

High Efficiency Energy Conversion Systems for Liquid Nitrogen Automobiles

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ABSTRACT

This investigation of the use of cryogenics as energy storage media for zero emission vehicles has found that using liquid nitrogen to liquefy the working fluids of one or more closed Rankine power cycles can be an effective means for increasing motive power. System configurations are presented which can realize a specific energy greater than 400 kJ/kg-LN₂ (110 W-hr/kg-LN₂) without relying on isothermal expanders. A zero emission vehicle utilizing such a propulsion system would have an energy storage reservoir that can be refilled in a matter of minutes and a range comparable to that of a conventional automobile.

INTRODUCTION

Mitigating increases in urban air pollution and greenhouse gases that come from vehicle tailpipe emissions is the primary motivation behind developing alternative transportation technologies that do not rely on combustion of fossil fuels. Consumer acceptance of a replacement transportation technology, however, is highly dependent on the new vehicle sticker price, operating expenses, reliability, and convenience of use. Thus it is advantageous for the energy storage system of a zero emission vehicle (ZEV) to have low initial cost, be quickly and economically recharged, and to provide driving performance comparable to that of conventional automobiles. In addition, the most desirable technological solutions will eliminate the release of automotive combustion products in areas of poor air quality, while also reducing the net amount of pollutants released to the environment as a consequence of their implementation. Careful consideration of the overall environmental impact of a particular ZEV technology and the corresponding costs of necessary infrastructure development is necessary to evaluate the ability of any new transportation system to meet the goals of society.

Currently, the battery-powered electric vehicle is the only commercially available technology that can meet ZEV

standards; however, these vehicles have not sold well. This is primarily due to their limited range, slow recharge, and high initial cost. All of these issues can be traced directly to the limitations of electrochemical energy storage, particularly lead-acid and Ni-Cd batteries. These heavy metal energy storage systems remain the dominant technology in the electric vehicle market, but exhibit specific energies in the range of only 30-40 W-hr/kg and energy densities of 60-90 W-hr/l.¹ This compares with about 3,000 W-hr/kg for gasoline combusted in an engine running at 28% thermal efficiency. Lead-acid batteries can take hours to recharge and must be replaced every 2-3 years. Recycling of metals from batteries does significantly reduce the amounts released to the environment; however, these processes are currently not 100% effective. Hence, in addition to significantly increasing operating cost per kilometer driven, the need for several battery replacements over the lifetime of the vehicle raises the specter of increased heavy metal pollution, were lead-acid and Ni-Cd battery-powered electric fleets ever to become widespread.^{2,3}

The potential of cryogenic energy storage for automotive propulsion has been under investigation at the University of Washington^{4,5} and elsewhere⁶⁻⁹ as an alternative to electrochemical batteries for ZEVs. It is anticipated that the use of an inert cryogen, such as liquid nitrogen (LN₂), for an energy storage medium would not pose any environmental burden and, in particular, would avoid the issues of heavy metals pollution associated with Pb-acid and Ni-Cd batteries. Since there exists a well established air manufacturing industry that can be expanded to accommodate large increases in demand, the economy of scale is expected to result in a LN₂ cost that is close to that of the energy consumed in its production (~0.5 kW-hr/kg-LN₂ for a large scale air manufacturing plant). The retail price of LN₂ may be further reduced by credit from additional sales of liquid oxygen and argon that are by-products of the liquefaction process. Straightforward modifications to current gasoline stations

would enable LN₂ vehicles to be refueled in minutes and, if the performance and range of cryogen vehicles could be made comparable to gasoline vehicles, the driving habits of motorists would not have to change at all.

Prior work has shown that using LN₂ as the working fluid of an ambient air-heated Rankine power cycle would result in net work output ranging from 50-90 W-hr/kg-LN₂, depending on how isothermal the expansion process can be made.^{4,5,10} Even though these specific energy values are superior to those of most electrochemical batteries, the energy density of LN₂ is at best 70 W-hr/l when used in an isothermal expansion process, which results in a 350 liter (90 gal) onboard storage vessel being needed to provide a vehicle with a range comparable to internal combustion engines. Even though this is not a prohibitively large “fuel” tank, increasing the effective energy density of the LN₂ by using more complex power cycles may be warranted in applications where minimal energy storage volume, zero emission and spark-free operation are required.

In what follows, means to recover work from LN₂ by using it as a heat sink for closed loop Rankine cycles are evaluated. Fundamental thermodynamic considerations are discussed which illustrate the energy storage capabilities of various cryogens. The basic cryogen energy conversion system is presented and applications of topping cycles are examined. The potential gains in specific energy and energy density of LN₂ are determined for a point design that illustrates the implementation of this concept.

THERMODYNAMIC CONSIDERATIONS

The maximum reversible work that can be realized by a chemically inert substance stored at temperature T_1 and pressure P_1 in an environment at temperature T_a is equal to its availability; $\Psi = h_1 - h_a - T_a(S_1 - S_a)$. The availabilities

of several cryogens of interest and that of compressed air stored at 20 MPa are shown in Table 1. It can be seen that the availability of LN₂ is approximately 3 times that of compressed air and more than 5 times greater than the specific energy of Pb-acid batteries (40 W-hr/kg). The availability of liquid methane (without combustion) is ~50% greater than that of LN₂ on a per mass basis; however, its available energy density is ~25% less than that of LN₂. In the case of compressed air storage at 20 MPa, the available energy density is so low that, even with an ideal isothermal expansion engine, there is not sufficient volume onboard conventional automobiles to provide comparable driving range. Liquefaction of air increases its energy density by several orders of magnitude, resulting in a much more compact energy storage system than that required for compressed air, even when the volume of the accompanying heat exchanger equipment is included.

An energy conversion system which uses ambient heat to vaporize the working fluid inherently reduces the availability of the cryogen in the process. The maximum reversible work that can be generated from any process is equal to the difference between the availability of the working fluid at its peak temperature and pressure and the availability at the end of the expansion process. In the case of an energy conversion system which uses several different working fluids, it is possible to effect a heat exchange process which increases the availability of one medium while decreasing that of another, resulting in a net increase in work output over that of using a single fluid. The availability analysis provides a direct means to evaluate the energy conversion efficiency of various cryogen power system configurations without consideration of many details of the associated processes. Having determined operating conditions of various working fluids which result in the effective use of consumable cryogen (e.g., LN₂, LAir), the mechanical components of an energy conversion system (e.g., heat exchanger area, pressure drop, expansion engine, etc.) can then be designed and the effects of real world inefficiencies evaluated.

Table 1: Availability of various working fluids relative to ambient conditions ($T_a = 300$ K)

Fluid	Storage Temp (K)	Density (kg/m ³)	Ψ (kJ/kg)	Ψ (W-hr/kg)	Ψ (W-hr/l)
N ₂	77.4	809	768	213	173
Air	78.9	886	737	205	181
O ₂	90.2	1140	635	176	201
CH ₄	111.6	423	1093	304	128
C ₂ H ₆	184.6	545	352	97.7	53.2
Compressed Air	300	233	258	71.5	16.7

CRYOGEN POWER CYCLE

A schematic of a cryogen energy conversion system is shown in Fig. 1. The cryogen “fuel” is stored in a vacuum jacketed vessel which has appropriate relief valves to safely accommodate boiloff. A cryopump pressurizes the fluid to a level somewhat above the injection pressure of the expander to make up pressure loss in the heat exchanger system. Turbines and either rotary or reciprocating fixed-displacement engines are appropriate expanders. The end use of the shaft power typically determines which expander technology is the most appropriate for a given application. Valves having controllable opening times can be used to provide variable cut-off for optimal LN₂ consumption in a piston expander, whereas adjustments in the LN₂ flow rate regulate power output from a turbine. The shaft power from the expander is then readily applied for vehicle propulsion via a standard

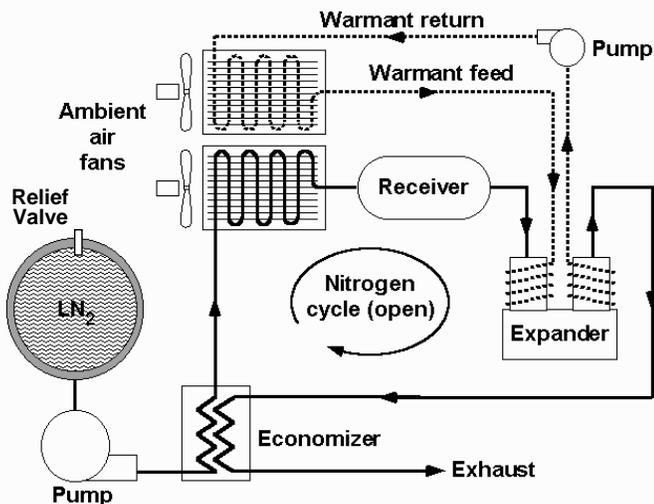


Fig. 1 Schematic of liquid nitrogen energy conversion system.

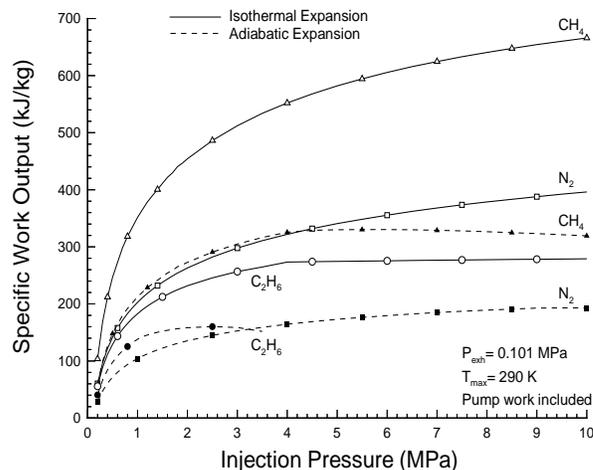


Fig. 2 Specific work of various fluids in adiabatic and isothermal expanders.

transmission or the generation of electricity for a hybrid system.

Since the rapid expansion process of the cryogen power cycle results in the temperature of the working fluid always being less than ambient, it is possible for a secondary heat transfer fluid (“warmant” in Fig. 1) to conduct sufficient heat into the engine to maintain the expander walls at near room temperature and to effect “quasi-isothermal” operation. Prior investigations have shown that reasonable piston and cylinder head geometries having high surface-to-volume ratios can be used to enhance heat transfer during expansion, resulting in potential net work output of approximately 85% isothermal.¹⁰ An alternative means of approaching isothermal operation is to use multiple expansions with intermediate reheats. Three expansions with two reheats result in a net work output of 80-85% isothermal; such triple expansion engines were applied quite successfully in the early part of the twentieth century for steamboat propulsion. For the purpose of estimating the maximum energy storage potential of LN₂, the work output from ideal engines operating with adiabatic and isothermal expansion processes can be readily quantified. Since there are several different concepts which can provide quasi-isothermal performance, the work output of a cryogen energy conversion system having a quasi-isothermal expander will be estimated as 85% the isothermal work.

Carefully designed all-weather heat exchangers are required to warm the working fluid to near ambient temperature without suffering a detrimental build-up of frost.¹¹ An innovative ambient evaporator concept involving multiple coaxial passes of the working fluid has demonstrated the ability to boil and superheat relatively large quantities of LN₂ without any frost accumulation (Williams et al., 1997). The warming of the heat transfer

fluid which is circulated around the cylinder heads and walls in a quasi-isothermal expander requires some additional heat exchanger components; however, the increase in power output significantly reduces the rate of LN₂ consumption, which correspondingly reduces the size of the cryogen vaporizer.

CRYOGEN TOPPING CYCLES

The specific energy of several working fluid candidates (N₂, CH₄, C₂H₆) for cryogen power cycles is plotted in Fig. 2 as a function of the injection pressure to both an adiabatic and an isothermal expander. A peak temperature of 290 K is assumed in each case and both the cryopump and expander are assumed to be isentropic. All media are expanded back to atmospheric pressure and the pressure drops in the heat exchanger systems are neglected. The end state of isothermal expansion process is assumed to be 290 K and 0.101 MPa for any injection pressure. The difference in the availability of the gas that is injected into the expander from its availability as it is expelled determines the specific work output.

For all working fluids shown in Fig. 2, the specific work of isothermal expansion from a given injection pressure exceeds that of the adiabatic expander, with the difference being greater as pressure is increased. Relatively little extra work is gained by operating the adiabatic cycles at pressures higher than 3 MPa. The adiabatic work of C₂H₆ is not plotted beyond 3.5 MPa because the end state after expansion corresponds to subcooled liquid phase. On a per mass basis it can be seen that the CH₄ cycle produces the most work for a given injection pressure, even though adiabatic expansion to atmospheric pressure drops the temperature to the saturation point when the injection pressure is greater than 4 MPa. The mixed-phase end state might preclude the use of adiabatic reciprocating

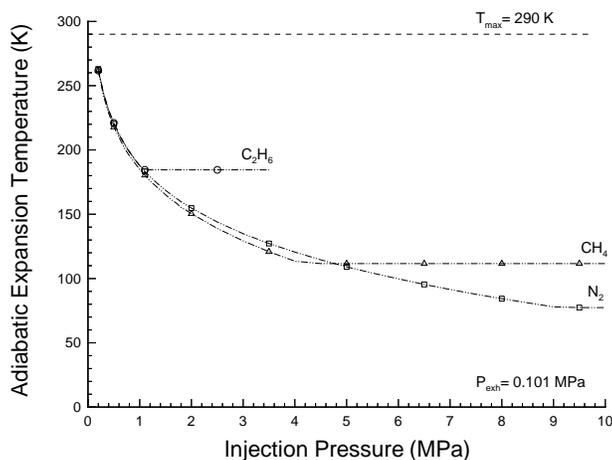


Fig. 3 Temperature after adiabatic expansion to atmospheric pressure.

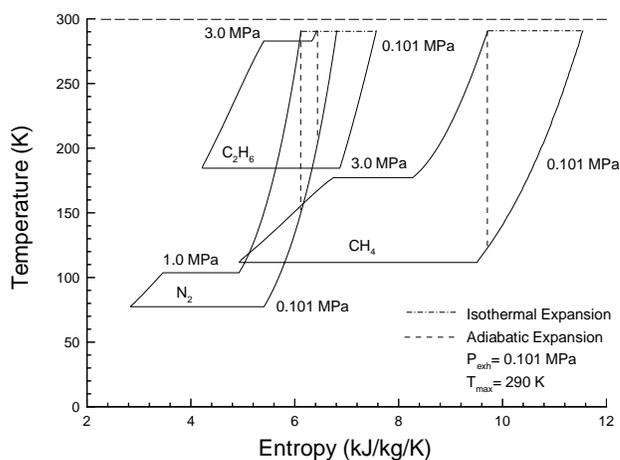


Fig. 4 Cryogen power cycles in the temperature-entropy plane.

expanders, but it may not pose an insurmountable problem for turbines. Maxima in the adiabatic expansion work for C_2H_6 , CH_4 , and N_2 are observed at approximately 2, 4, and 9.3 MPa, respectively. The adiabatic work maxima for CH_4 and N_2 occur at the injection pressures which result in the exhaust just reaching the saturation point, as discussed below, whereas the maximum for the C_2H_6 cycle corresponds to a mixed-phase end state.

The adiabatic expansion temperature of these working fluids is plotted versus injection pressure in Fig. 3. Mixed-phase flow after adiabatic expansion, characterized by the horizontal part of the temperature plots, results when the injection pressure is greater than 1, 4, and 9.3 MPa for the C_2H_6 , CH_4 , and N_2 power cycles, respectively. The enthalpy difference between the end state of the expansion process and that of the saturated liquid at atmospheric pressure is the heat rejection required to completely liquefy the C_2H_6 and CH_4 working fluids. The N_2 is vented back to the atmosphere and reliquefied at a stationary air manufacturing plant. The relatively large differences in saturation temperatures indicate that significant heat transfer between these media is possible and, since the majority of the heat transfer occurs during boiling and condensing processes, the heat exchanger system can be very compact.

The parts of the cryogen power cycles in which the media can exchange heat with a specified minimum temperature differential are readily displayed by temperature-entropy diagrams. An example of an energy conversion system using C_2H_6 , CH_4 , and N_2 at peak pressures of 3.0, 3.0, and 1.0 MPa, respectively, is shown in Fig. 4. Each of these working fluids is assumed to be stored at atmospheric pressure as saturated liquids. In the case where all of the expanders are adiabatic, the pressurized LN_2 is vaporized and superheated to within

10 K of the exhaust temperature of the adiabatically expanded CH_4 (129 K), then superheated further by heat exchange with the condensing C_2H_6 to approximately 175 K (10 K below C_2H_6 saturation temperature). Ambient heat is then required to bring the N_2 up to the peak temperature of the cycle (290 K). For the calculations presented here, the N_2 exhaust after adiabatic expansion is not used to liquefy any additional C_2H_6 even though there would be some benefit in doing so. The sum of the enthalpy differences between each point of the N_2 heating process along the 1.0 MPa isobar determines the total amount of heat that can be rejected from the other working fluids per kg- LN_2 .

Heat is continuously transferred to the CH_4 at 3.0 MPa as it passes through the C_2H_6 condenser until the CH_4 reaches 175 K. Heat exchange with ambient air then superheats the CH_4 to the peak cycle temperature. The mass flow of CH_4 that can be liquefied after being adiabatically expanded from 3.0 MPa by heat exchange with boiling LN_2 at 1.0 MPa is 0.42 kg- CH_4 per kg- LN_2 . This results in a C_2H_6 flow (adiabatically expanded from 3.0 MPa) of 0.7 kg- C_2H_6 per kg- LN_2 that can be liquefied by the combination of N_2 and CH_4 heat transfer.

The heat sink capability of LN_2 for isothermal expanders is determined by assuming 1.0 MPa LN_2 is used to liquefy CH_4 at 290 K and atmospheric pressure. The pressurized CH_4 , in turn, liquefies the C_2H_6 flow from a temperature of 290 K. Heat transfer is assumed to terminate in each of the N_2 - CH_4 and CH_4 - C_2H_6 heat exchangers once the N_2 and CH_4 have been warmed to 280 K. A small amount of ambient heat is then needed to warm the N_2 and CH_4 to the peak cycle temperature of 290 K, whereas the C_2H_6 is completely heated to 290 K

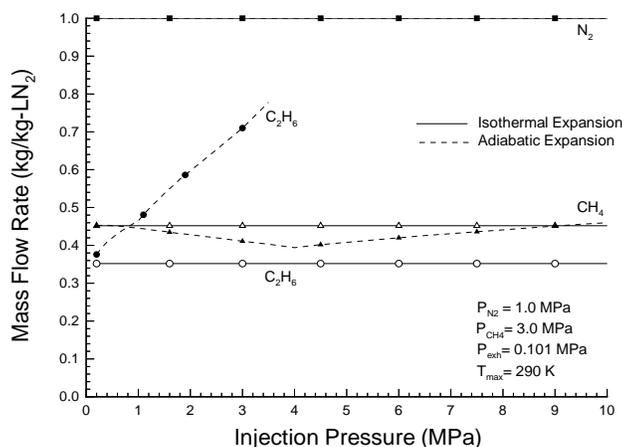


Fig. 5 Mass flow rates relative to 1 kg/s LN₂ at 1 MPa. C₂H₆ flow rate based on that of CH₄ at 3 MPa.

with ambient air. Thus the mass flow rate per kilogram of LN₂ for a ternary energy conversion system using isothermal expanders under these conditions is 0.36 C₂H₆ : 0.45 CH₄ : 1.0 LN₂.

The mass flow rates of C₂H₆ and CH₄ per kg-LN₂ over a wide range of injection pressures are shown in Fig. 5. Since the end state of the isothermal cycles is independent of the injection pressure, the corresponding flow rates remain constant. The flow rates for the adiabatic expanders are dependent on the heat sink capacities of 1.0 MPa N₂ and 3.0 MPa CH₄. The mass flow rate of CH₄ initially decreases with increasing pressure because the decreasing exhaust temperature after adiabatic expansion reduces the amount of heat that can be transferred to LN₂, even though the amount of heat to be rejected to liquefy the CH₄ is steadily decreasing. Once the end state of the CH₄ expander is at the saturation temperature, the reduction in necessary heat transfer with increasing injection pressure results in the liquefaction of more CH₄ flow. The mass flow rate in the adiabatic C₂H₆ cycle steadily increases with pressure because its saturation point is reached with relatively low expansion and the heat rejection requirement significantly decreases with decreasing quality in the mixed-phase end state.

Fixing the peak pressure for the N₂ allows the net cycle work per kg-LN₂ to be determined for a binary LN₂-CH₄ energy conversion system over a range of CH₄ injection pressures as shown in Fig. 6. Likewise prescribing the N₂ and CH₄ peak pressures enables the effect of pressure on the C₂H₆ topping cycle to be evaluated. The net specific work output of the binary system is the sum of the work outputs from the CH₄ cycles as a function of injection pressure added to the specific work output of the 1.0 MPa N₂ cycle. The addition of a CH₄ topping cycle to the N₂

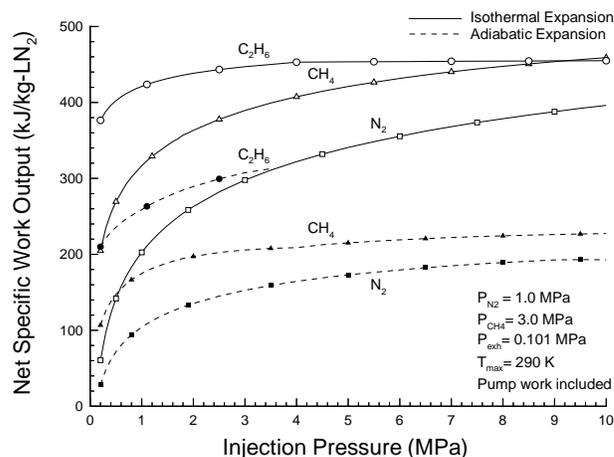


Fig. 6 Net specific work for binary and ternary cryogen energy conversion systems.

cryogen power cycle increases the net adiabatic work output by 30-100% in the pressure range of 1-4 MPa, whereas the isothermal work increases by 25-50% over the same pressure range. At a peak CH₄ injection pressure of 3.0 MPa, the binary system produces 200 and 380 kJ/kg-LN₂ from adiabatic and isothermal expanders, respectively.

The net work output of a ternary energy conversion system using C₂H₆ for the uppermost topping cycle is also shown in Fig. 6 for the case when the peak injection pressures of the LN₂ and CH₄ cycles are 1.0 MPa and 3.0 MPa, respectively. The addition of a C₂H₆ topping cycle boosts the net work output by over 100% in the adiabatic case and by about 80% with an isothermal expander. Thus it is possible to extract over 300 kJ/kg-LN₂ using adiabatic expanders and over 450 kJ/kg-LN₂ with isothermal expanders. This latter value indicates that a quasi-isothermal expander may achieve net specific work of over 400 kJ/kg-LN₂ (110 W-hr/kg-LN₂ or 90 W-hr/l-LN₂), which enables an availability utilization of over 50% while keeping the peak system pressure at 3.0 MPa.

In order to illustrate how to best use the LN₂, the effect of varying the N₂ injection pressure on the net specific work of a system having a peak pressure of 3.0 MPa for both the C₂H₆ and CH₄ topping cycles is shown in Fig. 7. Adiabatic and isothermal work of just the N₂ power cycle are also plotted. The work output for the binary and ternary systems when no work is generated by the vaporized N₂ (N₂ injection pressure = 0.101 MPa) is indicated by the left most plotting symbols. Not enough cases are plotted for these topping cycle parameters to resolve the performance of this system for N₂ injection pressures below 1.0 MPa; however, it is apparent from the negative slope of the topping cycle work curves that LN₂ is best used at lower pressure where it produces less work by itself yet has more

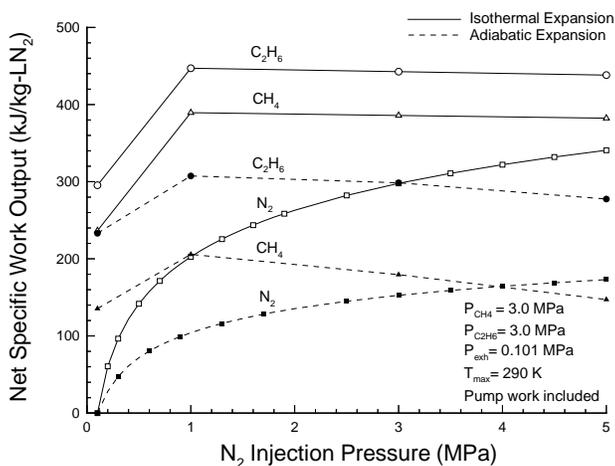


Fig. 7 Net specific work for binary and ternary systems when injection pressure of topping cycles is fixed at 3.0 MPa.

heat sink capability. The best use of CH_4 in an isothermal system was also found to be when it is used at injection pressures lower than 3.0 MPa ($\sim 500 \text{ kJ/kg-LN}_2$); however, the net work output of the adiabatic ternary system was not significantly affected. Thus the performance of the configuration presented in Fig. 6 is a reasonable estimation of what is possible for a ternary cryogen energy conversion system using these three media.

DISCUSSION

A significant operational aspect of a multi-fluid cryogen energy conversion system is that the minimum temperatures of the fluids within the ambient heat exchanger are at the condensation point of the uppermost topping cycle fluid. This increases the total surface area required to transfer the necessary amount of ambient heat into the system, yet minimizes the degree of difficulty of preventing frost accumulation because of the corresponding increase in the minimum temperature of the flows within the ambient heat exchanger. Hence, in humid environments where large flow rates of LN_2 are required to be vaporized, the additional expense and complexity of adding topping cycles may be warranted to enable long periods of frost-free operation, in addition to increasing the LN_2 utilization efficiency.

The choice of CH_4 and C_2H_6 for use in this work was primarily due to their saturation properties at atmospheric pressure. It is recognized that there are many organic compounds being applied in refrigeration processes that have favorable properties for cryogen energy conversion systems, and thus there most likely exist more effective combinations of working fluids and operating conditions that can better utilize LN_2 .

There are several ways to couple the shaft power from multiple expanders to an automotive drive train. Such systems are currently in use for many kinds of hybrid electric vehicles. Conversely, the expanders can all be connected to a common shaft, whether they are rotary or reciprocating devices. For example, a six cylinder engine may be configured to expand three different working fluids through three pairs of adjacent cylinders to minimize imbalance due to variation in mean effective pressures. Loss of working fluids in the closed loop cycles could probably be made up on a maintenance schedule similar to that for changing oil in conventional vehicles. The relatively low peak pressure and temperature of the system reduces the expander wall thickness requirements and thus the thermal impedance and engine mass are also reduced. Transient response times and system start up scenarios need to be investigated in more detail to better quantify the operating characteristics of these cryogen energy conversion systems. It is apparent that there are several complex issues yet to be resolved before an automotive cryogen power plant using multiple fluids can be implemented; however, there do not seem to be any fundamental inhibiting factors that preclude the eventual development of such systems.

CONCLUSIONS

The use of liquid nitrogen as a heat sink for several cascaded topping cycles has been examined. Operating conditions for binary ($\text{LN}_2\text{-CH}_4$) and ternary ($\text{LN}_2\text{-CH}_4\text{-C}_2\text{H}_6$) systems have been identified which can realize specific energies in the range of 200-380 kJ/kg-LN_2 and 300-450 kJ/kg-LN_2 , respectively, depending on the degree of isothermal expansion that can be realized. This results in the LN_2 being used with nearly twice the efficiency of a single expander operating at the same injection pressure. In general, it was found that the best use of LN_2 and CH_4 was at relatively low injection pressures ($< 1.0 \text{ MPa}$) in order to maximize utilization of their heat sink capabilities.

ACKNOWLEDGMENTS

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