NUMERICAL SIMULATION OF AN ORGANIC RANKINE CYCLE

Authors: *S. Poles, M. Venturin*

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Abstract: The aim of this paper is to simulate an Organic Rankine Cycle (ORC) using Scilab. The model is developed for estimating the operative conditions of the ORC system and its efficiency. Today, ORC technologies are widely used for simultaneous production of electrical and thermal energy (a.k.a. cogeneration). These systems can be a clean alternative to fossil fuels.

Contacts info@openeering.com

1. Introduction

In this article, we present a numerical solver for the simulation of an Organic Rankine Cycle (ORC) for the study of cogeneration, i.e. the simultaneous production of electrical and thermal energy.

Today, ORC cycles are used as an alternative to the use of fossil fuels, that raise serious environmental concerns. Exploiting ORC cycles, besides reducing the reliance on non-renewable and limited fossil fuels, can enhance environmental quality, reduce carbon emissions and be economically competitive. Moreover, cycles based on wood-burning cogeneration offer the advantage of clean elimination of wood wastes.

The ideal process of an ORC system with its major components is depicted in Figure 1 along with the thermodynamics states of the working fluid.

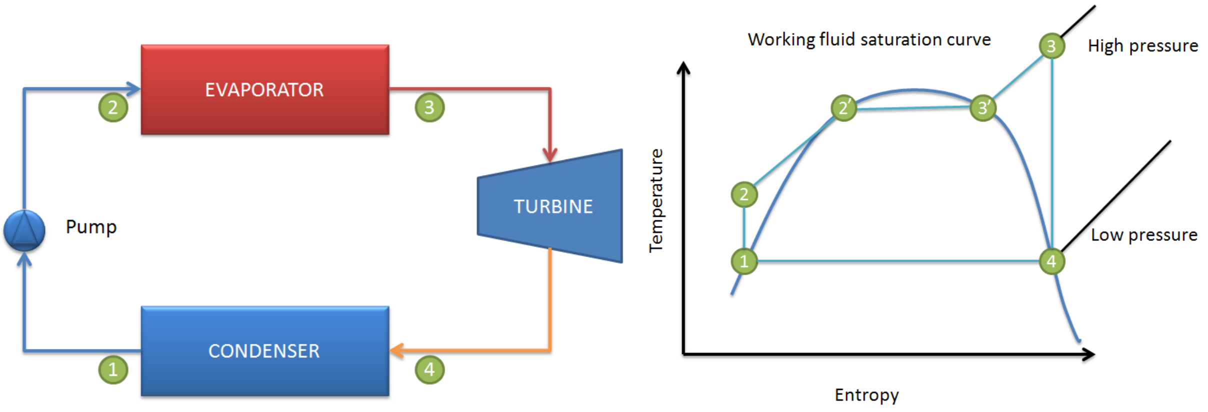


Figure 1: An ideal ORC cycle along with its thermodynamics states

This system is composed by an evaporator, a condenser, a pump and a turbine. From state 1 to 2, an ideal pump executes an adiabatic, reversible (isentropic) process to raise the working fluid from the pressure of saturated liquid to the pressure of saturated vapor. From state 2 to state 3, an evaporator heats the fluid at a constant pressure (isobar transformation) moving from a saturated liquid state 2’ to a saturated vapor state 3’ where all the liquid becomes vapor. Then the fluid is superheated until it reaches the state 3. After, the superheat vapor fluid enters in a turbine where it is produces an expansion through and adiabatic, reversible process. The superheat process is necessary in order to guarantee that in the turbine only vapor is present, this preserving the turbine blades from condensation and erosion. However, the amount of superheat should be kept as lower as possible in order to avoid waste of energy and maximize the performance of the entire cycle.

The typically used working fluid is an organic fluid which permits low-grade heat sources. It is characterized by low latent heat and high density. These properties are useful to increase the turbine inlet mass flow rate. Common working fluids that can be used are hexamethyldisiloxane (MM) and octamethyltrisiloxane (MDM).

In this work, we describe a numerical tool for the simulation of steady state solutions of ORC systems. This toolbox has been completely written in Scilab and is available for download at the Openeering site.

2. The ORC system

The considered ORC system is represented in Figure 2. Figure 3 depicts the thermodynamics states of the working fluid, and of the diathermic oil and the water used to heat up and cool down the working fluid.

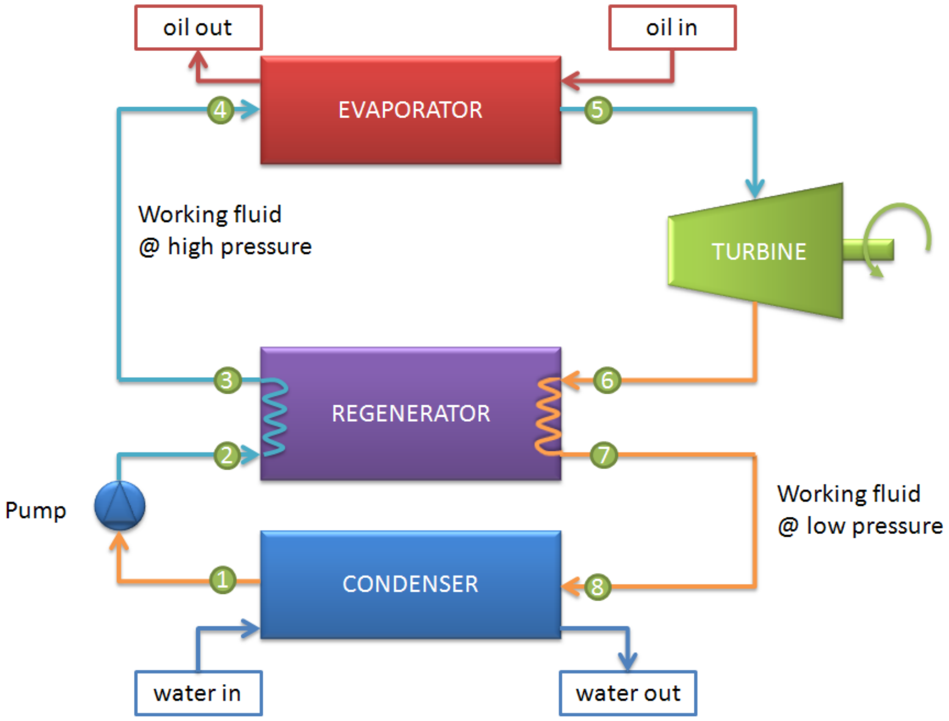


Figure 2: ORC cycle

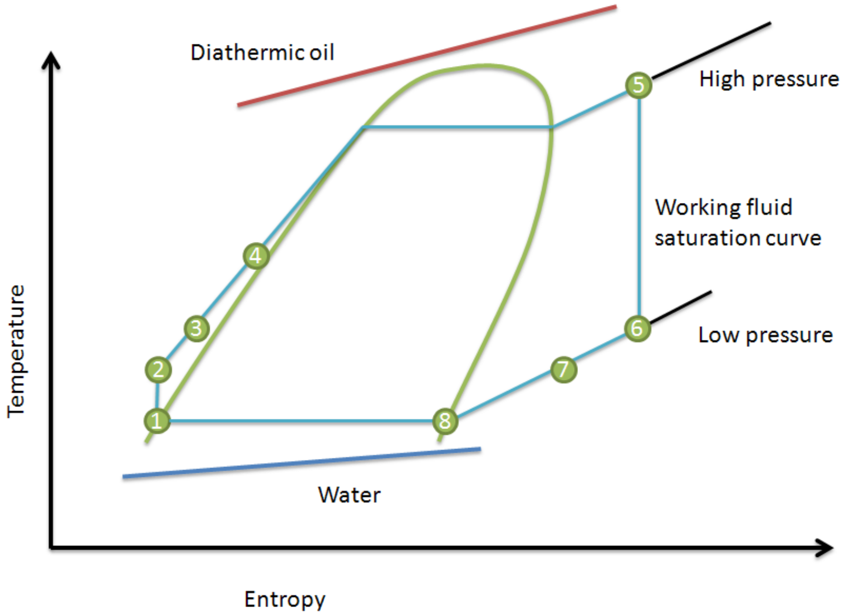


Figure 3: Thermodynamics states

The system described in Figure 2 is a bit more complex than the one in Figure 1. Indeed, this last system differs from the previous scheme by the introduction of a regenerator. The regenerator transfers energy from the fluid at hot temperature to the fluid at low temperature. This step increases the efficiency of the entire cycle because the external heat transfer now occurs at a higher average temperature.

2.1. The working fluid

In our simulation we used the organic MDM fluid with the following properties [1,2,3]:

Table 1: MDM properties

Molecular formula	$C_8H_{24}O_2Si_3$
Molecular weight	236.531 g/mol
Density	0.82 g/cm^3
Melting point	-82 ºC
Boiling point	153 ºC
Refractive index	1.384
Flash point	29 ºC
Vapor pressure	50 mmHg (at 72 °C)
Specific heat of vaporization	0.15 kJ/g
Specific heat of combustion	32.92 kJ/g
Acentric factor	0.531
Critical temperature	289.75 °C
Critical pressure	1420 kPa

In the ORC cycle the fluid changes its state from liquid to vapor and vice-versa. Hence, it is necessary to monitor this condition by means of an equation of state. Here, in our model we choose the Peng-Robinson equation of state, which identifies the state of the fluid giving a relation from the saturation temperature and pressure [4].

From Figure 4 to Figure 11 we report the properties of the MDM working fluid.

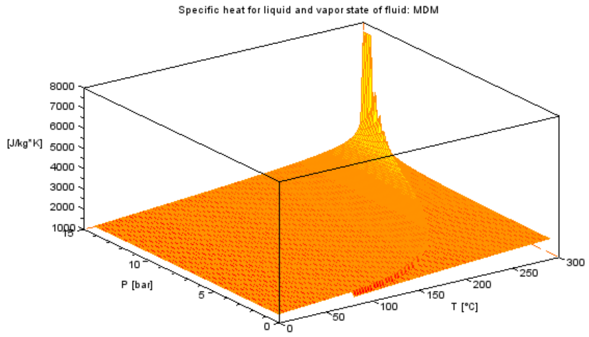


Figure 4: MDM specific heat

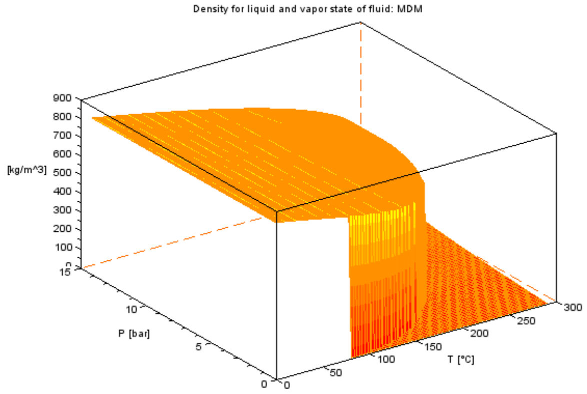


Figure 5: MDM density

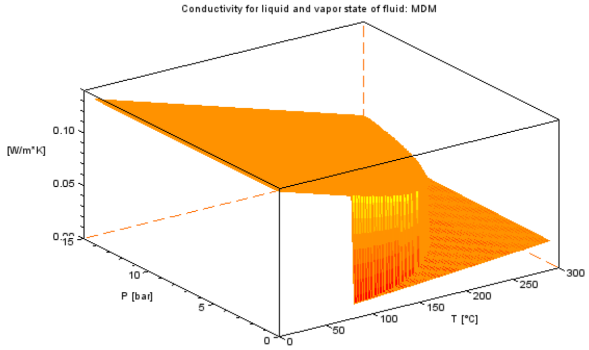


Figure 6: MDM conductivity

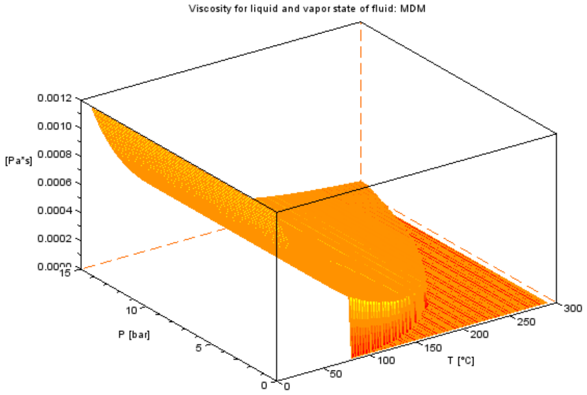


Figure 7: MDM viscosity

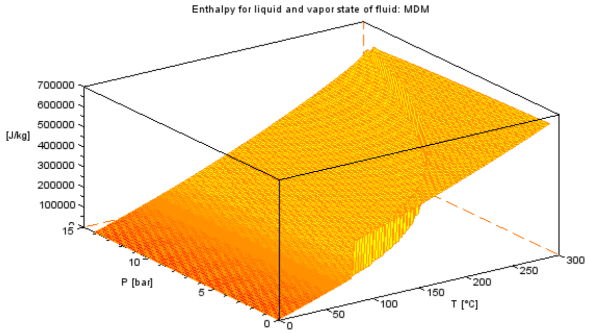


Figure 8: MDM enthalpy

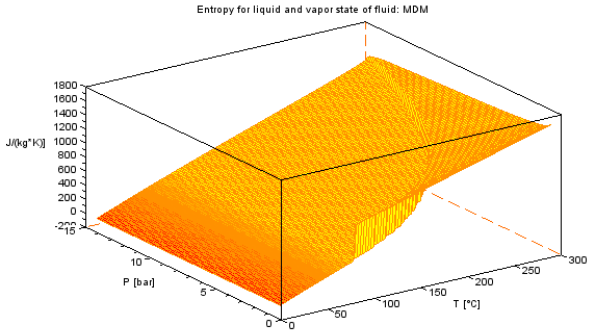


Figure 9: MDM entropy

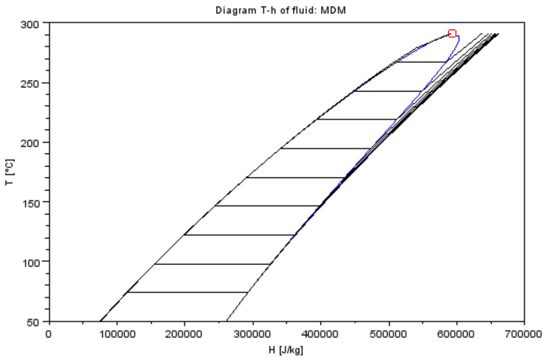


Figure 10: MDM T-H diagram.

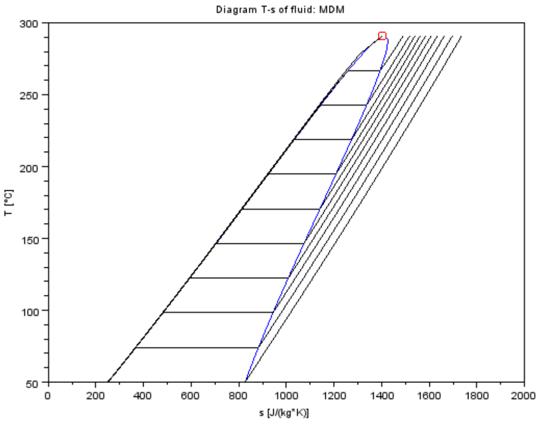


Figure 11: MDM T-s diagram.

2.2. Heat exchangers modeling for evaporator, regenerator and condenser

Modeling heat exchangers means providing the models that describe the heat transfer from hot to cold fluids. All the considered heat exchangers are of countercurrent flow type. A basic scheme of a generic heat exchanger is presented in Figure 12 where:

- **T hot in** is inlet temperature of the hot fluid;
- **T hot out** is outlet temperature of the hot fluid;
- **T cold in** is inlet temperature of the cold fluid;
- **T cold out** is outlet temperature of the cold fluid.

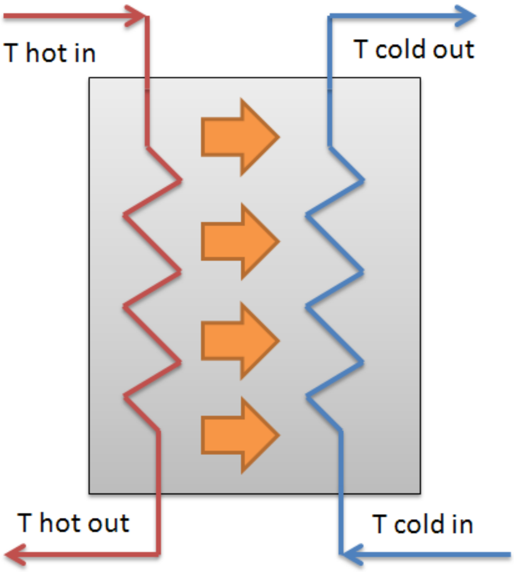


Figure 12: Heat exchanger scheme.

The governing equations for the heat exchanger are:

$$\begin{cases} \dot{Q} = UA \cdot \Delta T_{log-mean} \\ \dot{Q} = \dot{m}_{hot} \cdot \Delta H_{hot} \\ \dot{Q} = \dot{m}_{cold} \cdot \Delta H_{cold} \end{cases}$$

where:

- $\dot{Q}$ is the heat transfer rate [W];
- U is the overall heat transfer coefficient [W/m^{2}K];
- A is the overall area, i.e. the total area that separates the two fluids [m^2];
- $\Delta T_{log-mean}$ is the average effective temperature difference between the two fluids [K];
- $\dot{m}_{hot}$ is the mass flow rate of the hot fluid [kg/s];
- ΔH_{hot} is the enthalpy of the hot fluid from “T hot in” to “T hot out” [J/kg];
- $\dot{m}_{cold}$ is the mass flow rate of the cold fluid [kg/s];
- ΔH_{hot} is the enthalpy of the cold fluid from “T cold out” to “T cold in” [J/kg].

The computation total area A depends on the geometry of the heat exchanger (i.e. number of tubes, length of tubes, tube diameter, baffle spacing, baffle cut, etc.).

The computation of the term U is done using the following formula:

$$\frac{1}{U} = \frac{1}{hf1} + \frac{1}{hwall} + \frac{1}{hf2} + rfouling$$

where:

- $hf1$ is the heat transfer coefficient for the hot fluid;
- $hf2$ is the heat transfer coefficient for the cold fluid;
- $hwall$ is the wall resistance;
- $rfouling$ is the fouling resistance dues to the deposit of extraneous material upon the heat transfer surface.

Moreover, $hf1$ and $hf2$ do not depend only on the geometry of the heat exchanger but also on the Reynolds, Prandtl and Nusselt numbers [5].

2.3. Pump modeling

The pump model is depicted in Figure 13, where the efficiency is defined as

$$\eta_{pump} = \frac{h_1 - h_2}{h_1 - h_{2s}}$$

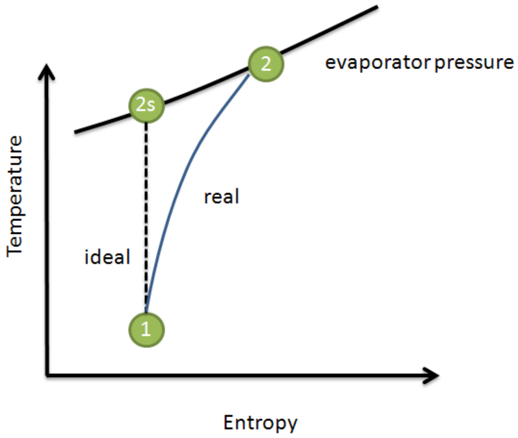


Figure 13: Isentropic definition for a pump.

2.4. Turbine modeling

The turbine model is similar to the pump one (see Figure 14),

$$\eta_{trubine} = \frac{h_1 - h_2}{h_1 - h_{2s}}$$

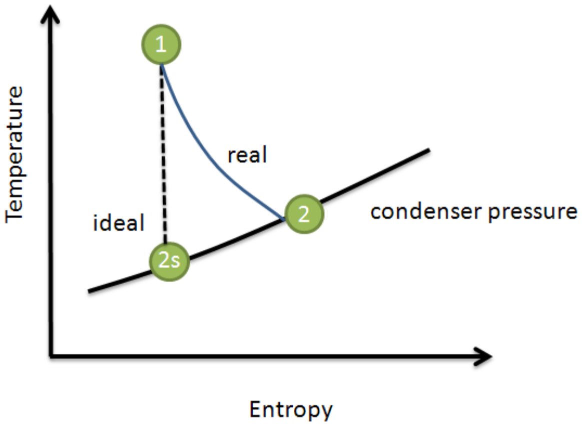


Figure 14: Isentropic definition for a turbine.

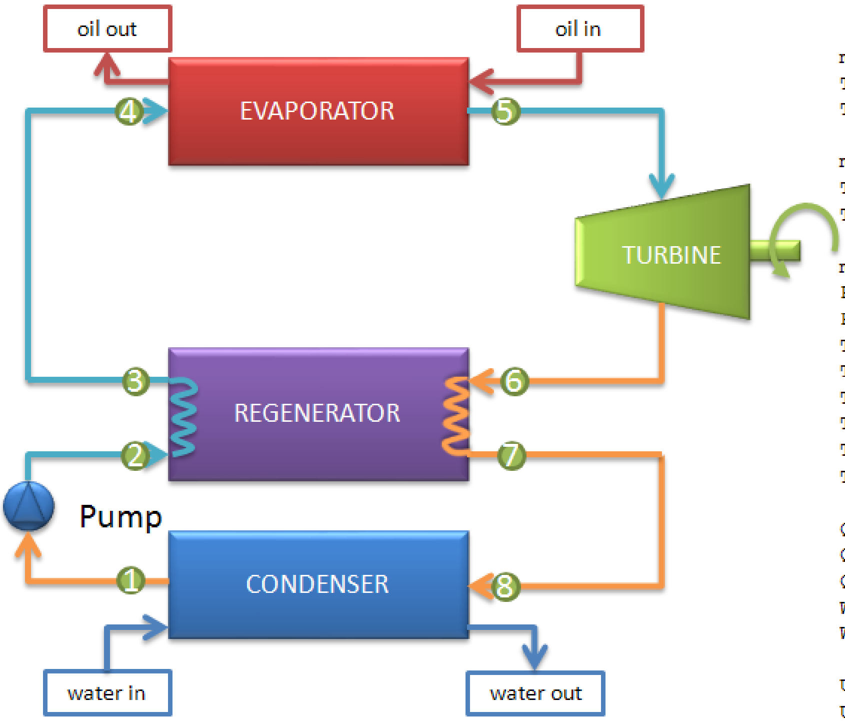
but it also includes an equation for the flow rate. In our implementation we use the elliptic law of Stodola [6,7].

3. Simulation results

The numerical solution of the entire scheme is not straightforward because of many nonlinearities. Particular attention should be paid especially to the definition of the constitutive laws obtained by interpolation/extrapolation of scattered data. The interpolation of scatter data is done minimizing the errors between experimental data and theoretical laws.

Due to the complexity of the problem, it is very difficult to find a feasible initial point for a Newton-like minimization approach. We may say that, in this case, a classical Newton approach is not able to solve the problem. For this reason, a hybrid optimization approach has been adopted. First, a robust and flexible genetic algorithm is used to identify a good feasible point. Genetic algorithms are very robust, but they usually require several iterations. Thus, after a feasible point is found, it is used as starting point for a faster Newton method. The combination of these two methods yields to a very powerful approach.

The obtained results are reported in Figure 15.



```
m_oil        =    9.16 [kg/s]
T_oil_in     =  310.00 [°C]
T_oil_out    =  224.76 [°C]

m_water      =   18.47 [kg/s]
T_water_out  =   80.00 [°C]
T_water_in   =   60.00 [°C]

m_fluid      =    7.76 [kg/s]
P_evap       =    4.91 [bar]
P_cond       =    0.09 [bar]
T_evap       =  225.38 [°C]
T_cond       =   78.92 [°C]
T_in_turb    =  291.86 [°C]
T_out_trub   =  261.89 [°C]
T_end_vap    =   93.54 [°C]
T_end_reg    =  224.51 [°C]

Q. Evap      =  878.69 [kW]
Q. Reg       = 2211.75 [kW]
Q. Cond      = 1548.00 [kW]
W_pump       =    7.82 [kW]
W_turb       =  385.51 [kW]

UA evap      =  207.85 [kW/°C]
UA cond      =  455.27 [kW/°C]

Eta cycle    =   19.78%
```

Figure 15: Obtained solution of the ORC system.

The *heat duty* of the heat exchanger with respect to the operation points is reported in Figures 16-19. From the evaporator it is possible to recognize the *pinch point* (see Figure 20). This point is useful for estimating improvements on the design of heat exchangers.

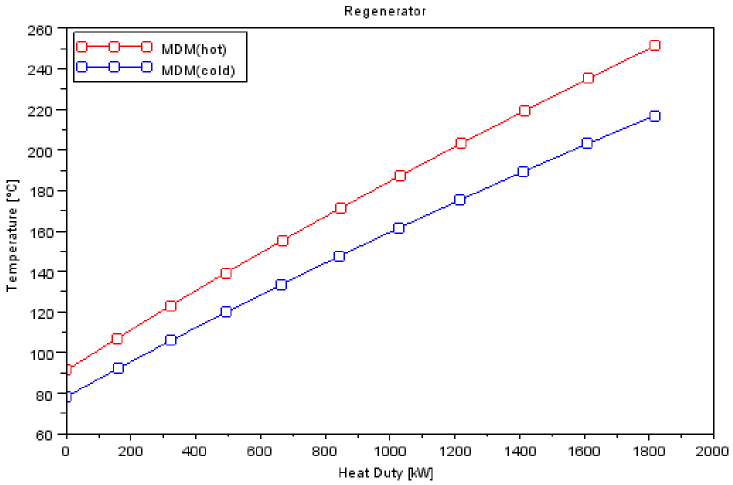


Figure 16: Heat duty of the regenerator.

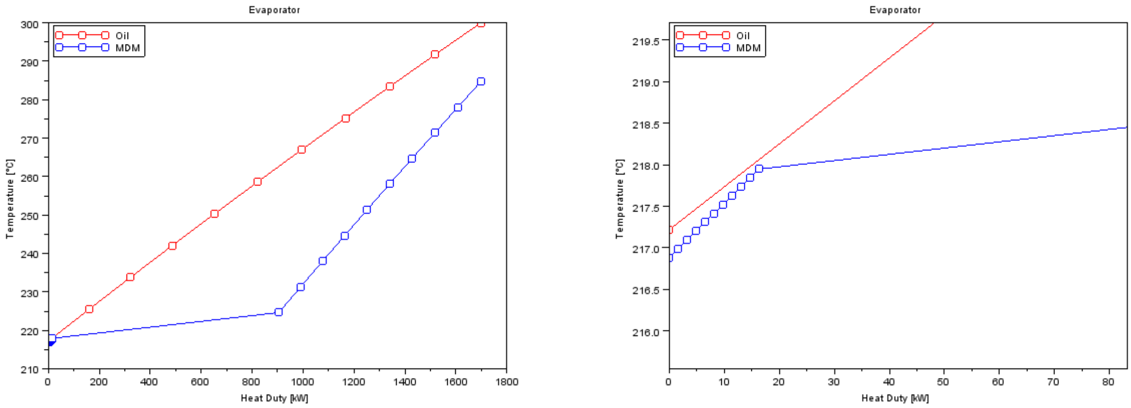


Figure 17: Heat duty of the evaporator (left) with an interesting area zoomed (right).

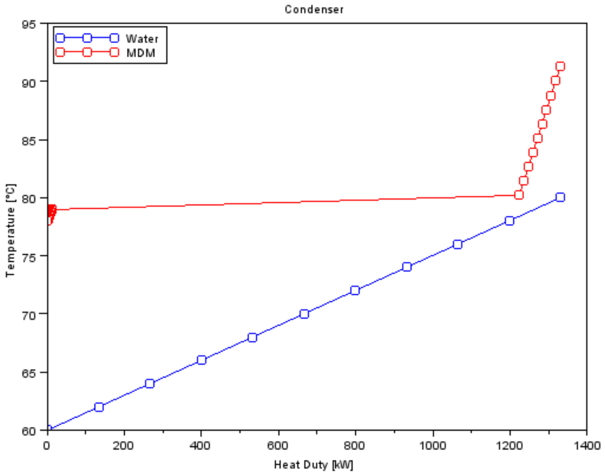


Figure 18: Heat duty of the condenser.

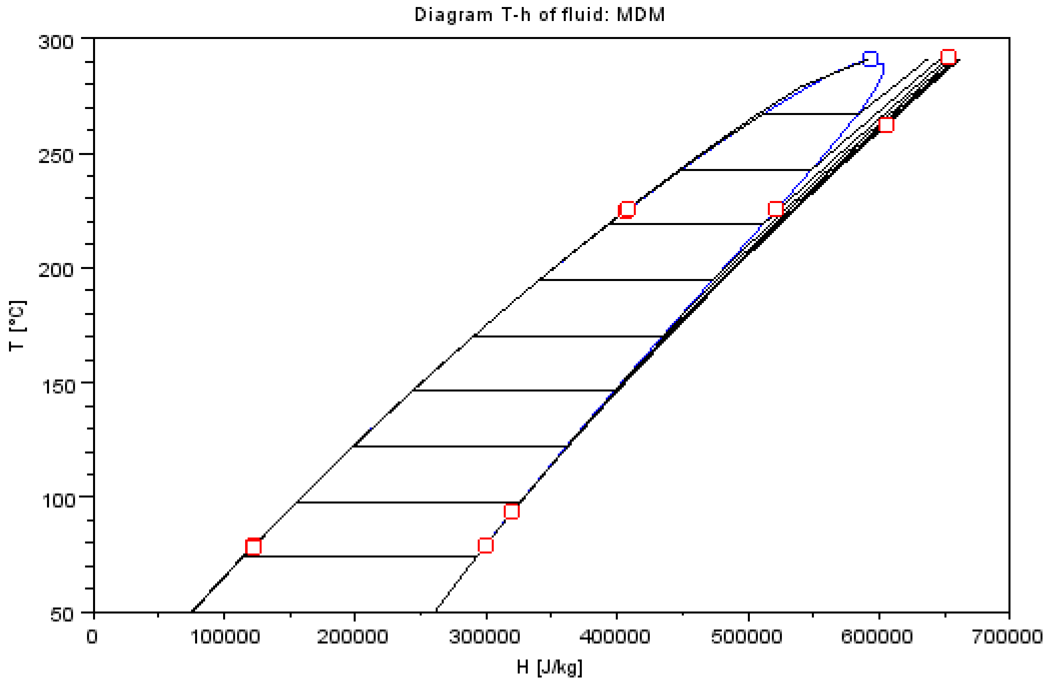


Figure 19: ORC simulation.

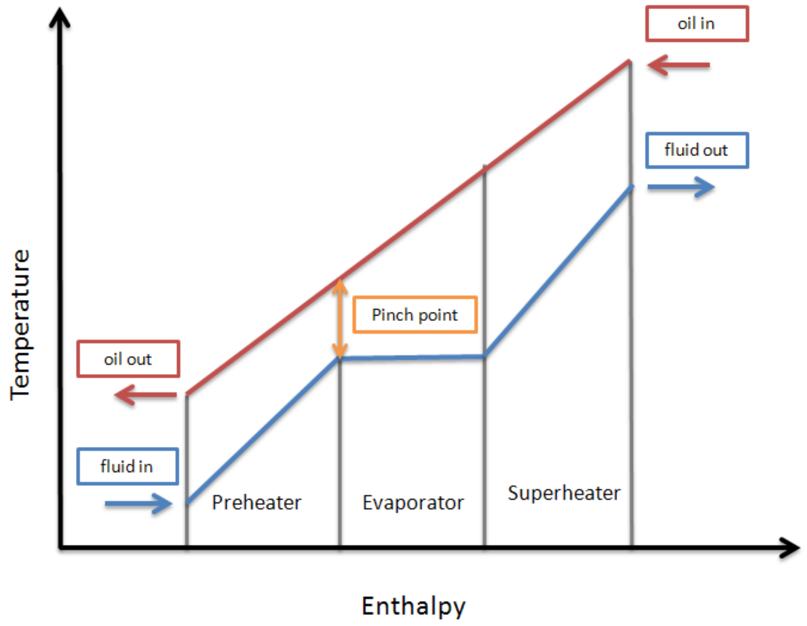


Figure 20: Pinch point

4. Conclusions

In this work, we developed a Scilab toolbox for the simulation of a parametric ORC system. A free version of the toolbox is available for download from the Openeering website. To download, install and use the package, please refer to the next section of this paper.

A more complete version of the toolbox can be required contacting the authors through the Openeering website.

5. Install the package

To install the package, please follow these steps:

1. Download the package ***"orcsolver.zip"*** from the Openeering site;
2. Unzip the file in a working directory (e.g. ***"D:\scilabpackages"***);
3. Open Scilab and move to the package directory (in our case ***"D:\scilabpackages\orcsolver"*** using the command ***cd "D:\scilabpackages\orcsolver"***;
4. Build the package using the command ***exec builder.sce***;
5. Load the package using the command ***exec loader.sce***;
6. Try the demos by clicking on the Scilab demonstration icon ⚙ in the toolbar and selecting the demos related to the ORC_Solver

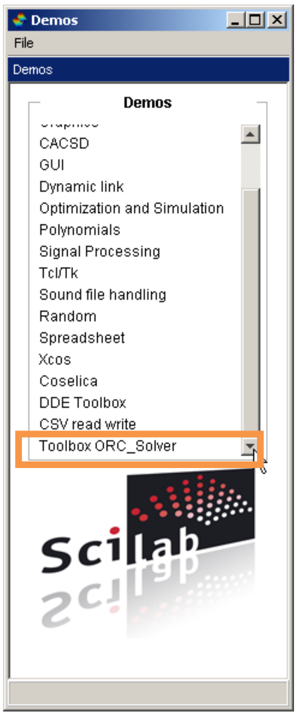


Figure 21: Scilab demonstration

7. For instance, run “demo enthalpy”

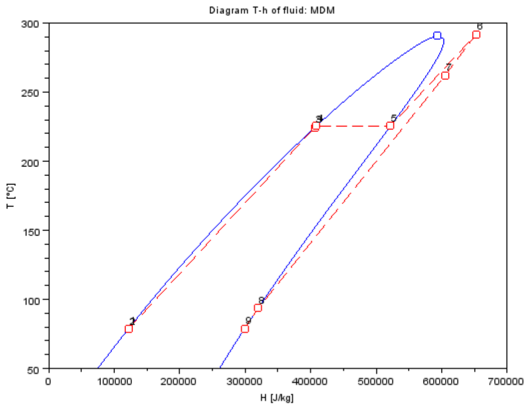
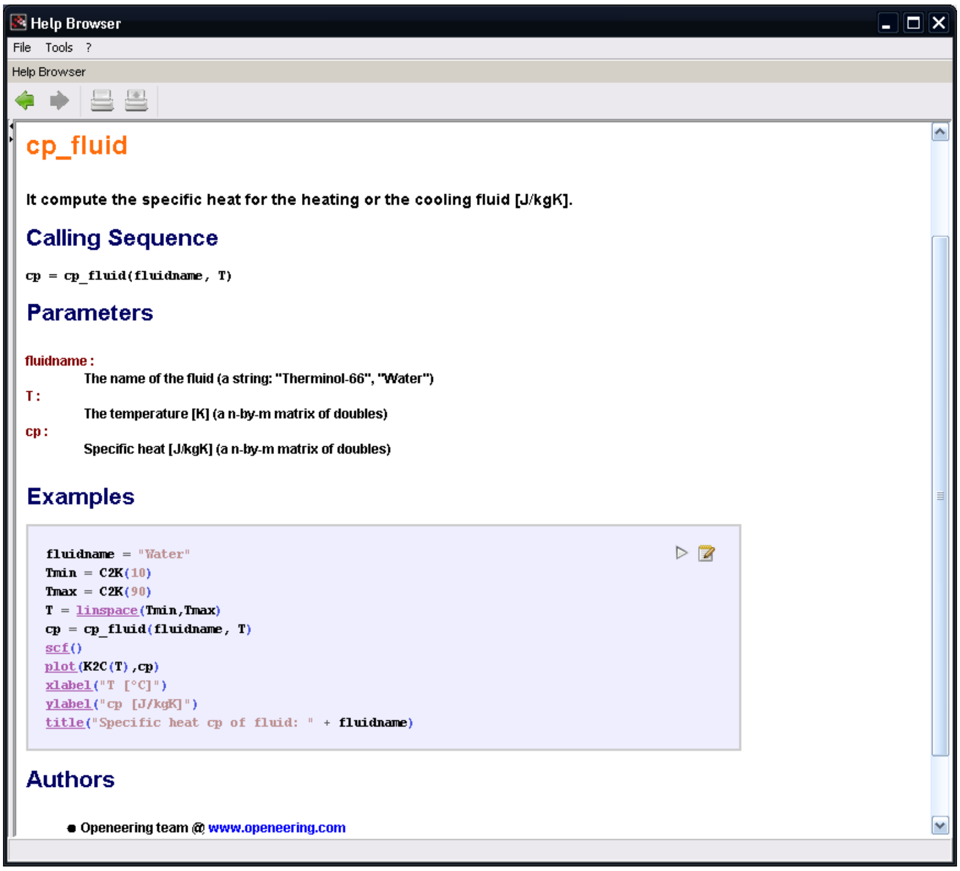


Figure 22: ORC_Solver enthalpy demo

8. Check the help for more information about the ORC_Solver toolbox usage.



cp_fluid

It compute the specific heat for the heating or the cooling fluid [J/kgK].

Calling Sequence

```
cp = cp_fluid(fluidname, T)
```

Parameters

fluidname :
The name of the fluid (a string: "Therminol-66", "Water")

T :
The temperature [K] (a n-by-m matrix of doubles)

cp :
Specific heat [J/kgK] (a n-by-m matrix of doubles)

Examples

```
fluidname = "Water"
Tmin = C2K(10)
Tmax = C2K(90)
T = linspace(Tmin,Tmax)
cp = cp_fluid(fluidname, T)
scf()
plot(K2C(T),cp)
xlabel("T [°C]")
ylabel("cp [J/kgK]")
title("Specific heat cp of fluid: " + fluidname)
```

Authors

- Openeering team @ www.openeering.com

Figure 23: Help content for the cp_fluid function.

6. References

[1] http://www.chemblink.com/products/107-51-7.htm

[2] http://www.wolframalpha.com/entities/chemicals/octamethyltrisiloxane/c8/jy/d7/

[3] http://www.fiz-chemie.de/infotherm/servlet/infothermSearch

[4] http://en.wikipedia.org/wiki/Equation_of_state

[5] http://en.wikipedia.org/wiki/Heat_transfer_coefficient

[6] http://en.wikipedia.org/wiki/Ellipse_Law

[7] G. Bonetti, Simulazione di un gruppo a vapore a fluido organico (ORC) cogenerativo, Thesis 2003/2004, Università di Trieste (http://digidownload.libero.it/bonettig/TESI/DOWN/TESI-ORC-BN.pdf) [Italian].