APPLICATION OF REFRIGERANT WORKING FLUIDS FOR MOBILE ORGANIC RANKINE CYCLES

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ABSTRACT

Cummins Inc. has been a leading developer of Organic Rankine Cycle (ORC) systems for application to heavy-duty, on-highway trucks in the United States for several years. Cummins has passed through several generations of ORC system architecture and has fielded several on-highway vehicles equipped with ORC systems as a part of research conducted in partnership with the United States Department of Energy. Throughout this development, Cummins has carefully evaluated potential working fluids for ORC application and has remained committed to using safe and environmentally friendly refrigerants such as R245fa and its recently introduced ultra-low GWP replacements for on-highway use.

Integration of Organic Rankine Cycle (ORC) systems into heavy duty, on-highway vehicles requires consideration of a significant number of factors, not the least of which is the choice of working fluid. The selection of fluid is primarily driven by safety, environmental and health effects of the fluid, potential performance considering the application at hand, availability, serviceability, etc. Given the working fluid, selection/sizing of various system components and optimization of the system architecture may be made.

This paper will briefly review Cummins' ORC history and discuss the background leading to Cummins' selection of refrigerant working fluids for on highway application. Details of technology that allow a refrigerant's safe and effective use in this application will also be discussed. An architecture comparison between systems using a refrigerant such as R245fa and ethanol will be made and a performance comparison between R1233zd(e), an ultra-low GWP replacement for R245fa, and ethanol will be presented.

1. INTRODUCTION

Since approximately 2003, Cummins Inc. has investigated the potential practicality and benefit of applying Organic Rankine Cycles (ORC) to its heavy duty diesel engines applied to on-highway, linehaul vehicles. Cummins settled upon non-flammable refrigerants, such as R245fa, as viable ORC working fluids. Refrigerants were already applied in the ORC industry and had a proven record of effective performance. Cummins evaluated many different working fluids but considerations of safety, environmental responsibility, feasibility, performance, etc., led the researchers to make R245fa their initial prime-path fluid of choice.

Cummins early ORC systems (see Figure 1, below) were designed before the introduction of Selective Catalytic Reduction (SCR) aftertreatment. These ORC systems took advantage of a high flowrate of Recirculated Exhaust Gas (EGR) and were expected to achieve nearly an 8% fuel economy benefit.

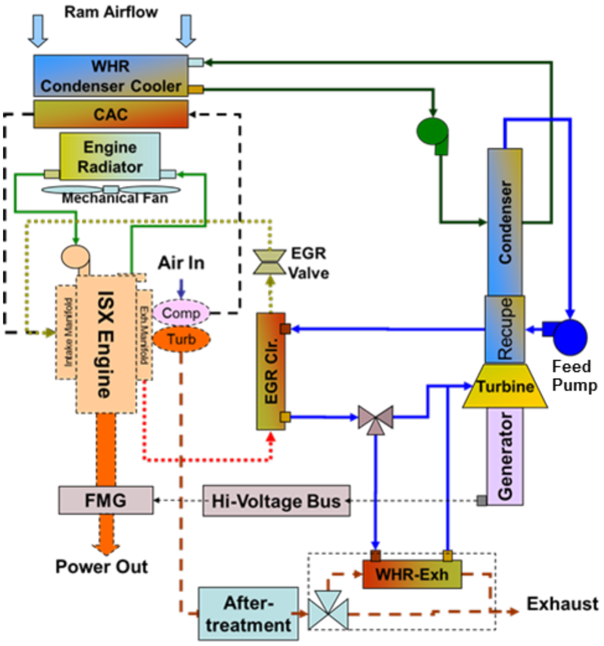

Figure 1: Early Cummins ORC system

At the time, conversion of recovered power to electricity was preferred as integration of the ORC with potential hybrid drive systems was anticipated. Compatibility of electronic systems, cost and complexity of electrical components, and the then expected drive cycle benefit of hybrid systems in linehaul applications drove the ORC architecture away from electrical integration. The concept of mechanically linking recovered power directly to the engine was developed into an architecture as presented in Figure 2, below.

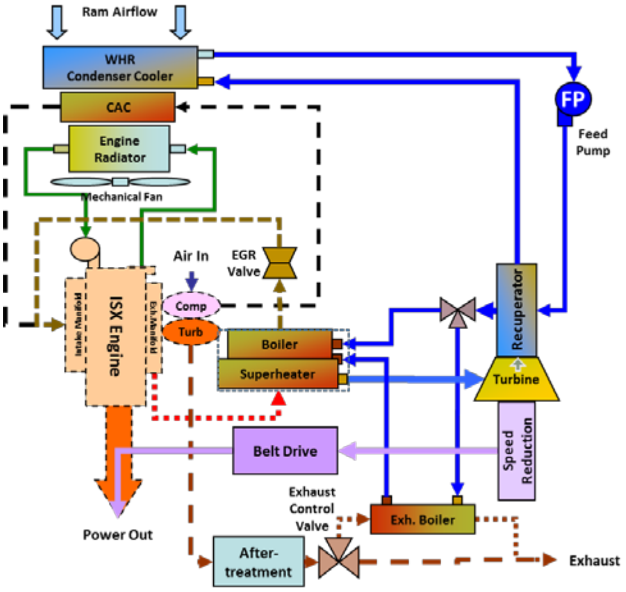

Figure 2: Mechanically-coupled ORC system architecture

Direct-to-air condensing was adopted to avoid an unnecessary pump parasitic. A speed-reducing gearbox and effective, self-contained lubrication system were designed using typical refrigeration-based technologies. Recovery of charge air heat was not pursued as it did not appear to offer a cost-effective benefit. System performance was reduced to approximately 5% fuel economy benefit at this point due to a significant reduction in EGR flow as a result of adopting SCR aftertreatment. The system architecture settled upon in Figure 2 was successfully demonstrated in-vehicle under the United States Department of Energy's Supertruck Program. Cummins applied R245fa as a working fluid throughout these developments but became aware of refrigeration industry plans to introduce ultra-low Global Warming Potential (GWP) 'drop-in' replacements.

2. Safe and Effective Application

Use of halogenated fluid to cool pre-combustion gases (such as EGR or air) necessarily requires a robust and durable method to prevent leakage of the fluid into the combustion airstream. In response to this challenge, Cummins investigated and embraced a heat exchanger architecture which provides a 'leak to atmosphere' feature. This architecture is described in SAE Paper 2006-01-2163 (David B. Sarraf, Heat Pipe Heat Exchanger with Two Levels of Isolation for Environmental Control of Manned Spacecraft Crew Compartment) and is presented in Figure 4 below. Initially, an isolation method of this nature was considered untenable as it would significantly deteriorate the heat transfer effectiveness of any EGR heat exchanger. However, analysis and hardware evaluation showed that any decrease in effectiveness was negligible. Extensive hardware reliability testing has since shown that a robust EGR heat exchanger design can be successfully executed in this manner. Solutions of this nature are available from several manufacturers.

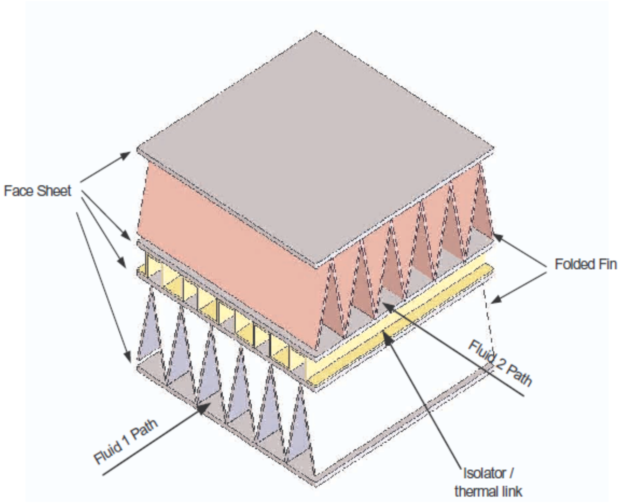

Figure 3: Schematic of a folded fin heat exchanger element with an isolation layer (Ref: SAE 2006-01-2163)

In addition to leakage through heat exchangers into the combustion airstream, leakage of refrigerant working fluid into air within and around the engine compartment was another potential opportunity for generation of harmful emissions. Cummins extensively studied leakage, and the potential for engine ingestion in this regard as well. Recognized standards such as SAE J2773 (Standard for Refrigerant Risk Analysis for Mobile Air Conditioning Systems) and SAE J639 (Safety Standards for Motor Vehicle Refrigerant Vapor Compression Systems) among others were applied to evaluate potential risk. It was concluded that the risk of applying refrigerant as an ORC working fluid posed no significantly greater risk than that which already existed from MAC systems. Impingement of refrigerant leaking upon hot engine surfaces (and tailpipe components) were also studied. It was determined that leaking refrigerant liquid or vapor would not significantly deteriorate but would simply tend to cool those areas of impingement.

3. R245fa Alternatives

Awareness of regulatory restrictions imposed upon Mobile Air Conditioning (MAC) systems in the European Union (EU) led Cummins to investigate alternatives to R245fa. R245fa, with a GWP of

~1000, though with no Ozone Depletion Potential (ODP), applied as a working fluid in a vehicle ORC system would achieve a significant reduction in the emission of carbon dioxide over the life of the vehicle. However, similarity of ORC systems to MAC systems suggested that similar legislated regulations may be applied to ORC systems using refrigerants. Contact with major manufacturers such as Honeywell, DuPont, etc., of R245fa and similar halocarbons revealed intentions to develop and release ultra-low GWP equivalents in the 2015 timeframe. These fluids, such as R1233zd(E), are now available in the market and offer an effective alternative to R245fa. Cummins performed comparative hardware performance testing with several of these alternative fluids (see Figure 4, below) with excellent results. Operating points such as A100, B75, etc. reflect engine operation at Environmental Protection Agency, Federal Test Procedure conditions.

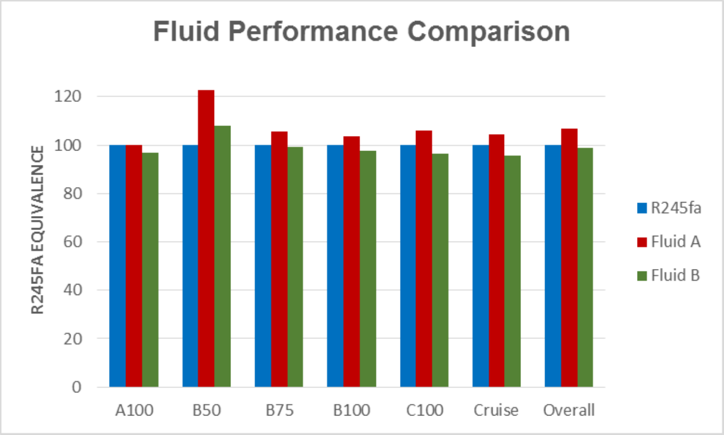

Figure 4: Performance comparison of R245fa against low-GWP equivalents

It was clear from the results that not only were there ‘drop-in’, ultra-low GWP replacements for R245fa readily available, but a slight increase in performance was potentially possible. As a result, Cummins decided upon a low-GWP alternative to R245fa as the concept moves towards a production configuration.

4. Comparisons with Ethanol

4.1 Performance

Ethanol has been taken up as a potential ORC working fluid by many system developers. Ethanol operates very well in this role. At first glance, it is an effective and low-cost choice. Ethanol is generally regarded as non-toxic and environmentally friendly. Typical ethanol ORC system architectures assume rejection of condensation heat into a coolant stream common with the engine (engine and ORC condenser plumbed in parallel, receiving the same radiator return temperature coolant). Many comparisons of performance between R245fa and ethanol simply adopt this cooling system arrangement to evaluate both fluids. However, in doing so, performance potential of R245fa (or R1233zd(e)) is obscured.

A model-based comparison of ethanol and R1233zd(e) at equivalent maximum (225°C) and minimum (80°C) temperatures, maximum operating pressures (2400 kPa) and equally arranged and capable ORC systems (same component efficiencies and effectiveness) shows a stark difference in performance (Figure 5, below).

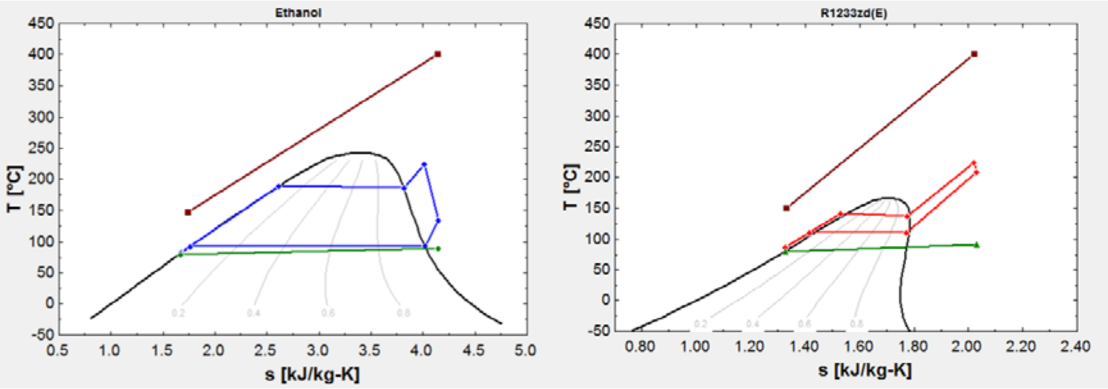

Figure 5: Performance comparison between ethanol and R1233zd(e) in equivalent systems with equal maximum temperatures/pressures and equal condensing temperatures.

For reference, net power from the ethanol system was 18.8 kW, net power from R1233zd(e) was 4.6 kW. Condenser heat rejection was 146 kW for ethanol and 158 for R1233zd(e). Input heat energy to both systems was diesel exhaust at 400°C flowing at 0.6 kg/s. Condensing temperature for ethanol is 93°C, R1233zd(e) is 111°C.

For system application, consideration is necessarily given to the availability of cooling. As presented above, Cummins settled upon a ‘direct to air’ condensing arrangement early in its development. The availability of near ambient air temperature cooling lent further reason to remain with refrigerant working fluids like R1233zd(e).

Ambient air temperature is, on average in the lower contiguous 48 United States approximately 12°C (http://www.ncdc.noaa.gov/). Average EU temperature is only slightly higher. In this case, the results are significantly different as presented in Figure 6, below.

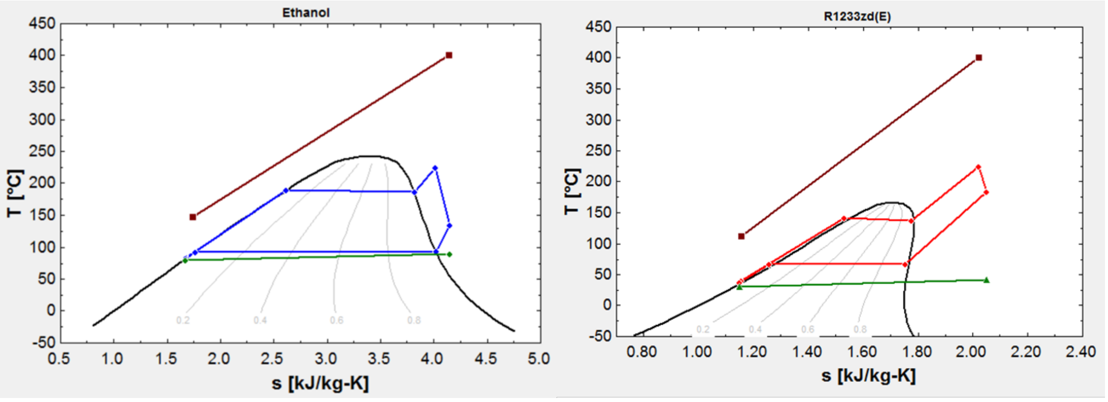

Figure 6: Comparison of ethanol and R1233zd(e) with equivalent systems but with condensing temperature appropriate for an in-vehicle R1233zd(e) system.

For reference in this case, net power from the ethanol system remained at 18.4 kW. Net power from the 1233zd(e) system increased to 14.3 kW. Condenser heat rejection remained 146 kW for ethanol but now increased to 174 kW for R1233zd(e). Input heat energy to both systems as above. Condensing temperature for ethanol remains at 93°C, R1233zd(e) is now 67°C.

An obvious feature of above the R1233zd(e) Temperature-Entropy (T-s) diagram is the opportunity to apply recuperation to the cycle. No such opportunity exists for ethanol due to its ‘wet’ nature. The amount of superheating remaining in the ethanol flow upon leaving the expander is too little to usefully recover. While the addition of a recuperator to an R1233zd(e) system necessarily adds cost to its arrangement, it provides a significant benefit in power and a reduction in heat rejection. Figure 7 below presents the cycles once again but now the R1233zd(e) cycle has a reasonably effective recuperator (effectiveness of 70%, 50 kPa 'cold side' restriction, 10 kPa 'hot side' restriction).

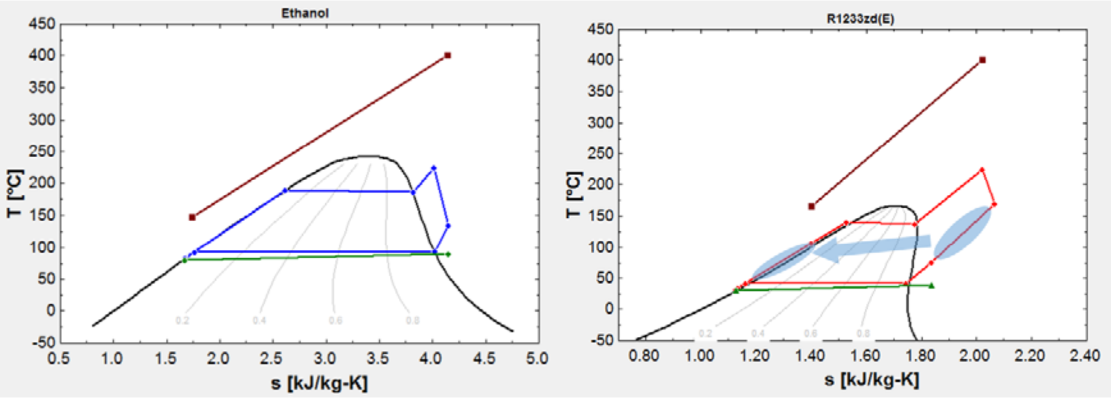

Figure 7: Comparison of ethanol and a recuperated R1233zd(e) cycle.

For reference, net power from the ethanol system remained at 18.4 kW, net power from the R1233zd(e) system increased to 22.7 kW. Condenser heat rejection remained 146 kW for ethanol and but now decreased to 131 kW for R1233zd(e). Input heat energy to both systems as above. Ethanol's condensing temperature remains at 93°C, R1233zd(e) is now 41°C.

While the results above are only model-based, they represent a fair comparison of the two working fluids considering their potential arrangement in-vehicle. The key take-away is that comparisons between refrigerant and ethanol systems should be made using systems optimized for each fluid. Modeling was performed using Engineering Equation Solver (EES) software with fluid properties currently available through NIST REFPROP. R245fa and R1233zd(e) modeled performance was validated from hardware test experience.

4.2 System Hardware Arrangements

The Cummins R245fa-based ORC system demonstrated during the Supertruck project is illustrated in Figure 8, below.

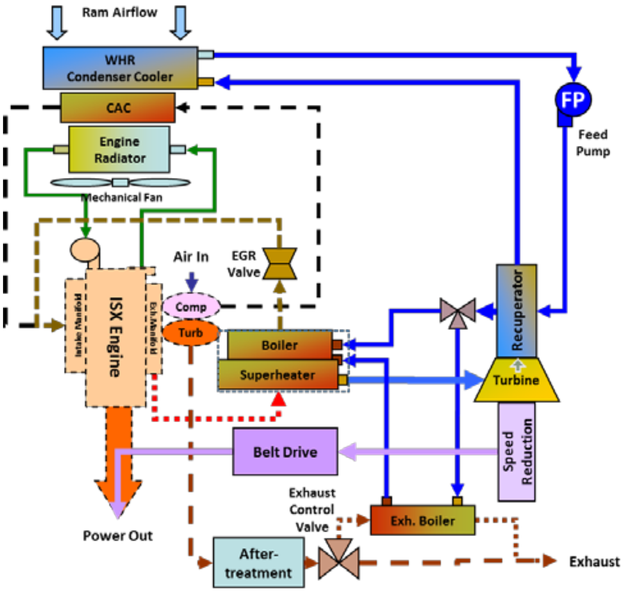

Figure 8: Cummins Supertruck ORC Arrangement

A potential ethanol-based ORC is presented in Figure 9.

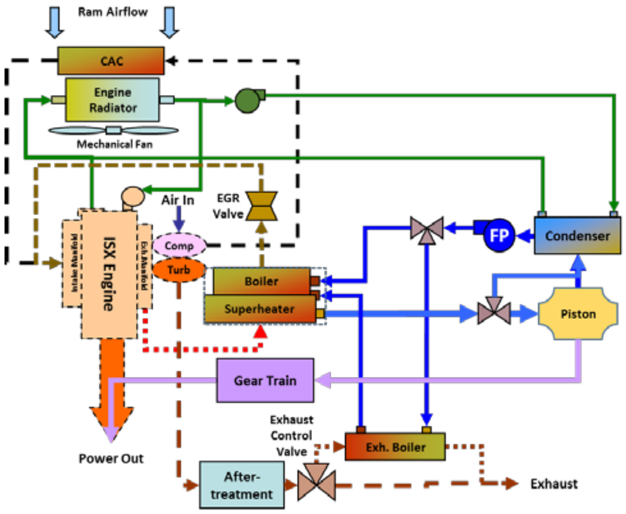

Figure 9: Potential ethanol ORC system arrangement

In this arrangement, the ethanol system has one fewer heat exchanger than the R245fa system since it doesn't call for a recuperator. In this arrangement, ethanol would be cooled with radiator return temperature coolant. If lower temperature condenser coolant is desired, an additional heat exchanger would be necessary, making the systems equivalent in their number of heat exchangers. It should also be noted that the ethanol condenser, plumbing, etc. must be manufactured from material robust against ethanol corrosion. Typically, stainless steels are applied when dealing with ethanol. In comparison, R1233zd(e) is compatible with aluminum and other lightweight, low-cost materials already commonly deployed in MAC systems.

The ethanol system requires either a shared main engine water pump or a separate water pump, likely electrically driven to provide coolant to that system's condenser. The refrigerant system, being directly cooled to air, does not require this.

An ethanol system, using a low-speed, piston-type expander may directly mechanically couple its power to the engine's geartrain. However, an additional bypass valve around any positive-displacement expander will be necessary to guard against possible liquid ingestion/hydraulic lock and potential damage to the expander and the engine's geartrain. In comparison, refrigerant-based systems using a high-speed turbine expander, will need speed-matching equipment to provide mechanical power coupling to the engine. ORC systems using isentropic or dry working fluids and turbine machines will not need to apply a bypass valve given adequate control of liquid superheating. Turbines are robust to low flowrates of low pressure wet or liquid working fluid. Additionally even a high flow of 'wet' vapor may enter the turbine as, on expansion/acceleration through entry nozzles, the fluid rapidly becomes superheated vapor, leaving little risk of expander blade erosion.

4.3 Other Considerations

Application of either ethanol or refrigerant must consider the arrangement of sealing against the intrusion of outside air. This is not typically an issue during operation as both systems should operate with a 'low-side' (condensing) pressure greater than atmospheric pressure. However, during cold operation or during cold storage, the fluid's saturation pressure can be significantly important. Figure 10, below, presents a comparison of the saturation curves for R1233zd(e) and ethanol.

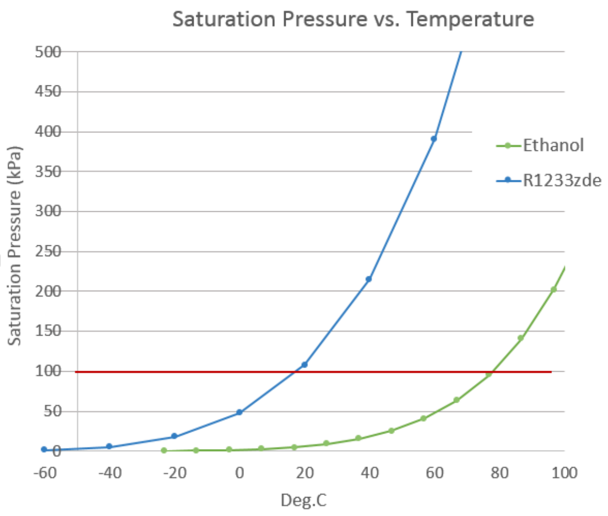

Figure 10: Comparison of saturation pressures

As shown in Figure 10, the saturation pressure of ethanol falls below atmospheric pressure at temperatures less than ~80°C. At room temperature, it's only about 8 kPa absolute. This means that during shutdown, especially in cold ambient temperatures, there will be a significant risk of air ingress to the ethanol system. Blending ethanol with water further suppresses the saturation pressure. R1233zd(e)'s saturation pressure falls below atmospheric pressure as well at approximately 18°C but it does not reach a significantly hard vacuum until nearly -40°C and degrades at a substantially slower rate. Air ingress will cause unnecessarily high expander back-pressure and decreased system performance. Either system, if executed with mechanical power coupling thus requiring an output shaft seal, would need a seal robust both to pressure during operation as well as vacuum when stored.

Additionally, in regard to low saturation pressures, feedpump cavitation may be expected to occur more frequently in systems using ethanol. Extremely low feedpump Net Pump Suction Head Required (NPSHR) will be a necessary requirement, or an additional 'boost' pump will become necessary. This problem is not only related to cold temperatures. Some ethanol systems have been shown to have vented their condensers to atmosphere in an attempt to increase feedpump inlet available suction head (NPSHA). While this may allow better operation close to sea level, higher altitude operation (and thus lower atmospheric pressure) may lead to feedpump cavitation and a loss of performance if condensing temperatures are below 80°C.

5. Further Development

Application of ORC systems to mobile internal combustion engines is not a new idea but it is certainly not a field whose opportunities have been fully explored. It is hard to imagine the potential performance mobile ORC might provide today had it undergone the same intensity and duration of research and development as the internal combustion engine. Though, as a bottoming cycle, it may never reach the thermal efficiency of the engines to which it is applied, it can certainly grow in its ability and benefit. In doing so it will meet and exceed the economic challenges which have typically kept it from production implementation.

It's quite easy to recovery heat. The real challenge is how to reject it. Thermodynamically, any recovered energy cycled through a heat engine loses some of its energy potential making it more difficult to reject. Given the finite cooling capacity available in current and future heavy duty vehicles, a thorough understanding of cooling system function and its duty-cycle based load will determine how much potential benefit any bottoming cycle can provide. Unused cooling capacity during engine operation below worst case conditions is potential ORC benefit. The optimized sharing of cooling capacity between the engine and ORC is an area of research 'outside the cylinder' which should be developed as vigorously as are combustion, air handling, and aftertreatment.

The engines to which ORC systems are being applied today will certainly change as the emphasis for increased efficiency and reduced emissions continues. Further development of ever more capable NOx reducing aftertreatment may very well result in the removal of EGR. Increased emphasis upon exhaust energy recovery will occur but it will also focus attention to potential recovery of other engine waste heat streams. Charge air and engine coolant may become viable opportunities for cost-effective recovery. An ORC system architecture which can usefully approach these waste heat streams will certainly be the most viable long-term solution. Today's typical engine coolants offer a bulk temperature considered to be too low for effective use. However, the potential for hotter coolant (and thus more thermally efficient diesel engines) is a real possibility. In this case, an additional 'necessary' heat stream (as is EGR today) of recoverable energy will become available for the ORC to convert to useful power.

ORC system components are just beginning to attract the attention of manufacturers. As typical system arrangements coalesce across the industry, availability of more capable and more cost effective components will increase. Development of ORC components is just beginning and will certainly offer performance and efficiency benefits as it grows.

As mobile ORC is a new and relatively undeveloped field which will affect a significant portion of the engine system, there will necessarily be a great deal of work to establish standards, methods, and procedures around its safe and effective application. The handling of its fluids, the ratings of its components, the controls interaction between ORC and other engine systems will all require careful review and consideration by the industry's governing bodies and professional organizations.

6. Conclusions

This paper covers the use and application of R245f or R1233zd(e) and potentially other halocarbons as working fluids in mobile ORC systems. A brief review of the ORC project at Cummins and system architectures from the project's early phases through its most recent demonstrations have been shared and discussed. Reasons for Cummins' choice and adherence to low GWP refrigerant as its on-highway ORC working fluid have been provided. System considerations and features that allow the safe and effective application of these fluids in mobile ORC systems have been shared. Mention and comparison of ultra-low GWP working fluid alternatives to R245fa has been made. A model-based comparison of R1233zd(e) and ethanol has been provided to show that performance between the two working fluids is not quite as different as may be gathered from other work. Application considerations between the two fluids have also been discussed to offer developers some insight as to why R1233zd(e) is an appealing and viable working fluid for application in mobile ORC systems. Considerations for future development have been provided and briefly discussed.

ORC application to on-highway engines was once considered to be a 'tried and failed' technology. The emphasis on efficiency and emissions has resurrected it once again. The potential benefit it offers is the most significant efficiency increase available in quite some time and perhaps, for some time to come. New materials, controls, components, and ideas will help it leap the economic hurdle to reach mainstream, production implementation.

ACKNOWLEDGEMENT

The author wishes to acknowledge the United States Department of Energy, Office of Vehicle Technologies without whose partnership and support the opportunity to explore and develop mobile ORC systems would not have been possible.