

**Footprint of the OTELLO™ Heat Engine
of
International Innovations Limited (IIL)**

Dr Christos N. Markides
Clean Energy Technologies Laboratory
Department of Chemical Engineering
Imperial College London

Date:
20th of April, 2010

Note:

All results and conclusions contained in this report are based solely on the software tool for the prediction of the performance of the OTELLO™ developed for International Innovations Limited by the University of Newcastle, with the permission of and by request of International Innovations Limited. The Disclaimer on Page “i” of the accompanying report by the University of Newcastle also applies to the contents herein.

1. Introduction

The OTELLO™ thermal hydraulic generator (THG) is a heat engine system owned by IIL, with significant similarities to their MOREAMPS THG system. Both systems are based on sound thermodynamic and operational principles, and can be used to recover waste heat in order to produce useful work and generate electricity. They both comprise a ‘refrigerant circuit’, which contains the working fluid (liquid-vapour) that undergoes a thermodynamic cycle similar to a Rankine cycle, and a ‘hydraulic circuit’ that transforms the displacement work output from the piston or bladder accumulator in the refrigerant circuit to electrical power. In this document we focus on the OTELLO™ THG system.

The OTELLO™ cycle, as described in previous literature, comprises: isentropic compression, followed by constant pressure and then constant volume heat addition, followed by isentropic expansion, and finally constant pressure heat rejection. In the OTELLO™ THG system heat is obtained from a bath of hot liquid that acts as an intermediary heat store between the external waste heat source and the system. This is expected to make the OTELLO™ THG a relatively versatile system, in that it will be possible to adapt with relative ease to a diverse range of waste heat sources. On the other hand, the MOREAMPS THG system does not use a thermal bath. Here, the working fluid is externally heated and vaporised as it flows through heat exchanging components before entering the piston or bladed accumulators where it expands displacing the hydraulic fluid and producing mechanical work. Both THG systems can also be powered by solar heat.

An advantage of both the OTELLO™ and MOREAMPS THG systems is their use of standard components available from international suppliers such as Hydac (www.hydac.com) and Honeywell (www.honeywell.com). The THG systems can be constructed entirely from off-the-shelf components. Using standard components lowers the overall cost, but also allows the warranties and replacement of parts to be covered by the suppliers. At the heart of these systems are the ‘pneumatic hydraulic accumulators’ made by Hydac. It is intended that Honeywell will supply valves, speed drives, controls, instrumentation and working fluids.

IIL engaged the clean energy commercial arm (www.newcastleinnovation.com.au) of the University of Newcastle (UoN), Australia to predict the performance of a 1 MW power output OTELLO™ over a source temperature range of 120 – 200 °C. Typically, natural gas (primarily consisting of methane)-burning Stirling engines (e.g. www.whispergen.com), or spark-ignition internal combustion (Otto) engines (e.g. www.freewatt.com) have waste heat temperatures in the range 80 – 120 °C for the cooling water and 500 – 750 °C for the exhaust gases. Three working fluids were considered in this theoretical study: R245fa, R410a and CO₂, with cold sink temperatures of 25 °C, 25 °C and 20 °C respectively. Based on these preliminary calculations the theoretical efficiency of the OTELLO™ was found to be in the range 6.4 – 13.7% for R245fa, 3.4% – 12.2% for R410a, and 0.1 – 8.0% for CO₂.

The purpose of this current document is to examine more closely the footprint of the OTELLO™ heat engine, by using the software tool developed by the UoN and used to generate the results presented in their study.

2. Methodology

The present document focuses on R245fa as the working fluid, as this fluid was shown to be associated with the highest OTELLO™ efficiencies. All other input parameters as employed by the UoN were:

Total net output power, $W_{\text{net}} = 1 \text{ MW}$

Accumulator volume capacity, $V_{\text{acc}} = 0.03 - 2.5 \text{ m}^3$

Accumulator aspect ratio, $AR = H/D = 5$

Volume expansion (swept volume) ratio, $V_{\text{max}}/V_{\text{min}} = V_5/V_4 = 4$

Source (bath) temperature, $T_s = 120 - 200 \text{ }^\circ\text{C}$

Approach temperature between working fluid and bath, $T_a = 40 \text{ }^\circ\text{C}$

Maximum cycle temperature, $T_4 = T_s - T_a = 80 - 160 \text{ }^\circ\text{C}$

Ambient temperature, $T_\infty = 25 \text{ }^\circ\text{C}$

Fluid exit temperature, $T_5 = 67 \text{ }^\circ\text{C}$

Minimum cycle pressure = $p_1 = p_5 = 0.2 \text{ MPa (2 bar)}$

Bath Reynolds number, $Re = 40,000$

The geometry of the accumulators will not affect the efficiency of the OTELLO™, which is 8.2%, 10.9% and 13.7% for source (bath) temperatures T_s of 150 °C, 170 °C and 200 °C respectively and all other conditions as per above. It will however have a strong effect on the cycle frequency and hence the number of required accumulators N to achieve a power output $W_{\text{net}} = 1 \text{ MW}$. A study into the effects on the performance of the OTELLO™ of the accumulator aspect ratio $AR = H/D$ and the accumulator volume capacity V_{acc} at small accumulator sizes is crucial, as the OTELLO™ heat engine shows vastly improved performance characteristics when these parameters are optimised due to the much improved heat transfer and faster cycling times. Here, we consider the effects of accumulator geometry (i.e. diameter D , height H , aspect ratio $AR = H/D$) on the performance and expected footprint of the OTELLO™.

3. Results and Discussion

We examine first the effect of varying the accumulator diameter D for a fixed accumulator volume V_{acc} . Figure 1 shows that, for all other parameters being fixed (and equal their respective values in the UoN report), including a fixed source (bath) temperature T_s , as the diameter D decreases the total number of accumulators required to generate a net power output W_{net} of 1 MW decreases. The following parameters were used to generate the data in Fig. 1:

Total net output power, $W_{\text{net}} = 1 \text{ MW}$

Volume expansion ratio, $V_{\text{max}}/V_{\text{min}} = V_5/V_4 = 4$

Source (bath) temperature, $T_s = 170 \text{ }^\circ\text{C}$

Approach temperature between working fluid and bath, $T_a = 40 \text{ }^\circ\text{C}$

Maximum cycle temperature, $T_4 = T_s - T_a = 130 \text{ }^\circ\text{C}$

Ambient temperature, $T_\infty = 25 \text{ }^\circ\text{C}$

Fluid exit temperature, $T_5 = 67 \text{ }^\circ\text{C}$

Minimum cycle pressure = $p_1 = p_5 = 0.2 \text{ MPa (2 bar)}$

Bath Reynolds number, $Re = 40,000$

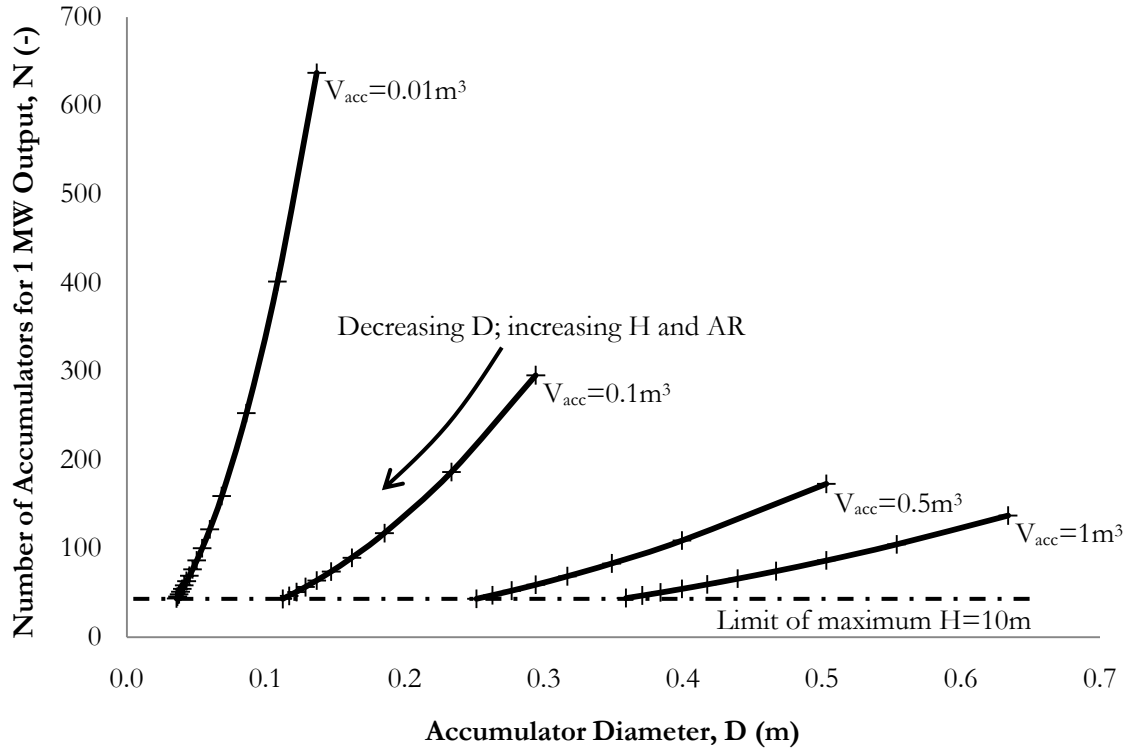


Figure 1: Effect of accumulator diameter D on the number of accumulators N required to generate $W_{\text{net}} = 1$ MW with conditions as per the UoN study. Plots generated at 4 different accumulator volumes V_{acc} from 0.01 to 1 m^3 and a volume expansion ratio $V_{\text{max}}/V_{\text{min}} = 4$.

Note that for a given volume V_{acc} , i.e. along any solid line in Fig. 1, as the diameter D decreases, the height of the accumulator H must increase and the aspect ratio $AR = H/D$ must also increase. Hence, in the generation of data that is shown in Fig. 1, an upper limit of 10 m was placed for the accumulator height H , for all accumulator volumes V_{acc} . This is indicated in the figure by a horizontal dashed line. Interestingly, the minimum number of accumulators N_{min} is independent of the choice of accumulator volume V_{acc} and is equal to 43 accumulators. If the limit for the maximum permissible accumulator height was placed instead at $H = 3$ the minimum number of required accumulators N_{min} would have been 144 , and if it had been placed at $H = 5 \text{ m}$ the minimum number of accumulators N_{min} would have been 87 , again independent of the choice of V_{acc} .

A second way to investigate the effect of accumulator geometry on the number of accumulators N required to generate $W_{\text{net}} = 1$ MW, is to plot the number of accumulators N as a function of their aspect ratio $AR = H/D$ for a given accumulator volume V_{acc} . Figure 2 shows that, for all other parameters being fixed including a fixed source (bath) temperature T_s , the required number of accumulators N decreases with increasing aspect ratio $AR = H/D$ for a given accumulator volume V_{acc} . The data shown here are identical to that presented in Fig. 1 (see bottom of Page 3 for full list). Note that for a given volume V_{acc} , i.e. along any solid line in Fig. 2, as the aspect $AR = H/D$ increases the height of the accumulator H increases and the accumulator diameter D decreases. The upper limit on H of 10 m placed on the investigation for all accumulator volumes V_{acc} is shown again as a horizontal line.

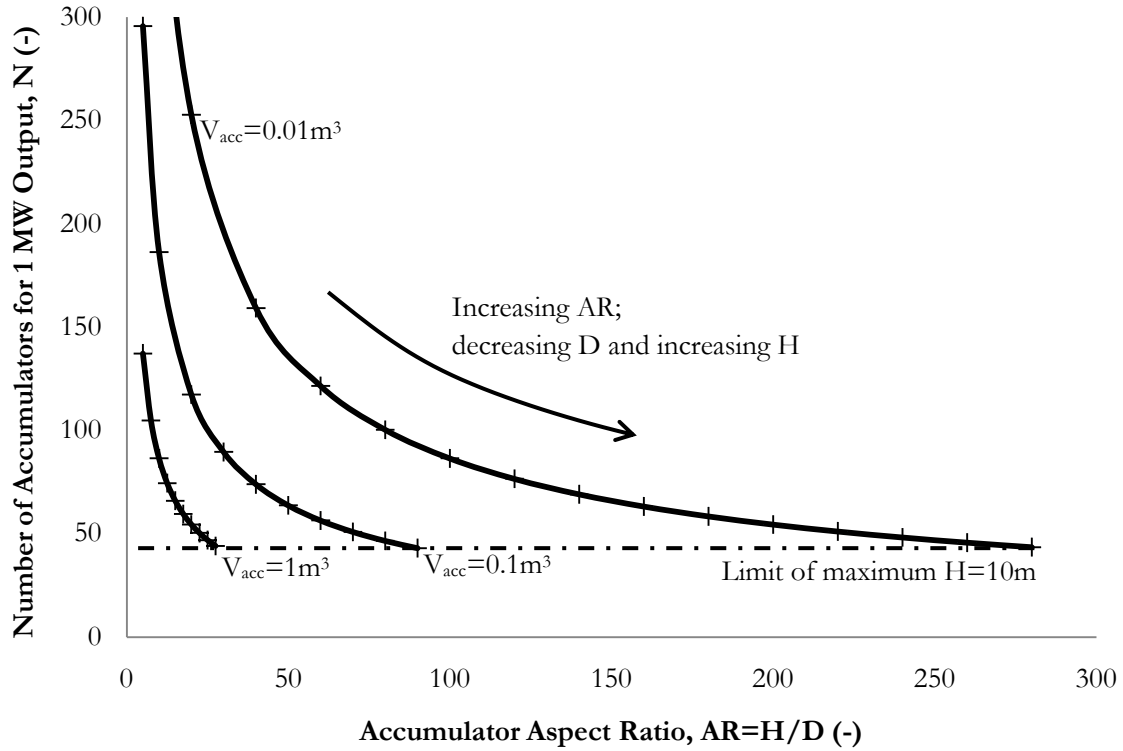


Figure 2: Effect of accumulator aspect ratio $AR = H/D$ on the number of accumulators N required to generate $W_{net} = 1$ MW with conditions as per the UoN study. Plots generated at 3 different accumulator volumes V_{acc} of 0.01, 0.1 and 1 m^3 , and with a volume expansion ratio V_{max}/V_{min} of 4, corresponding to the same data as that shown in Fig. 1.

It can be seen, as in Fig. 1, that the minimum number of accumulators N_{min} is independent of the choice of accumulator volume V_{acc} and is equal to 43 accumulators for accumulator an height limit of $H = 10$ m. Again, as before, if the maximum permissible accumulator height is $H = 3$ or 5 m instead, the minimum number of accumulators N_{min} is 144 or 87 respectively, independent of the accumulator volume V_{acc} .

It becomes clear from the data presented in Figs. 1 and 2 that the number of accumulators N is minimised when the accumulator height H is maximised and is independent of the accumulator diameter D and volume V_{acc} . However, this minimum number of accumulators N_{min} is a function of the thermodynamic cycle (i.e. T_s , V_{max}/V_{in} , etc.). Hence, it was decided to investigate the effect on N_{min} of changing the source (bath) temperature T_s , as well as the volume expansion ratio parameter V_{max}/V_{min} . This parameter was used in the UoN report and is defined as the ratio of the volumes at the beginning (V_{min}) and end of the expansion process (V_{max}) that occurs within the accumulators.

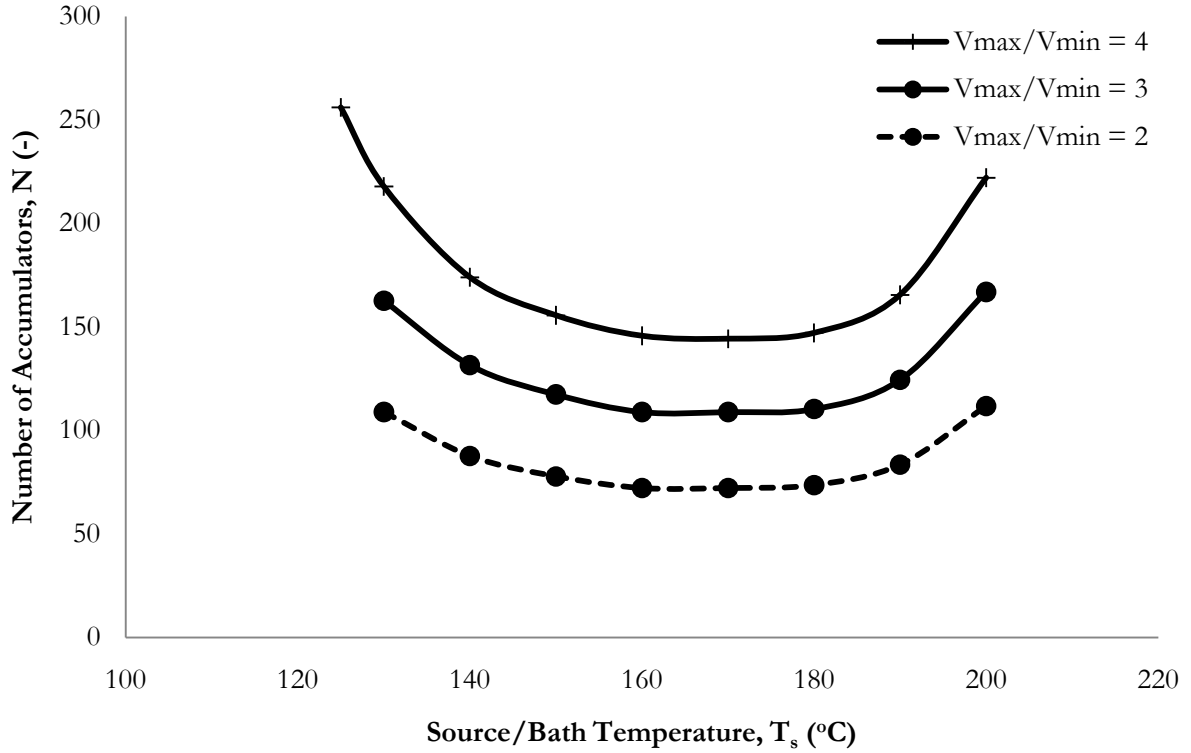


Figure 3: Effect of source (bath) temperature T_s on the number of accumulators N required to generate a power output $W_{net} = 1$ MW, with a maximum permissible accumulator height H of 3 m. Plots generated at 3 different volume expansion ratios $V_{max}/V_{min} = 2, 3$ and 4.

Figure 3 has been generated with an accumulator height H of 3 m. It shows that for each choice of volume expansion ratio parameter V_{max}/V_{min} , the working fluid characteristics are such that the number of accumulators N is minimised at a source (bath) temperature T_s in the range 160 – 170 °C. This is a result of the following two opposing factors: (i) at lower source (bath) temperature T_s the thermal efficiency decreases and hence the heat necessary to generate a power output W_{net} of 1 MW increases; whereas (ii) at higher source (bath) temperatures T_s the time necessary for the working fluid in the accumulators to “charge up” in temperature due to heat transfer from the bath fluid to this higher value also increases, thus increasing the cycle time. At low source (bath) temperatures T_s factor (i) is strongest, while at high source (bath) temperatures T_s it is factor (ii) that dominates. Somewhere in between lies the “optimal” temperature range $T_s = 160 – 170$ °C. In this temperature range the minimum number of accumulators N_{min} is 144 for a volume expansion ratio parameter $V_{max}/V_{min} = 4$ (as also mentioned below Figs. 1 and 2), 109 for $V_{max}/V_{min} = 3$, and 72 for $V_{max}/V_{min} = 2$.

Figures 4 and 5 are similar to Fig. 3, but with the accumulator height H extended to 5 and 10 m respectively. The conclusions are the same as before concerning the “optimal” source (bath) temperature T_s in the range 160 – 170 °C. From Fig. 4, the minimum number of accumulators N_{min} for $H = 5$ m is 87 for a volume expansion ratio $V_{max}/V_{min} = 4$ (as also mentioned in the discussion relating to Figs. 1 and 2), 65 for $V_{max}/V_{min} = 3$, and 43 for $V_{max}/V_{min} = 2$. Also, from Fig. 5, the minimum number of accumulators N_{min} for $H = 10$ m is 43 for a volume expansion ratio $V_{max}/V_{min} = 4$ (as demonstrated in Figs. 1 and 2), 33 for $V_{max}/V_{min} = 3$, and 22 for $V_{max}/V_{min} = 2$.

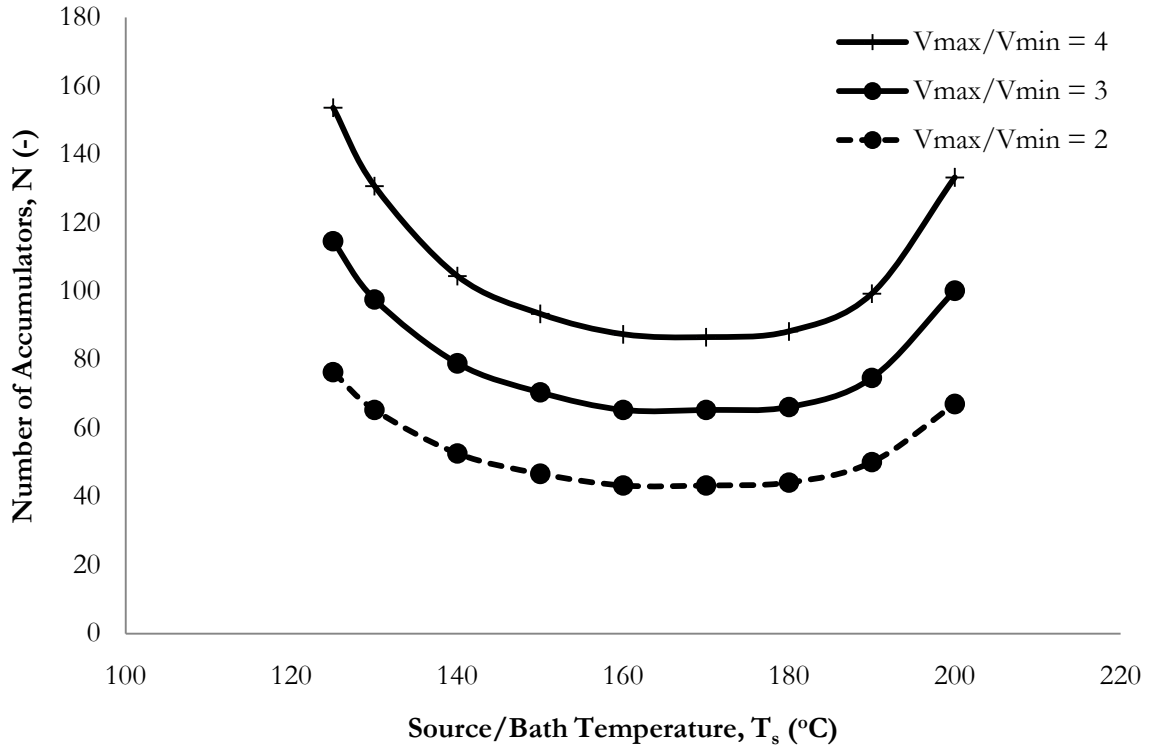


Figure 4: Effect of source (bath) temperature T_s on the number of accumulators N required to generate $W_{net} = 1$ MW, with a maximum permissible accumulator height H of 5 m. Plots generated at 3 different volume expansion ratios $V_{max}/V_{min} = 2, 3$ and 4.

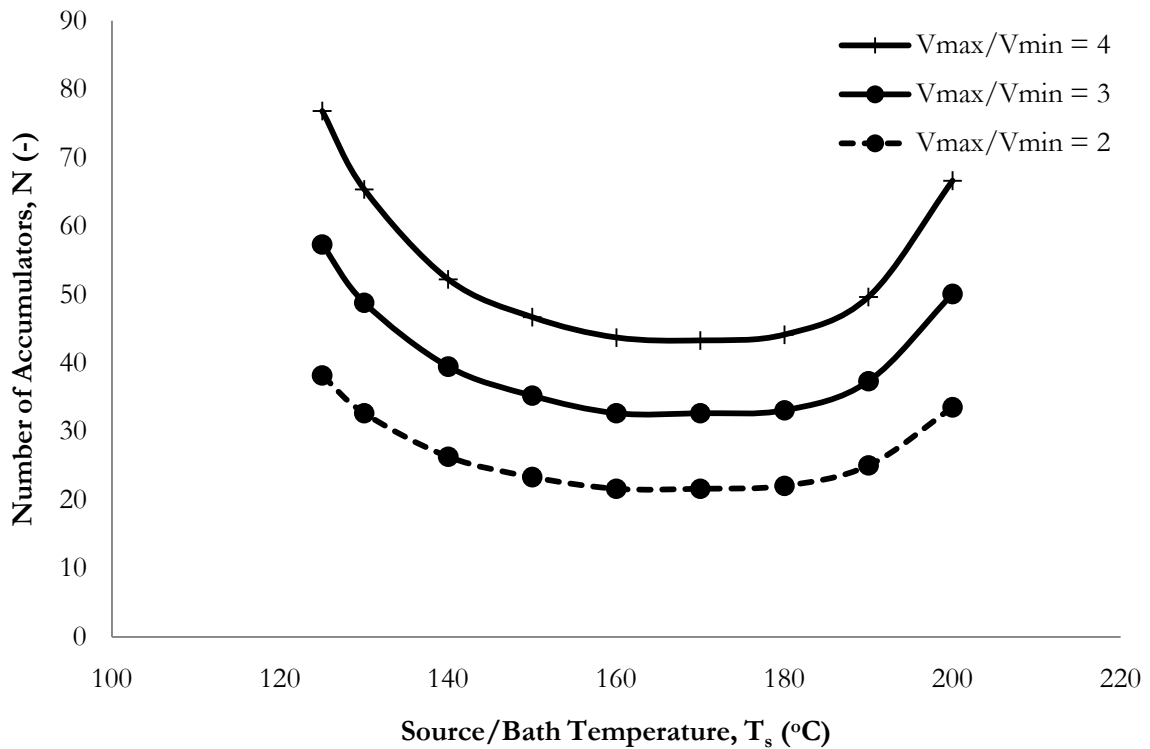


Figure 5: Effect of source (bath) temperature T_s on the number of accumulators N required to generate $W_{net} = 1$ MW, with a maximum permissible accumulator height H of 10 m. Plots generated at 3 different volume expansion ratios $V_{max}/V_{min} = 2, 3$ and 4.

4. Summary and Conclusions

The OTELLO™ and by extension MOREAMPS THGs are similar systems based on sound thermodynamic principles (i.e. a variant of the well-established Rankine cycle) that have the capability to produce clean electricity from waste heat or solar energy. Both systems can be made from off-the-shelf components at relatively low cost.

Summarising the results presented in Section 3, R245fa is an “optimal” working fluid (in terms of heat transfer rate, efficiency and minimal number of accumulators) for the OTELLO™ for source (bath) temperatures $T_s = 160 - 170$ °C, with approach temperatures $T_a = 40$ °C, minimum cycle pressures $p_1 = p_5 = 0.2$ MPa and fluid exit temperatures $T_5 = 67$ °C. At these conditions lowering the volume expansion ratio parameter V_{\max}/V_{\min} leads to a reduction in the number of accumulators N necessary for the generation of $W_{\text{net}} = 1$ MW of power, while the theoretical thermal efficiency remains close to 11%.

For a given choice of the volume expansion ratio parameter V_{\max}/V_{\min} , the number of accumulators N is minimised when the accumulator height H is maximised and is independent of the volumetric capacity of the accumulators V_{acc} . There is considerable scope to use these parameters to design these systems according to the needs of a particular application.

At source (bath) temperatures $T_s = 160 - 170$ °C and for a maximum permissible accumulator height $H = 3$ m, the minimum number of accumulators N_{\min} is 144 for a volume expansion ratio $V_{\max}/V_{\min} = 4$, 109 for $V_{\max}/V_{\min} = 3$, and 72 for $V_{\max}/V_{\min} = 2$. Also, for the same source (bath) temperatures T_s , but for a maximum permissible accumulator height $H = 5$ m, the minimum number of accumulators N_{\min} is 87 for a volume expansion ratio $V_{\max}/V_{\min} = 4$, 65 for $V_{\max}/V_{\min} = 3$, and 43 for $V_{\max}/V_{\min} = 2$, and finally, for a maximum permissible accumulator height $H = 10$ m, the minimum number of accumulators N_{\min} is 43 for a volume expansion ratio $V_{\max}/V_{\min} = 4$, 33 for $V_{\max}/V_{\min} = 3$, and 22 for $V_{\max}/V_{\min} = 2$. The results are summarised in the table below.

Table 1: Summary of results for the minimum number of accumulators required for the OTELLO™ N_{\min} for a source (bath) temperature $T_s = 160 - 170$ °C, as a function of volume expansion ratio V_{\max}/V_{\min} and accumulator height H .

	H = 3 m	H = 5 m	H = 10 m
$V_{\max}/V_{\min} = 2$	72	43	22
$V_{\max}/V_{\min} = 3$	109	65	33
$V_{\max}/V_{\min} = 4$	144	87	43