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Performance Benefits for Organic Rankine Cycles with Flooded Expansion and Internal Regeneration

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ABSTRACT

An organic Rankine cycle (ORC) is often used in waste heat recovery applications. These are typically small-scale applications where cycle thermal efficiency is low, and the benefits of traditional cycle enhancements (such as reheat stages or feed-water heaters) do not typically outweigh the costs required to implement them. An ORC with flooded expansion and internal heat regeneration is an alternative enhancement that provides comparable benefits at reduced cost and complexity.

The improvement in efficiency for the ORC with flooded expansion and internal regeneration is analyzed for several working fluids and for two flooding media: water and Zerol 60 compressor lubricant. It is shown that internal regeneration alone provides most of the efficiency enhancement for dry working fluids (R600a, n-Pentane, and R245fa). n-Pentane is shown to offer the most efficient cycle even without flooded expansion in most cases. A quantitative comparison is given between the proposed cycle and the reheat and feedwater heater cycles with internal regeneration. In applications where a hydrocarbon may not be appropriate as a working fluid, R245fa and R717 show promise as alternatives. R717, which shows the most benefit from flooded expansion and internal regeneration, requires this enhancement in order to be competitive with the dry working fluids.

1. INTRODUCTION

An organic Rankine cycle (ORC) is commonly used to extract work from a heat source which is not hot enough to operate a steam Rankine cycle. Due to the small temperature difference between the heat source and sink, the cycles operate at low thermal efficiencies. In addition, ORC are typically employed in small-scale applications. Without economies of scale, the investment in traditional Rankine cycle enhancements, such as reheat stages or feedwater heaters is not as attractive as it is for large-scale power production. Whereas large-scale facilities often employ a combination of several efficiency enhancements, ORC are typically not enhanced.

A flooded expansion process and internal regeneration are alternative enhancements for an ORC with comparable benefits to the traditional feed-water heater or reheat stage. Flooded expansion is achieved by literally "flooding" the expansion device with a liquid that is in thermal equilibrium with the working fluid while simultaneously expanding the working fluid through the same device. (Flooding can be handled well with both scroll and screw type expanders.) Because the liquid which floods the expander has a higher heat capacity than the vaporized working fluid, it is able to act as a buffer against the temperature drop which normally occurs in the working fluid during the expansion process. The result is an expansion of the working fluid that takes place more isothermally.

The main advantage of the flooded expander enhancement is that it is simpler and less costly than traditional Rankine cycle enhancements. Concepts involving the idea of flooded expansion (and compression) have been studied for Ericsson cycles by Hugenroth (2006a). For vapor compression systems, flooded compression with

regeneration was studied by Bell *et al.* (2009). However, no literature has been found to date which evaluates the potential benefits of flooded expansion and regeneration for Rankine cycles.

This paper presents a thermodynamic analysis of ORC with flooded expansion and internal regeneration. The analysis is shown over a range of source temperatures with different working fluids and flooding media.

2. CYCLE MODEL

2.1 System Components
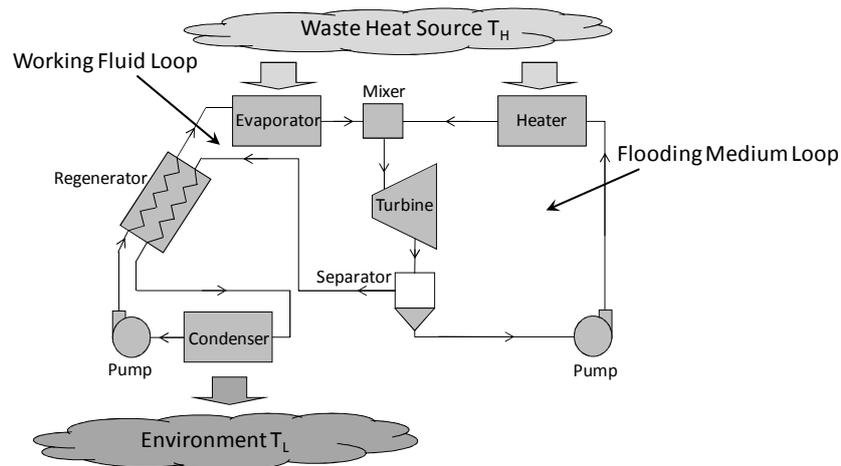A schematic of the cycle is given in Figure 1.

Figure 1: Schematic diagram showing the ORC with internal regeneration. The working fluid cycles through the left-hand loop, while the flooding medium cycles through the right-hand loop. Both fluids flow together through the turbine.

In the cycle, both the working fluid and the flooding medium are pumped to the high system pressure. At this point both fluids are heated to the same temperature using the heat source. The fluids are then mixed and expanded together through the turbine. After the expansion process, the working fluid is separated from the flooding medium. The flooded expansion guarantees that the working fluid is still significantly superheated at the expander outlet. This enables the use of an internal regenerator to preheat the fluid coming out of the pump exit. The remaining heat in the working fluid is then rejected to the environment. At the other side of the separator, the flooding medium is simply pumped back to the high-side pressure, and enough heat is added to restore it to the high-side temperature of the cycle.

2.2 Working Fluids and Flooding Media
The following working fluids were studied: R717, R744, R600a, n-Pentane, R245fa, and R410A. They were selected because they are either natural refrigerants or because they are not chlorinated. Working fluid properties were either found directly in Engineering Equation Solver (EES) (Klein, 2009) using the built-in property functions or by calling the REFPROP (Lemmon *et al.,* 2007) equations of state through EES as an external procedure. REFPROP was used where EES property functions were more strictly limited by temperature (as in R245fa) and, in the case of R410A, were also less accurate.

Two flooding media were tested with the above fluids. The first was Zerol 60, a compressor lubricant. Its equations of state were derived using the Maxwell equations for thermodynamics from a knowledge of the oil's specific heat and density as functions of temperature (it is assumed to be incompressible). These functions were found in a brochure for Zerol and used by Hugenroth (2006a) to model flooded expansion and compression for an Ericsson cycle. The second flooding medium tested was water, whose equations of state are readily available in EES and REFPROP.

2.3 Component Models

The system components are modeled using basic thermodynamic equations. In place of a heat exchanger model, a temperature difference of 10°C is imposed between the heat source and the cycle maximum high-side temperature and between the environment and the cycle minimum low-side temperature. This was done to speed up the computation of the model in order to find optimum parameters (see Section 2.4). The environment temperature was fixed at 20°C. The regenerator effectiveness was set at 0.8. Where the two fluids mix, they are assumed to be in perfect thermal equilibrium. Solubility of the working fluid in the flooding medium is not considered. The flooded expansion process is modeled by applying the technique used by Hugenroth *et al.* (2006b) to model flooded compression. First, an ideal expansion process is considered. In this process, the total change in entropy is zero. However, the individual fluids experience entropy changes because there is significant heat transfer between them. Thus the following equation holds for an ideal flooded expansion process

$$\dot{m}_{wf} \Delta s_{wf,s} + \dot{m}_{flood} \Delta s_{flood,s} = 0 \tag{1}$$

Once the ideal expansion state is found, the ideal work produced is given by

$$\dot{W}_{ideal} = \dot{m}_{wf} \Delta h_{wf,s} + \dot{m}_{flood} \Delta h_{flood,s} \tag{2}$$

This work is path-independent because the expansion process is assumed to be adiabatic with respect to the environment. Based on this ideal work output, an isentropic efficiency is defined such that

$$\eta_{turb} = \frac{\dot{m}_{wf} \Delta h_{wf} + \dot{m}_{flood} \Delta h_{flood}}{\dot{m}_{wf} \Delta h_{wf,s} + \dot{m}_{flood} \Delta h_{flood,s}} \tag{3}$$

If the isentropic efficiency is given or assumed, the actual expander exit state can then be found.

EES was used to solve the cycle model. In the case of Zerol-flooding, EES was allowed to solve iteratively for the state points resulting from equations (1) and (3). In water-flooding, equations (1) and (3) were written as functions of temperature and pressure only. This could be done because the water was constrained to stay in the subcooled region, and the working fluid, by design, is always superheated at the expander exit. The pressure is known because it is fixed by the condensing temperature of the working fluid. Then, the modified false-position method (Chapra and Canale, 2006) was applied to solve for the outlet temperature of the ideal expansion process. With this state known, the modified false-position method was applied again to solve for the outlet temperature of the actual expansion process.

2.4 Model Optimization

In addition to environmental boundary conditions, heat exchanger temperature differences, regenerator effectiveness, and expander and pump efficiencies, the model has two free design parameters: system pressure ratio and mass flow ratio of flooding medium to working fluid. Optimization was performed at each design point to maximize the cycle efficiency with respect to these parameters. Optimum values for the flooding mass flow ratio are typically less than unity.

The benefits of flooding with internal regeneration were compared for all working fluids as a function of heat source temperature and isentropic efficiency of the pumps and expander.

3. RESULTS AND DISCUSSION

3.1 Flooded Expansion vs. Baseline

It is instructive to compare the benefits of flooded expansion with internal regeneration to a baseline cycle in which no enhancements have been applied. For brevity, this discussion will be limited to the case in which the isentropic efficiencies of the pumps and expander are set to 0.8. Figure 2 gives the Second Law efficiency (thermal efficiency relative to the Carnot efficiency) of the baseline cycle as a function of heat source temperature for each of the refrigerants studied. In all cases reported in Figure 2, the quality at the expander outlet has been constrained to be no less than 0.94 on a mass basis.
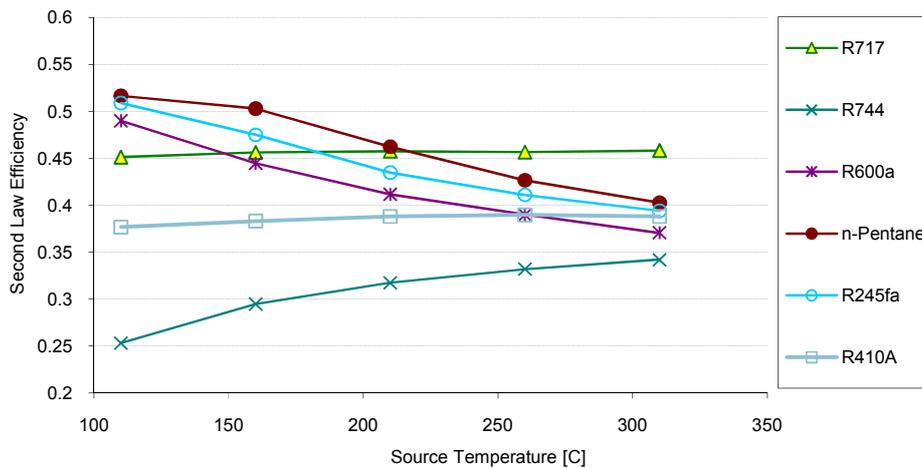
Figure 2: Comparison of the Second Law efficiency for the baseline ORC as a function of source temperature for all working fluids studied.

It can be seen form Figure 2 that the Second Law efficiency is the highest at lower heat source temperatures for dry working fluids (where the saturated vapor line has a positive slope in a T-s diagram), such as R600a, n-Pentane, and R245fa. Because of their vapor dome shapes, these fluids allow for zero superheat at the expander inlet. This gives them an advantage at low heat source temperatures. However, as the source temperature increases, R717 becomes the most efficient fluid for the baseline cycle. This is because, at sufficiently high source temperatures, the vapor dome shapes for the dry working fluids limit the work that can be extracted by the expander by imposing significant superheat at the expander outlet. For example, n-Pentane expands to a superheat of 127°C for a source temperature of 310°C. In contrast, R717 expands to within 2°C of the saturation temperature with the same heat source.

In the next step, the baseline cycle was modified to include internal regeneration only. Figure 3 shows the results for the Second Law efficiency of the ORC as a function of heat source temperature if only internal regeneration is applied for the same operating conditions considered in Figure 2.
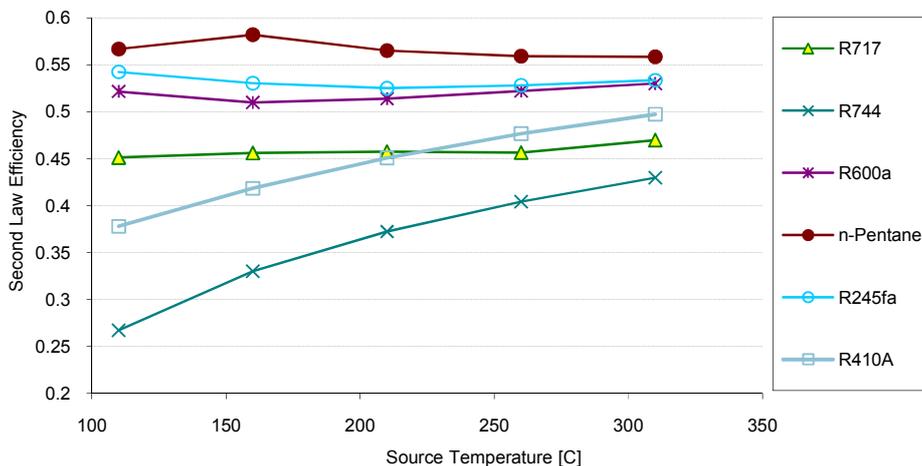

Figure 3: Comparison of the Second Law efficiency as a function of source temperature for the ORC if only internal regeneration is applied.

By comparing the results shown in Figures 2 and 3, it can be seen that internal regeneration significantly improves the Second Law efficiency of the cycles for several of the working fluids. In particular, improvements are achieved at high heat source temperatures. Figure 4 shows the relative improvement in efficiency of the internal regeneration

cycle in comparison to the baseline cycle. For clarity, cycle efficiencies are always given in decimal form, and relative improvements in efficiency are given as percentages.
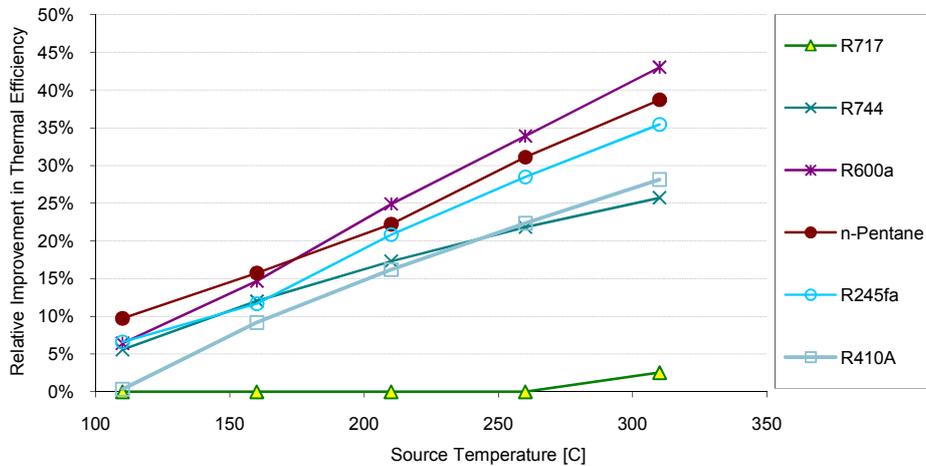

Figure 4: Comparison of the improvement in thermal efficiency as a function of source temperature for the ORC with internal regeneration relative to the baseline cycle.

Note that R410A and R717 experience no benefit from internal regeneration at lower temperatures because the shape of the vapor dome does not allow for a sufficiently superheated state at the expander exit. However, dry working fluids show significant improvement because these fluids have a large built-in potential for internal heat regeneration. In this case, the high superheat at the expander exit is utilized rather than wasted, and the cycle efficiency is improved dramatically.

In the next step, the internal regeneration cycle was further modified by including flooded expansion. Figures 5 and 6 show the relative improvement of the cycle with internal regeneration and flooded expansion over the cycle with internal regeneration only as a function of heat source temperature, using Zerol-flooding and water-flooding, respectively.
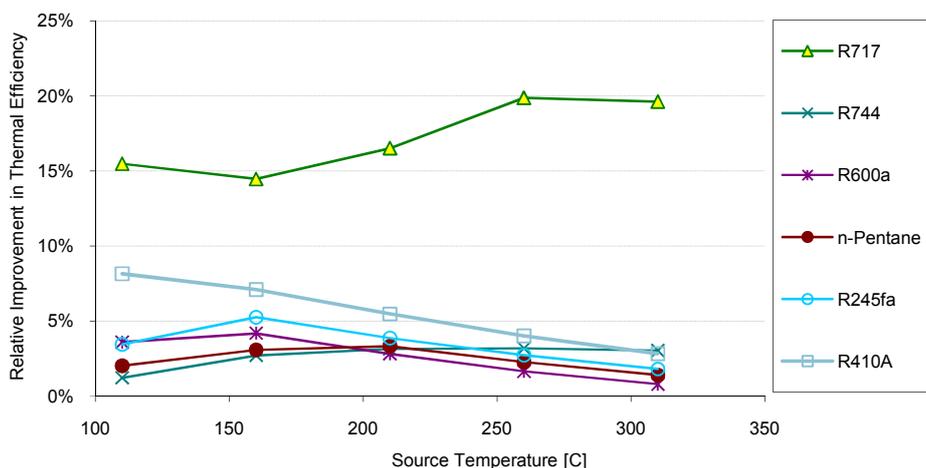

Figure 5: Comparison of the improvement in thermal efficiency as a function of source temperature for the ORC with Zerol-flooded expansion and internal regeneration relative to the ORC with internal regeneration only.
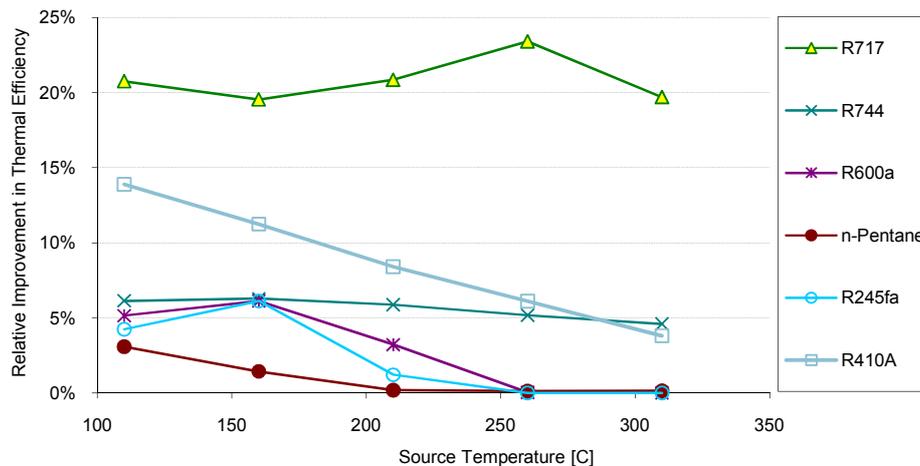
Figure 6: Comparison of the improvement in thermal efficiency as a function of source temperature for the ORC with water-flooded expansion and internal regeneration relative to the ORC with internal regeneration only.

Note that the improvement due to flooded expansion is greatest for R717 and R410A. This is because the superheated conditions at the expander exit due to a more isothermal expansion allow for internal heat regeneration that would not normally be available with these working fluids. Additionally, at lower source temperatures, the more isothermal expansion permits the cycle to operate with zero superheat at the expander inlet, where normally, significant superheat would be required in order to achieve sufficiently high quality at the expander exit. In contrast, the dry working fluids show less benefit from flooded expansion because most of the internal regeneration performed in the cycle was already available before the working fluid was expanded more isothermally.

As expected, the model predicts higher work output from the more isothermal flooded expansion than from the baseline expansion process. However, this effect is not responsible for improvements in thermal efficiency. This is because the flooding loop also requires pump work and additional heat input. For a given pressure ratio, the added work output is not great enough in proportion to these extra inputs, causing a decrease in thermal efficiency if internal regeneration is not also employed.

An item to note from Figure 6 is that water is not a suitable flooding medium for R600a, n-Pentane, or R245fa at sufficiently high source temperatures. This is because, at higher temperatures and at the condensing pressures for these working fluids, water evaporates. The two-phase water is not able to act as a buffer against temperature drop during expansion because it too drops in temperature as it expands. It also cannot be pumped back to the high-side pressure directly after expansion without first being condensed. If the water were condensed before being pumped, more heat would be required at the heater, and cycle efficiency would be further reduced.

It is apparent from Figures 5 and 6 that water-flooded expansion offers greater improvement than Zerol-flooded expansion for some working fluids and heat source temperatures. However, if maximum cycle efficiency is the objective, it is necessary to go back to absolute cycle efficiencies. The most efficient refrigerant shown in Figure 3 is n-Pentane. Because n-Pentane benefits more from Zerol-flooded expansion than from water-flooded expansion, it will be useful to look at the Second Law efficiency of the Zerol-flooded expansion cycle with regeneration. This plot is given in Figure 7.
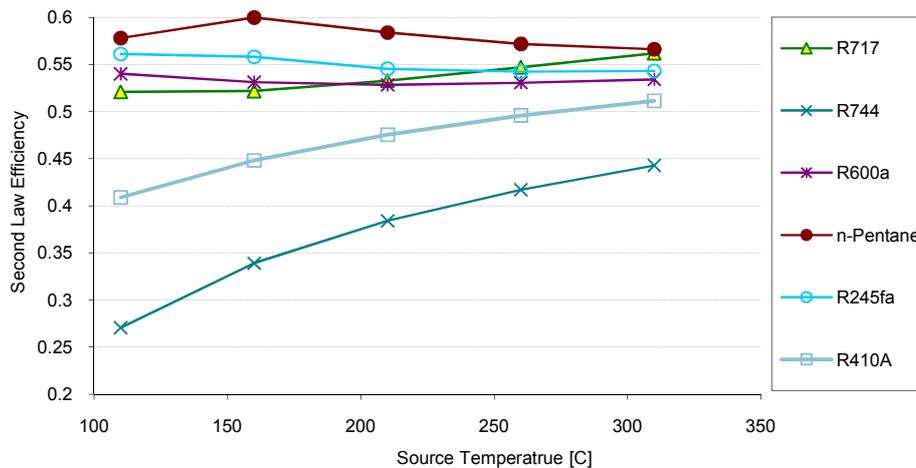
Figure 7: Comparison of the Second Law efficiency as a function of source temperature for the ORC with Zerol-flooded expansion and internal regeneration.

It can be seen from Figure 7 that n-Pentane still offers the highest cycle efficiency for the Zerol-flooded case. A comparison with Figure 3 reveals that, even without the added benefit of flooded expansion, n-Pentane typically offers higher efficiency than the other working fluids studied with flooded expansion. There are two exceptions: R717 with water-flooding at source temperatures of 260°C and 310°C is more efficient; however, the difference between these efficiencies and n-Pentane with regeneration alone is less than 0.005 in both cases. Also, since the benefits of flooded expansion for n-Pentane are less than 5% of the internal regeneration cycle efficiency, one may determine that the most economical improvement is simply the addition of an internal heat exchanger to an ORC with n-Pentane as the working fluid. However, in applications which would not allow the use of hydrocarbons, R245fa (which shows somewhat greater improvement from flooding) or R717 (which requires flooding to be competitive) may be choices in which a flooding loop is also economical.

3.2 Flooded Expansion vs. Reheat and Open Feedwater Heater with Internal Regeneration

It is also of interest to know how flooded expansion with internal regeneration compares to the traditional cycle enhancements mentioned in Section 1: 1) a cycle with one reheat stage and internal regeneration, and 2) a cycle with one open feedwater heater and internal regeneration. Figures 8 and 9 give the relative improvement in efficiency of the reheat cycle and the open feedwater heater cycle respectively, in comparison to the Zerol-flooded cycle. All cycles use internal heat regeneration where possible. Values greater than zero indicate that the traditional enhancement is more efficient than the Zerol-flooded cycle. Note that R744 has been excluded from Figure 9 because its critical point is too low for an effective open feedwater heater to be implemented within the range of temperatures studied.

A brief example of how to interpret the results in Figures 8 and 9 follows:

From Figure 7, the Second Law efficiency for n-Pentane with Zerol-flooded expansion and internal regeneration at a source temperature of 310°C is 0.566. The value from Figure 8 at this point is 2.24%. This means that the reheat cycle is 2.24% more efficient than the Zerol-flooded cycle. This gives the reheat cycle a Second Law efficiency of 0.579 for an absolute improvement in Second Law efficiency of 0.013 over the Zerol-flooded cycle.
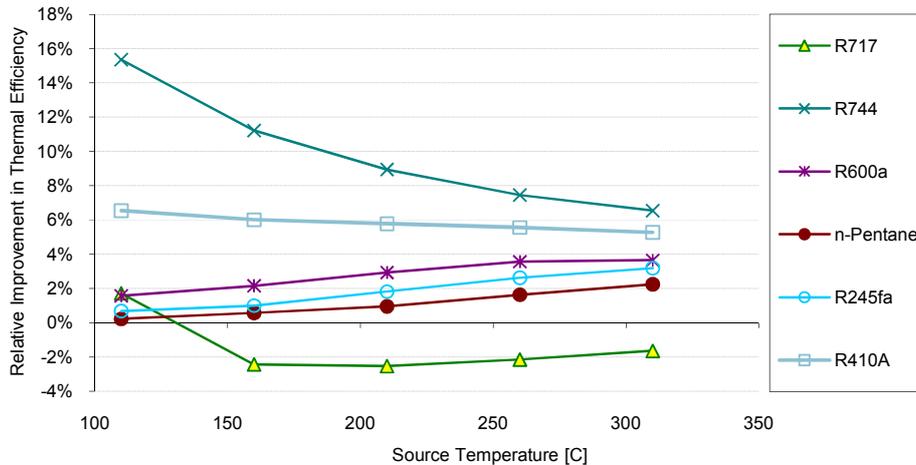
Figure 8: Comparison of the improvement in thermal efficiency as a function of source temperature for the ORC with one reheat stage and internal regeneration relative to the ORC with Zerol-flooded expansion and internal regeneration.
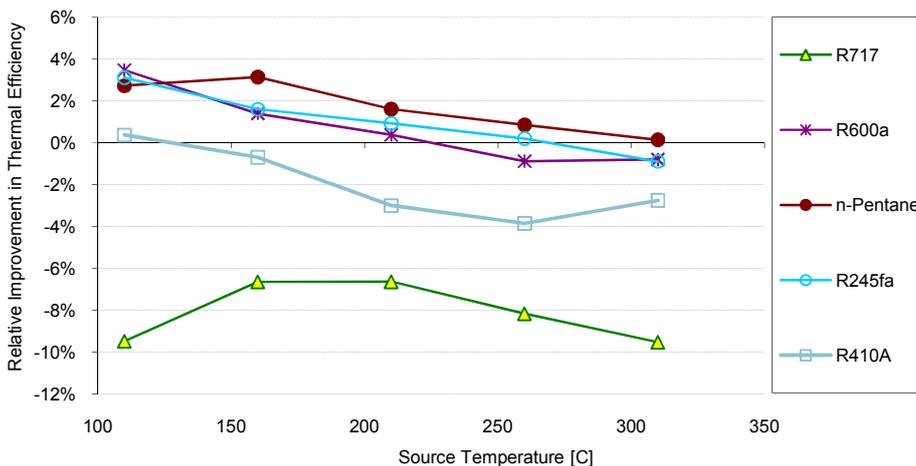

Figure 9: Comparison of the improvement in thermal efficiency as a function of source temperature for the ORC with one open feedwater heater and internal regeneration relative to the ORC with Zerol-flooded expansion and internal regeneration. (R744 has been omitted because its critical point is too low for an effective feedwater heater to be implemented.)

It can be seen from Figures 8 and 9 that the Zerol-flooded expansion cycle offers efficiencies for the dry working fluids which are competitive with the reheat and open feedwater heater cycles (differences are within 4% of the Zerol-flooded cycle efficiency). Also of note is the fact that n-Pentane with internal regeneration alone is still the most efficient cycle in almost all cases. There are only two more exceptions to this rule: R245fa with open feedwater heater at a source temperature of 110°C and R245fa with reheat at a source of 310°C. The difference between these efficiencies and n-Pentane with regeneration alone are 0.012 and 0.002 respectively.

Thus nearly the same conclusions hold as in Section 3.1. n-Pentane with internal heat regeneration alone provides the best overall performance for an ORC. However, if non-flammable working fluids must be chosen, R245fa and R717 are good alternatives. In the case of R245fa, the cycle thermal efficiency improvements due to flooded expansion may be more economical than the slightly better improvements available by a reheat stage or feedwater heater. Lastly, for R717, flooded expansion is the only option which will make it competitive with the dry working fluids.

4. CONCLUSIONS

- n-Pentane offers the best cycle efficiency of the working fluids studied.
- A simple internal heat regenerator provides most of the efficiency enhancement for dry working fluids (R600a, n-Pentane, and R245fa)
- The addition of flooded expansion with internal regeneration offers about 5% more improvement over the regenerative cycle for dry working fluids. However, it offers significant improvement for other working fluids because of the additional potential for internal regeneration it creates.
- For dry working fluids, flooded expansion with internal regeneration offers improvements in thermal efficiency which are competitive with the more traditional reheat and open feedwater heater cycles with internal regeneration.
- n-Pentane with internal regeneration alone is typically more efficient than all other working fluids tested with flooded expansion and internal regeneration. Even when compared to the traditional reheat and open feedwater heater cycles, n-Pentane with internal regeneration alone is still almost always the most efficient choice.
- Where hydrocarbons may not be appropriate as working fluids, R245fa and R717 are the best alternatives. Flooded expansion may make more sense with R245fa than with n-Pentane. It may also be more economical to implement than the reheat stage or feedwater heater even though efficiency gains are slightly lower. Flooded expansion is the only enhancement which will make R717 competitive with the dry working fluids.

NOMENCLATURE

			Subscripts	
h	specific enthalpy	(kJ/kg)		
$\dot{m}$	mass flow rate	(kg/s)	*flood*	flooding medium
s	specific entropy	(kJ/kg-°C)	H	heat source
T	temperature	(°C)	L	environment
$\dot{W}$	power	(kW)	s	constant mixture entropy
η	isentropic efficiency	(-)		
			turb	turbine
			wf	working fluid
			ideal	isentropic

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