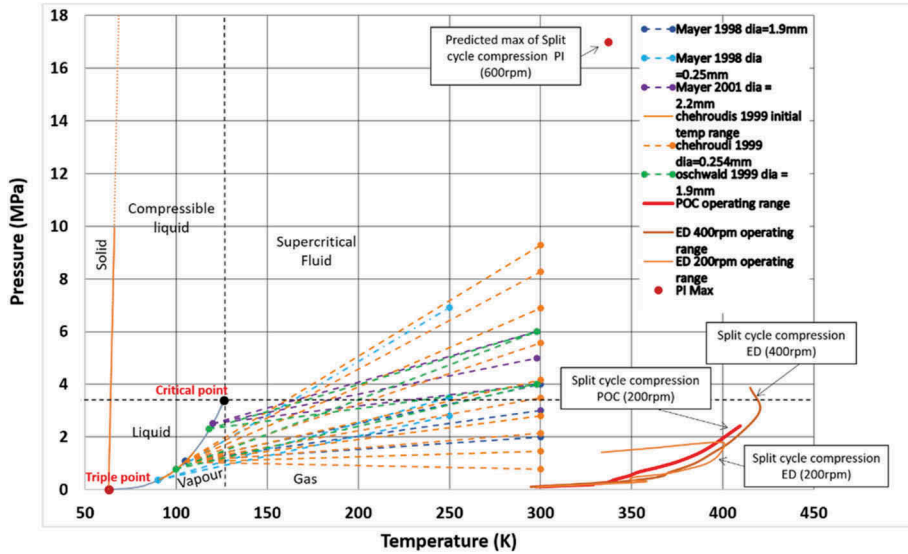


Figure 2. Phase diagram chart of nitrogen with experiments done by Mayer, Chehroudi and Oswald. The operating conditions range of a split cycle compression chamber is also displayed for comparison. The initial and final conditions of the cryogenic experiments are represented by solid line and solid dots. The line linking initial conditions to final conditions is displayed as dashed line. 'dia' represents injector diameter. POC represents Proof of Concept and ED represents Engineering Demonstrator split cycle engine prototypes.

Table 1. Operating conditions of compression chamber in various split cycle prototypes.

Split cycle prototype	Compression chamber				Coolant	Efficiency	
	Cylinder (No x Bore x Stroke) (mm)	Max Pressure (MPa)	Max Temp (K)	Crank-shaft Speed (rpm)		Work Saving	Total efficiency
Proof of Concept (POC)	1 x 300 x 200	3.25	413	50 - 200	Water	28%	
Engineering Demonstrator (ED)	1 x 385 x 400	10	425	200 - 600	Water		50%
Commercial Demonstrator (CD)	2 x 385 x 450	17		600	Water		58 - 60%
CryoPower	PLANNED	7	PLANNED		LN2		>55%

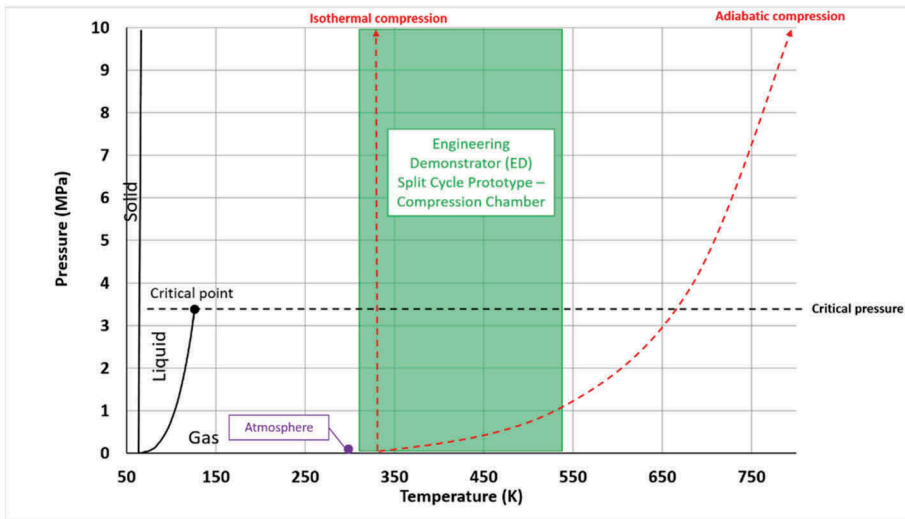


Figure 3. Phase diagram of nitrogen with chamber conditions in a typical isothermal compressor highlighting the critical point.

3.2 Current experiments at the University of Brighton

Due to the limited experiments available under the conditions relevant to the RSCE, an experimental effort has started at the UoB in the last couple of years in order to enhance existent data bases. Two series of experiments have been undertaken to study the behaviour of a liquid nitrogen spray. The first experiments were performed under steady state conditions through a plane orifice into ambient air. The second series of experiments used a gasoline injector modified to operate on liquid nitrogen. In both cases, the liquid nitrogen was supplied from a 120 litre tank that could be pressurised up to 18 bar. The nozzle and injector were submerged in a bath of liquid nitrogen to sub-cooled the assembly and prevent the cryogen boiling in the injector. With reference to Figure 4, at a macroscopic scale the cryogenic spray has the appearance of a gasoline fuel spray. However, at the micro scale no spherical 'blobs' and ligaments are observed. Although simpler structures are observed in other sprays, such as in the dense region of a diesel fuel spray, the fundamental origin for these structures in the cryogenic spray is as yet unexplained. The fundamental spray formation and in particular break up and evaporation processes must be understood to enable accurate models to be built to support the efficient design of the isothermal compressor.



Figure 4. LN₂ spray into ambient air. The left image shows the spray in whole. The right image is the magnified image of the location marked by black rectangle in the whole spray.

4 CHALLENGES ARISING FROM THE THERMO-PHYSICAL PROPERTIES OF CRYOGENIC FLUIDS

As mentioned above, the primary goal of using either water or cryogenic fluids in the compression chamber of RCSE is to efficiently absorb the heat/energy arising due to the rise in pressure. The requirement is to absorb the heat in a way that will enable the compression chamber to remain at an ideally constant temperature during compression. How this absorption will occur depends on the thermo-physical properties of the fluids at the specific operating conditions, which are both sub-critical and super-critical depending on the fluid itself, the piston position and the injection timing. Water which was previously used to absorb the heat during compression has a much higher critical pressure of around 22 MPa. This high pressure was not encountered in the compression chamber, hence water remained sub-critical for the whole compression process. LN₂ on the other hand, has a critical pressure of 3.39 MPa. The pressure in the compression chamber of RSCE starts from an atmospheric pressure and goes up to the maximum pressure of above 10.0 MPa. Depending on the timing of injection of liquid nitrogen, it can either boil at sub-critical pressures or transform into super-critical fluid where the pseudo-boiling influences the heat absorption. This difference in the use of water or LN₂ as coolant is expected to influence the design parameters of injection for good heat absorption.

In an effort to explore further what is/are the optimal conditions to inject the LN₂, the two most important thermodynamic properties for the case of phase change, i.e. the latent heat of vaporisation (the energy absorbed by the cryogen in order to change phase under constant temperature) and the heat capacity C_p (the energy (ΔH) required to change the temperature (T) of the cryogen) (Eqn 1)) are examined closely. In order to better demonstrate this Figure 5 has been included. The figure demonstrates the isobaric specific heat capacities and specific enthalpies vs temperature for nitrogen at pressures from 0.1 MPa to 10 MPa. A reminder that the latent heat (Enthalpy of vaporisation ΔH_{vap}) is the enthalpy difference ($H_{vap} - H_{liq}$) between two phases of a substance at the same temperature (Eqn 2). However, the definition of the latent heat is more relevant for sub-critical cases, as will be demonstrated in the following paragraphs.

$$\Delta H = C_p \Delta T \quad (\text{Eqn 1})$$

$$\Delta H_{vap} = H_{vap} - H_{liq} \quad (\text{Eqn 2})$$

Starting with the specific heat capacity and looking at Figure 5, note that for sub-critical pressures (0.1, 1, 2, and 3 MPa), as the temperature approaches the boiling temperature at a given pressure, the specific heat capacity increases and at the boiling temperature there is a discontinuity. The discontinuity at the boiling point is represented by a red line. For super-critical pressures on the other hand (pressure higher than 3.39 MPa) there is a maximum heat capacity at some temperature (higher temperature for higher pressure), which is less than the heat capacity at critical pressure and critical temperature. The peak is continuous and shows no discontinuities signifying the inseparability of liquid and gas phases. The general trend of the profile for super-critical pressures is, with increase in pressure, the peaks tend to fall and flatten out. When the point that the heat capacity picks for super-critical pressures, the fluid can absorb a large amount of heat without significant rise in temperature but increases in volume without undergoing phase transition. This is what in the literature indicated as the pseudo-boiling point. For super-critical pressures, in addition to the specific heat maximum at pseudo-boiling point, other properties such as density, viscosity, thermal conductivity and enthalpy very rapidly. Although the large specific heat results in very little change in temperature with the absorption of heat, this small temperature change results in large gradients of thermos-physical properties as seen for 4.0 MPa (curve 2) in Figure 6.

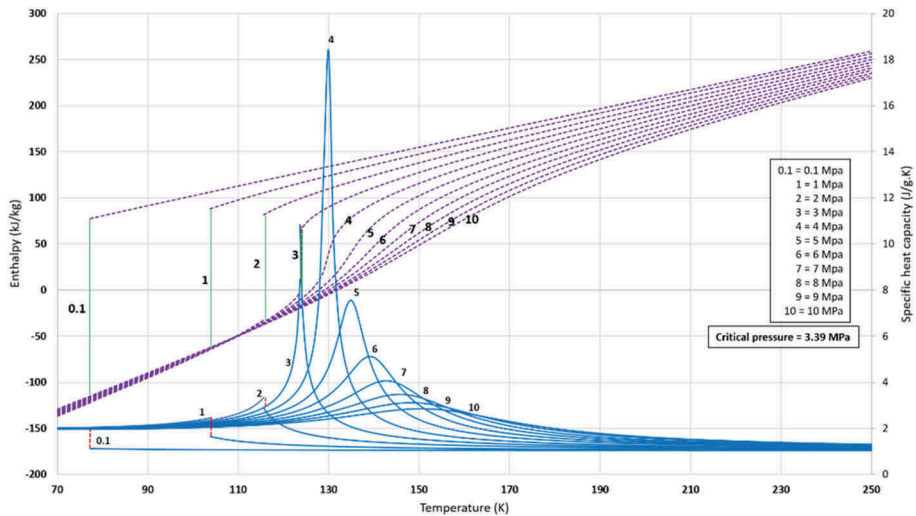


Figure 5. The isobaric specific heat capacities and specific enthalpies vs temperature for nitrogen at pressures from 0.1 MPa to 10 MPa. The dashed line in purple represents enthalpies and the continuous line in blue represents heat capacities. The discontinuities in specific heat capacity corresponding to the red line and discontinuities in enthalpy corresponding to green line locate the boiling point.

In addition to specific heat capacity, latent heat is also of interest. For sub-critical pressures as temperature increases enthalpy of vaporisation decreases and reaches zero once the fluid attains its gas phase. It is thus a very useful quantity for sub-critical liquids to quantify the heat absorbed due to phase change at constant temperature but not of much interest for super-critical fluids since it becomes zero. This of course does not mean that supercritical fluids do not change phase. As subcritical fluids, they start from a liquid-like phase at lower temperatures and as the temperature further increases, they eventually reach the gas phase. Banuti [12] describes that at low sub-critical pressures the latent heat is concentrated at the boiling point, whereas at super-critical pressures this latent heat is distributed over a temperature range around the pseudo-boiling point. This is the reason why in the graph enthalpy difference is used to visualise this, instead of latent heat of vaporisation. The discontinuities in the enthalpy at sub-critical pressures directly quantify the latent heat or enthalpy of vaporisation.

To understand the distributed latent heat and the heat absorption associated with it, an isobaric process (assume the cylinder pressure almost constant for a small change in volume dV) with heat generated is considered. At sub-critical pressures far below the critical pressure such as 0.1 MPa in the Figure 5, when a liquid is injected, the heat absorbed by the liquid raises its temperature without phase change occurring. The temperature increase is proportional to the heat capacity of the liquid. As the temperature reaches the boiling point the liquid transitions into gas, during which it absorbs a large amount of heat without any further raise in temperature, which is the latent heat concentrated at the boiling point. After the transition into gas, the fluid has a different heat capacity than that of the liquid state. Further absorption of heat results in a raise in temperature of the fluid proportional to its gas phase heat capacity. At higher sub-critical pressures, the trend

is similar, although gradients in heat capacity start appearing as the pressure increases towards the critical pressure as seen in 2 and 3 MPa in the Figure 5. The corresponding difference in the specific enthalpies decreases. This signifies that the heat absorption due to rise in heat capacity increases while heat absorption due to vaporisation decreases.

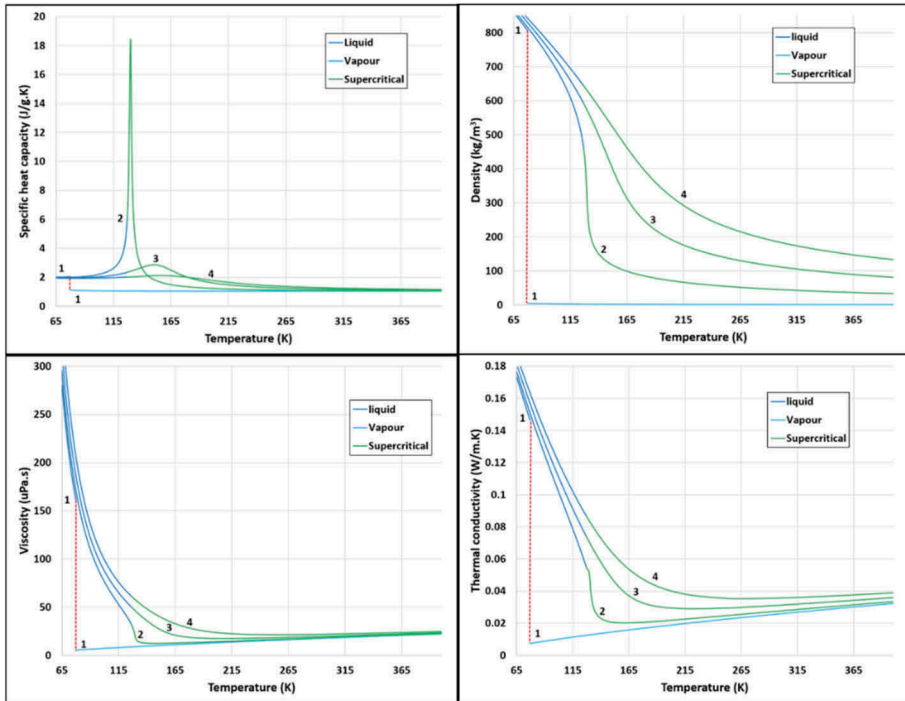


Figure 6. Thermo-physical properties of nitrogen at four pressures 1 - Atmospheric pressure (0.1 MPa), 2 - Just above critical pressure (4.0 MPa), 3 - Max pressure in the compression chamber of Engineering Demonstrator (ED) prototype of split cycle engine (10.0 MPa) and 4 - Max pressure in the compression chamber of planned Commercial Demonstrator (CD) prototype of split cycle engine (17.0 MPa). The red dashed line represents the discontinuity between liquid and vapour phase.

At super-critical pressures as the liquid is injected, the temperature of the liquid increases proportional to its heat capacity until it nears the pseudo-boiling temperature. Here the heat absorbed not only raises its temperature but also gradually changes the state from liquid to gas with several intermediate states over a relatively wide range of temperature. Here the heat is absorbed both due to the heat capacity increase and the intermediate phase transitions. This is because the latent heat is distributed over a range of temperature. This distributed latent heat or in other words, combination of heat absorption to raise the temperature and gradually transition the state from liquid to gas in super-critical pressures is attractive for application in RSCE compression. The combined rate of heat absorption is more

than that of the rate of heat absorption due to the heat capacity of a fluid alone. Second, while vaporisation absorbs heat instantaneously, it is hard to distribute this absorption of heat throughout the compression process to achieve isothermal compression. Whereas this combined heat absorption spread over a temperature range, is advantageous to gradually but constantly cool the surrounding throughout the compression process.

In order to highlight the differences between the atmospheric conditions and the conditions taking place in the RSCE, some more thermo-physical properties (density, viscosity, thermal conductivity) of nitrogen corresponding to atmospheric pressure, near critical pressure and two prototypes of RSCE are represented in Figure 6. It should be reminded that the reason the properties at both the sub and super-critical region are of interest is because the pressure in the compression chamber starts from atmospheric pressure and goes up to the maximum pressure. It can be seen from the figure that at sub-critical pressures the thermo-physical properties suddenly change from that of the liquid to gas at the boiling point. Whereas, at super-critical pressure of 4 MPa which is just above the critical pressure, there is a large gradient in thermo-physical properties near the pseudo-boiling temperature. Here a small variation in temperature can result in large variation in these thermo-physical properties as described above. At higher supercritical pressures the gradients of thermo-physical properties become less steep.

Figure 7 compares the rise in specific heat capacity of cryogenic liquids and other naturally occurring liquids including water (that was previously used in the split cycle) at pseudo boiling point for various super-critical pressures. Evidently it can be seen that compared to fuels such as dodecane and iso-octane, the cryogenic fluids such as nitrogen, hydrogen and methane show a significantly higher rise in specific heat capacity at super-critical pressures.

In conclusion the challenges in designing the injection of cryogenic fluids into compression chamber is two-fold. First one is the distributed latent heat of cryogenic fluids around the pseudo-boiling point influencing the heat absorption. The second is the drastic rise in specific heat capacity and the associated gradients in thermo-physical properties influencing the flow evolution. The combination of heat absorption and flow evolution should be understood properly to achieve uniform constant temperature throughout the compression chamber.

5 NUMERICAL MODELLING

The variation of the thermo-physical properties of cryogenic fluids poses many challenges at the numerical modelling of these fluids. In the following paragraphs we will focus on the challenges associated with the calculations of these properties and the selection of an appropriate equation state. Until now in the literature it is not very clear which one is the optimum for cryogenic fluids under compression conditions. Other numerical challenges associated with for example the choice of the liquid break up model although are also very important are outside the scope of this work and will be investigated in future work.

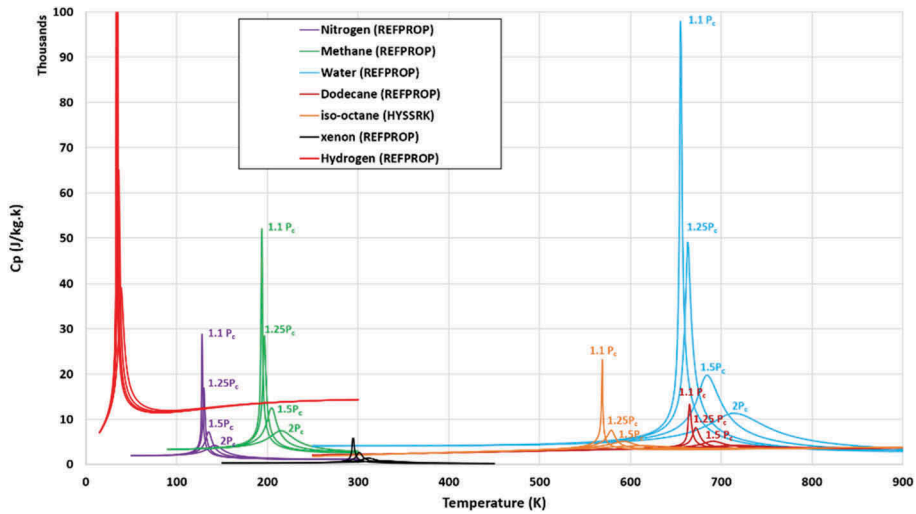


Figure 7. Specific heat capacity of various fluids at supercritical pressures of $1.1P_c$, $1.25P_c$, $1.5P_c$ and $2P_c$, where P_c is the critical pressure of the respective fluid.

5.1 Real fluid equation of state (EOS)

An Equation of State (EOS) which accurately describes the state of matter at both sub-critical and super-critical condition needs to be employed to model the thermodynamic anomalies which occur at near critical temperatures. It is a requirement that the EOS predicts the rapid changes in fluid's specific heat capacity density, viscosity, thermal conductivity and enthalpy near the critical point and the pseudo boiling point with sufficient accuracy in order to lead to accurate prediction of the heat absorbed by the compressed air.

Although Benedict-Webb-Rubin EOS has been used by few researchers due to its comparatively increased accuracy, Peng-Robinson (PR) and Soave-Redlich-Kwong (SRK) EOS are the preferred ones for numerical simulations by many researchers [13]–[15] for the case of cryogenics due to reduced numerical complexity. Figure 8 shows Kim et al [13] and Muller et al [15] estimation of specific heat capacity and density of nitrogen using PR and SRK for 4 MPa. The NIST data are also plotted for comparison. It can be seen from the figures that both PR and SRK fail to capture the peak of specific heat capacity accurately. This might have significant influence on the flow simulation. For example, if the specific heat maximum is not captured accurately, then the simulation of injected cryogenic spray will be very different than the real one. This is due to the outer fluid quickly overcoming the pseudo-boiling point as temperature of the fluid can rise more rapidly than the real case. And the inner fluid will experience major heat transfer into it earlier than the real case which is further affected by the lower than actual specific heat maximum predicted by SRK or PR. The density predicted by PR and SRK are fairly accurate, though the density from NIST seems to lie in between the values of PR and SRK.

Additionally, the specific heat capacity and density of nitrogen at a high super-critical pressure of 17 MPa has been estimated using PR and SRK, and compared against REFPROP [16] from NIST (see Figure 9). REFPROP is NIST's Reference Fluid

Thermodynamic and Transport Properties Database. It can be seen that PR and SRK lie very close to the REFPROP plot of specific heat capacity. In the density plot SRK captures the density reasonably well whereas PR shows significant error at lower temperatures. Assessing from the low super-critical pressure predictions by Kim [13] and the high supercritical pressure predictions we calculated, the SRK would be the first choice to model the conditions in RSCE compression chamber.

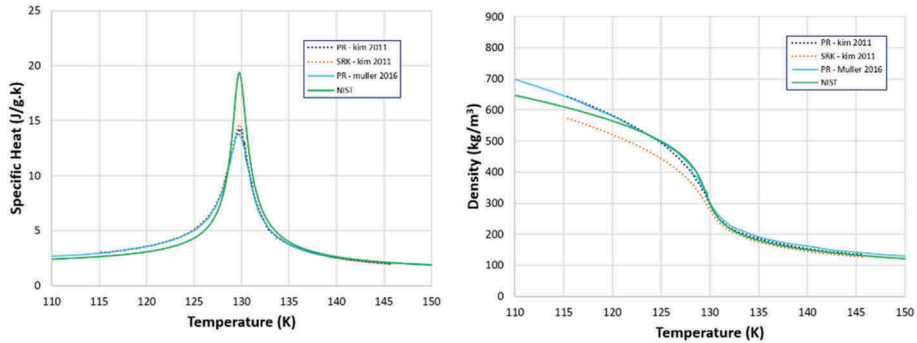


Figure 8. Estimation of specific heat capacity (left) and density (right) of nitrogen at 4 MPa using PR and SRK by Kim[13] and Muller[15].

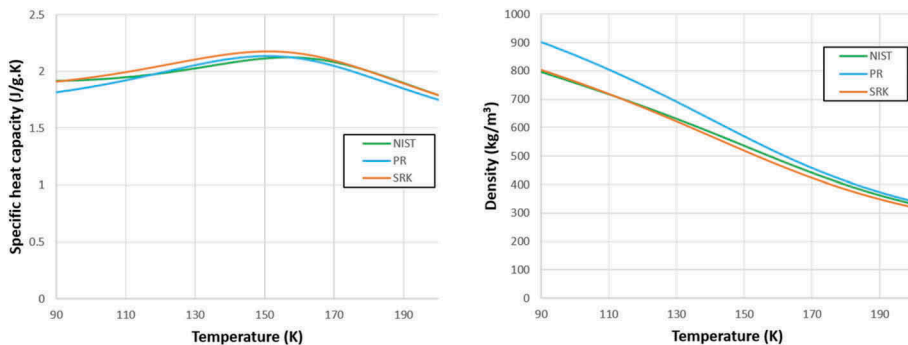


Figure 9. Estimation of specific heat capacity (left) and density (right) of nitrogen using PR and SRK compared against REFPROP (NIST) at 17 MPa corresponding to the maximum pressure in the planned Commercial Demonstrator (CD) split cycle engine.

6 CONCLUSION

In this paper the basic concepts of operations of a hybrid engine currently under development by Ricardo Innovations, Dolphin N2 and the University of Brighton, the recuperated split cycle engine, have been presented. The focus was the thermodynamics of the isothermal compression taking place in the engine with the injection of either water or cryogenic fluids. Injection of cryogenic fluids into the compression chamber to achieve isothermal compression could further enhance the efficiency of RSCE towards achieving their full potential. A RSCE with quasi isothermal compression

can achieve up to 60% BTE. A critical review of existent literature showed that there are fundamental gaps in knowledge on cryogenic fluids at conditions relevant to the RSCE. We showed that the absorption of heat and evolution of spray is different than what has been examined in the literature since as the piston moves the fluid is found to be both at sub and super-critical state. We examined in detail the thermos-physical properties of both water and LN₂ at both sub and super-critical conditions and we highlighted the peculiarities relevant to the specific heat and the latent heat of evaporation. We also performed an analysis relevant to existent EOS and their accuracy both at low and high chamber pressures. In terms of future work further experiments on liquid nitrogen at conditions relevant to split cycle compression chamber needs to be undertaken. Moreover, the role of the breakup mechanism of the cryogenic liquids will be explored.

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REFERENCES

- [1] R. Morgan, N. Jackson, A. Atkins, G. Dong, M. R. Heikal, and C. Ienartowicz, "The Recuperated Split Cycle - Experimental Combustion Data from a Single Cylinder Test Rig," *SAE Int. J. Engines*, vol. 10, 2017.
- [2] G. Dong, R. E. Morgan, and M. R. Heikal, "Thermodynamic analysis and system design of a novel split cycle engine concept," *Energy*, vol. 102, pp. 576–585, 2016.
- [3] G. Dong, R. Morgan, and M. Heikal, "A novel split cycle internal combustion engine with integral waste heat recovery," *Appl. Energy*, vol. 157, pp. 744–753, 2015.
- [4] M. W. Coney, C. Linnemann, and H. S. Abdallah, "A thermodynamic analysis of a novel high efficiency reciprocating internal combustion engine—the isoengine," *Energy*, vol. 29, no. 12, pp. 2585–2600, 2004.
- [5] N. Jackson, A. Atkins, J. Eatwell, and R. Morgan, "An alternative thermodynamic cycle for reciprocating piston engines," 2015.
- [6] "SAE 2014 Heavy-Duty Diesel Emissions Control Symposium," *Johnson Matthey Technol. Rev.*, vol. 59, no. 2, 2015.
- [7] W. Mayer, A. Schik, C. Schweitzer, and M. Schaeffler, "Injection and mixing processes in high pressure LOX/GH₂ rocket combustors," in *32nd Joint Propulsion Conference and Exhibit*,.
- [8] W. O. H. Mayer *et al.*, "Atomization and Breakup of Cryogenic Propellants Under High-Pressure Subcritical and Supercritical Conditions," *J. Propuls. Power*, vol. 14, no. 5, pp. 835–842, 1998.
- [9] W. Mayer, J. Telaar, R. Branam, G. Schneider, and J. Hussong, "Raman Measurements of Cryogenic Injection at Supercritical Pressure," *Heat Mass Transf.*, vol. 39, no. 8, pp. 709–719, Sep. 2003.
- [10] B. Chehroudi, D. Talley, and E. Coy, "Fractal geometry and growth rate changes of cryogenic jets near the critical point," in *35th Joint Propulsion Conference and Exhibit*, .
- [11] M. Oswald and A. Schik, "Supercritical nitrogen free jet investigated by spontaneous Raman scattering," *Exp. Fluids*, vol. 27, no. 6, pp. 497–506, Nov. 1999.
- [12] D. Banuti, "The Latent Heat of Supercritical Fluids," *Period. Polytech. Chem. Eng.*, vol. 63, no. 2, pp. 270–275, 2019.

- [13] T. Kim, Y. Kim, and S.-K. Kim, "Numerical study of cryogenic liquid nitrogen jets at supercritical pressures," *J. Supercrit. Fluids*, vol. 56, no. 2, pp. 152–163, 2011.
- [14] T. S. Park, "LES and RANS simulations of cryogenic liquid nitrogen jets," *J. Supercrit. Fluids*, vol. 72, pp. 232–247, 2012.
- [15] H. Müller, C. A. Niedermeier, J. Matheis, M. Pfitzner, and S. Hickel, "Large-eddy simulation of nitrogen injection at trans- and supercritical conditions," *Phys. Fluids*, vol. 28, no. 1, p. 15102, 2016.
- [16] E. W. Lemmon, I. H. Bell, M. L. Huber, and M. O. McLinden, "NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology." 2018.