



## Liquids for Rankine Engines

The Rankine cycle is a way to convert heat to mechanical energy. It was originally devised for water and steam, but any liquid can potentially be used. On a Mollier diagram (plotting pressure against enthalpy), this process can be represented by a trapezium over the saturated liquid and saturated vapour curves. It is often drawn on an entropy-temperature diagram too.

Water has a number of advantages (not least its abundance), but the steam must be superheated to reduce moisture in the steam, which would lead to corrosion of the turbine blades. Systems using organic working fluids are called Organic Rankine Engines (OREs). The working fluid is usually selected by the temperature of the heat input to the system. Toluene is commonly used, as are butane and pentane.

Please note that much of the data presented is estimated by interpolation, and in some cases by extrapolation from like materials.

### Heat of vaporisation

R134a is a refrigerant, and in that heat cycle it is desirable to have a high heat of vaporisation for maximum heat transfer; 216 kJ/kg at the boiling point, compared to only 90.8 kJ/kg for PP50, and 104 kJ/kg for PP30. In contrast, in OREs, a low heat of vaporisation is preferred. Note that heat of vaporisation decreases as temperature rises for a given fluid. Comparing the heat of vaporisation at a given temperature for the FLUTE<sup>®</sup> liquid.

<i>FLUTE<sup>®</sup> Liquid</i>	<i>Heat vap. at 80°C</i>
PP50	73.1
PP1	78.0
PP2	84.7
PP3	86.9
PP6	87.96
PP9	87.2

### Heat capacity

Heat capacity is important as the liquid must be heated to the boiling point (85°C, at the relevant pressure). We do not have figures for heat capacity at 85°C, but a good approximation is available from the change in enthalpy from 80°C to 90°C. A low heat capacity is again desirable.

<i>FLUTE<sup>®</sup> Liquid</i>	<i>Heat cap. at 85°C</i>
PP50	1.19
PP1	1.08



PP2	1.00
PP3	0.95
PP6	0.99
PP9	0.98

### **Critical temperature**

The working fluid must have a critical temperature higher than the operating temperature of the unit (perhaps by 10 to 15°C).

### **Enthalpy change with constant entropy**

The other important parameter is a large change in enthalpy as the fluid goes through the turbine ( $\Delta H_{\text{turbine}}$ ), as this corresponds to a high energy input into the turbine.

Rather than trying to get this from the graphs, according to the papers by Lee, Devotta and Holland, we can determine  $\Delta H_{\text{turbine}}$  from data we already have...

$$H_{D2} = H_{D1} + \Delta H_{D1 \rightarrow D2}$$

$$H_{D2} = H_{D1} + T\Delta S_{D1 \rightarrow D2} \text{ (T is the temperature of the condenser)}$$

$$H_{D2} = H_{D1} + T\Delta S_{D1 \rightarrow R2} \text{ (because R2 to D2 has constant entropy)}$$

$$\Delta H_{\text{turbine}} = H_{R2} - H_{D2}$$

$$\Delta H_{\text{turbine}} = H_{R2} - H_{D1} - T\Delta S_{D1 \rightarrow R2}$$

$$\Delta H_{\text{turbine}} = H_{R2} - H_{D1} - T(S_{R2} - S_{D1})$$

Given the values in the data tables,  $\Delta H$  can be determined for a temperature drop from 80°C to 30°C, for illustrative purposes.

<i>FLUTEC Liquid</i>	<i><math>\Delta H</math> (turbine) 80-&gt;30°C</i>
PP50	14.7
PP1	15.0
PP2	15.5
PP3	15.6
PP6	16.3
PP9	16.1

### **Theoretical Rankine power cycle efficiencies**

This data is taken from the papers published in the early 80s (which all used data from ISC Chemicals; the company that originally developed the FLUTEC liquids). Efficiency depends on the upper working temperature (data is for 85° only) and the temperature drop (I have selected 15°C, 40°C and 65°C).

The efficiency is the energy out at the turbine (enthalpy change at constant entropy), minus the energy input at the pump (usually taken as zero), divided by the heat input (a function of the heat capacity and the heat of vaporisation), expressed as a percentage.



<i>FLUTEC Liquid</i>	15°C	40°C	65°C
PP50	3.76	8.96	13.03
PP1	3.68	9.14	14.29
PP2	3.43	9.05	14.53
PP3	3.83	9.57	14.86
PP6	3.93	9.38	14.57

AKJ

Mar/2007 (updated Jan/2012)