Steam Power Generation

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Class for the students of Groeningen University

Abstract

A presentation will be shown about the classical techniques used to generate power from steam. We will review basic thermodynamics, liquid-vapour equilibrium, Rankine cycles and variations thereof (superheating, two stages turbines, bleeding, ...). Beyond the different sources of primary energy curently used (nuclear, petroleum, coal, natural gas, ..), we will emphasize the opportunities for renewable sources of energy (geothermal, biomass, waste ...). An account of the Organic Rankine Cycles (ORC) and of the combined heat and power (CHP) installations will also be given. Then, after presentation of CYCLEPAD (a software devoted to the analysis of thermodynamic cycles), we will use it for the resolution of a few problems.

1 Using Cyclepad

Cyclepad is a program designed to help students understand themodynamic cycles. It also has some features that can make it useful for professionals. Mainly, it can perform some calculations with a limited number of real fluids (like e.g. water) that cannot be easily done by hand.

Cyclepad can be used and distributed freely and is available at different places on the internet. For example on the original author's site:

http://www.qrg.northwestern.edu/projects/NSF/cyclepad/cyclepad.htm

Cyclepad can be freely distributed, so you can also download it from my own web pages: `http://ptob.free.fr/thermo/` . Notice you must conform to the licence: `http://ptob.free.fr/thermo/gim2/cyclepad/cyclepadlicence.html`.

1.1 General structure.

The general structure of the program is as follows:

There are two modes of operation: In the first one called *Build Mode* in the software, you can design an application. In this mode of operation, the background screen color is blue. When you enter this mode, you have to choose between two different kinds of designs (open cycle or closed cycle). The first kind of design is referred by the software as open cycle. This doesn't mean that the cycle should necessarily be open in the thermodynamic sense. This rather applies to what is known in the thermodynamic literature as open systems which means that there may be matter entering or leaving the system. In most cases, this involves the flow of fluids through thermal devices. Conversely, closed cycle refers to a closed system i.e. a well defined amount of matter with no inlet or outlet.

1.1.1 Build mode

A design is constituted by a series of devices connected by lines. In order to complete a design, you have to define the devices and the lines linking the devices. In an open system design, the devices will have inlets and outlets and the lines may be thought of as pipes leading the fluid from the outlet of a device to the inlet of the next device. In this mode, whenever we link any two devices, the software displays a round element on the line which will represent the thermodynamic state of the fluid at that place in the system. In a closed design, the devices represent the different kinds of evolution of the system. The elements on the lines then represent the state of the fluid before and after the evolution whereas in an open design, it represents the state of the fluid at the inlet and at the outlet of a device.

We will only use the closed kind of design here.

When a design is complete, i.e. when nothing is left undefined anymore, cyclepad prompts you with the choice to enter the *Analyze mode* or to go back to the *build mode*. You can go back to the design and change the position of the elements or change the labels (right click) ..... You can also go back to the design mode at any time by clicking on the mode menu on the upper panel.

1.1.2 Analyze mode

If you decide to enter the *Analyze mode*, then the background screen color will switch to white. You can still see all the elements but, if you click on any of these, a new window will pop up. Such a window is called a meter by the software. it allows you to enter the data and also to display the results. For a device, the meter allows you to specify your assumption about its behaviour (isotherm, adiabatic, ...). For a state of the fluid, you are allowed to enter the thermodynamic parameters (pressure, temperature, ...). The assumptions that are input by the user are displayed in green while the data inferred (deduced) by the program are displayed in blue. Only the former can be changed by the user, because the latter are consequences of the assumptions.

Contradictions: Whenever the system reaches a contradiction, (i.e if you enter data that are in conflict with the previous assumptions), a contradiction window will pop up. In its upper part, it will show the mutually inconsistent facts (assumptions or consequences thereof) and in the lower part, it will display a set of assumptions that can be retracted to recover a system without contradictions. The user has to analyse what is wrong in his design and then retract at least one of the assumptions to continue the analysis. WARNING! the assumptions should be retracted from the contradiction windows not from anywhere else. Never try to retract the assumption from the meter panels. If you do so, the system may start to work improperly. In that case, you may try to save your work and open it again but there is no warranty that it will work. Things may turn even worse, the system may hang and the only choice which will be left to you will be to start it all over from the beginning. YOU HAVE BEEN WARNED.

1.1.3 Units and preferences.

You can change the units from the <Edit> –> <preferences> menu. You can also choose the terminology (US or UK) in the miscellaneous panel. There are a few differences here, for example the mass fraction of vapour in a liquid vapor mixture at equilibrium is called dryness in UK while it is called vapor quality in the US.

Some other preferences may be changed in the <advanced< tab. For example <isentropic means ideal> or <consider velocity>. A short explanation is given for each of these modes.

1.1.4 Sign conventions for heat and work

The sign convention for the energy quantities is here as follows: The heat is considered positive when it is absorbed by the system and negative when it is rejected by the system. For mechanical work, the convention is reversed i.e. mechanical work or power is considered positive when it leaves the system and negative when it enters the system. This makes sense from the technical point of view because you can use the work given by the system to you (to the outer world) so you can consider it positive. In that case, you should write the first law of thermodynamics: $\Delta U = Q - W$.

I generally prefer the "physical" point of view which considers that heat or work are two different expressions of the same physical entity (energy) so that the same sign conventions should apply. Table 1 below sums up the different approaches found in different sources in the literature.

	Q>0	Q<0	W>0	W<0	First law
Cyclepad or "Technical"	in (system)	out	out	in	$\Delta U = -W + Q$
"Physical convention"	in	out	in	out	$\Delta U = W + Q$

Table 1: Sign conventions for energy

1.2 A worked example: simple Rankine cycle.

Consider a simple Rankine cycle with a boiling temperature of 200°C, no superheating, an isentropic turbine, a condenser delivering saturated liquid at 30°C and a pump to recirculate the liquid to the boiler. The working fluid will be water.

1. Enter the *build mode*. Then create the 4 elements and link them as on the picture (fig. 1): the boiler will be modelled by a heater (the water absorbs heat at this stage) while the condenser will be a cooler (the water rejects heat at this stage). Notice the condenser could be modeled as a heat exchanger but then, we would have to go into more details about the refreshing water on the second side of the exchanger.

2. Enter the *Analyze mode*: Click on the turbine, then on the meter, click on <make an assumption> and choose <works isentropically>. If the system considers isentropic as ideal (see above) then it will enforce adiabatic otherwise, do it by hand by clicking again on <make an assumption>. Do the same for the pump and similarly, chose <works isobarically> for the boiler and the condenser.

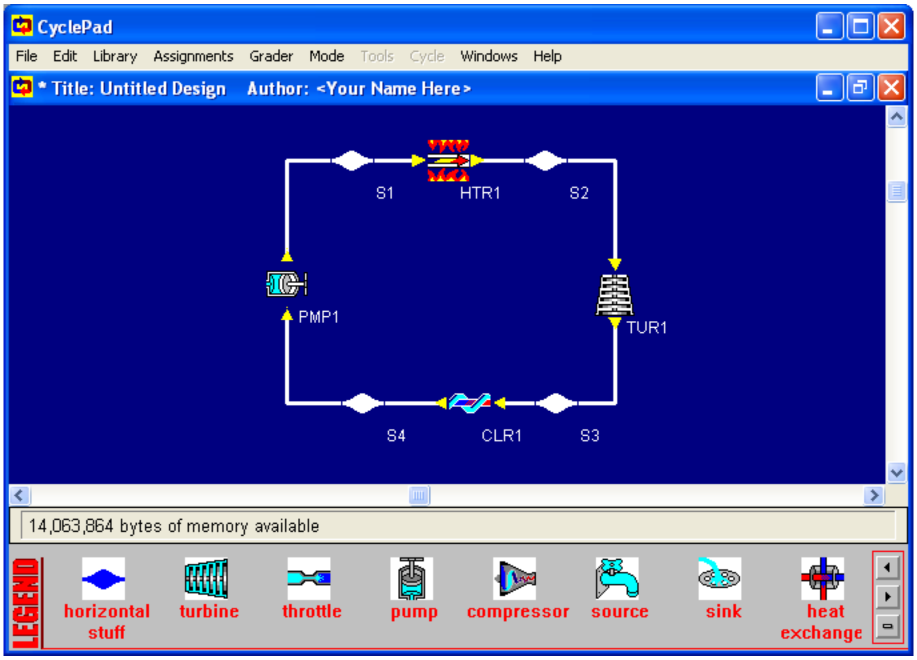

Figure 1: Cyclepad example: Rankine cycle

3. Now click on the point at the outlet of the boiler and define the substance as water. (you can see that now, water appears in blue at all other points). Then define the temperature (assume a value) as 200°C. Now define the phase as saturated and the dryness (or quality) as 1. This means that at this point we have a saturated vapour. This is not considered as a gas by the software. For the phase to be considered as a gas by the software, the vapour has to be superheated. (i.e. T>Tsat at a given the pressure).

4. Now click on the point at the outlet of the condenser. Select the phase as saturated and the dryness as 0 to define the state of the fluid as saturated liquid. In the same way as for the gas, the phase is considered liquid by CYCLEPAD only if it is undercooled (i.e. T<Tsat). Now if you set the temperature at this point to 30°C, it will be entirely defined and you may notice that all the calculated properties will appear in blue.

5. Now click on the point at the outlet of the turbine. Notice that all the parameters have been calculated. Indeed, the pressure is well defined because the condenser is isobar and the pressure at the outlet has just been defined in the preceding step. The entropy is also defined because the turbine being

isentropic it is the same as at the inlet which has already be defined. Hence the state is entirely defined.

6. Now click on the point at the inlet of the boiler, you will find again that everything has been calculated for the same kind of reasons.

7. The cycle is entirely defined now, but we can still add some information on the rates of transfer with time. We may for example enter the mass flow rate (m-dot) so that the power can be calculated. Conversely, it is possible to enter the usable mechanichal power developped by the turbine (shaft power) or the thermal power (Q-dot) input in the boiler so that the necessary mass flow rate can be calculated.

2 Exercises

2.1 Isentropic expansion of saturated steam

1. Make a cyclepad project with a turbine connected to a source and a sink. Set the substance to water. Set the turbine behaviour to isentropic (and adiabatic if necessary). Set the conditions of the entering vapour as follows: saturated, dryness=1, temperature =150°C.

2. Set the pressure value to 2 bars at the outlet of the turbine and observe the calculated state. Determine the shaft work.

3. Draw this evolution on the Mollier diagram (H,S) and the enthalpic diagram (P,H).

4. Change the so called "isentropic efficiency" (nu-s) to 80% and observe how the final point is moved and how the shaft work is affected. Draw on the diagrams.

2.2 Exercise 2 simple CHP plant

CHP stands for combined heat and power. (It is also called cogeneration in certain contexts for example regulatory european literature)

Consider a waste to energy recovery plant. Here, the waste will be burned to provide the heat needed for the boiler and the superheaters. The plant is designed to produce electricity with turbines and the heat rejected at the condenser will be used to heat a group of buildings. It will work according to a Rankine-Hirn cycle with two expansion stages and with a first and second superheat before each expansion.

1. Create a Cyclepad design for this cycle. The boiler will be modelled by 3 subsequent heaters (one for heating the liquid until saturation, one for vaporizing it, one for superheating the vapor) after the first turbine there is a second superheating that can also be modelled as a heater. After the second turbine, the fluid enters the condenser which will be modelled as a heat exchanger. Be careful so as to use the proper side of the exchanger i.e the hot side (the water rejects heat in the condenser, its enegy goes from high to low (red to blue)). The second side of the exchanger will be part of a second loop. This second loop will use another flow of water to distribute the heat in the buildings that need to be heated. These will be modelled as a single cooler (The water is cooled while the heat it is rejecting is used to heat the buildings).

2. The boiling temperature will be set to 200°C and the vapour is superheated until 380°C (in both superheaters). The pressure after the first expansion is set to 10 bar and after the second expansion to 1.5 bar. The liquid exhausting from the condenser will be considered saturated liquid at the temperature defined by the pressure. All heaters, and both sides of the exchanger will be considered isobar. Both turbines and the pump will be considered isentropic (and adiabatic).

3. Suppose the heating power needed for the buildings is 1000 kW and suppose the water arrives at the buildings at a temperature of 90°C and leaves them at 70°C. Check the power delivered by the turbines and the heating power needed for the boiler and superheaters. Check also the mass flow rate of vapor needed in the first loop to meet this demand.

2.3 Organic Rankine Cycle

Unfortunately, cyclepad doesn't have many substances available to make calculations. In this exercise we will see how we can use some data from the internet instead.

We will design a simple Rankine cycle with R-245fa as a working fluid. This is a new refrigerant whose chemical formula is CF5H3 (1,1,1,3,3-pentafluoroethane). The Pressure enthalpy diagram is given below . More precise data can be extracted from the webbook site made available on the internet by NIST: http://webbook.nist.gov/chemistry/

1. Suppose you have a geothermal water at 110°C under pressure and you want to use it to produce electricity in a turbine with the above fluid. We can design a plant working as a Rankine cycle where the fluid entering the turbine is a saturated vapour of R-245fa (we don't need superheat here) at 100°C.

Suppose the pressure at the outlet of the turbine is 4 bar and the turbine works isentropically.

2. Use the above cited internet site to determine the pressure, specific enthalpy and specific entropy for the inlet point. (Be sure to choose kJ/kg and kJ/kgK as units).

3. Generate a table of points in the superheated region at the pressure of the outlet of the turbine with an increment of temperatures of 1°C. Looking at the entropy, determine the final point with a minimum precision of 1°C.

4. Draw the cycle on the diagram and calculate the specific work delivered by the turbine.

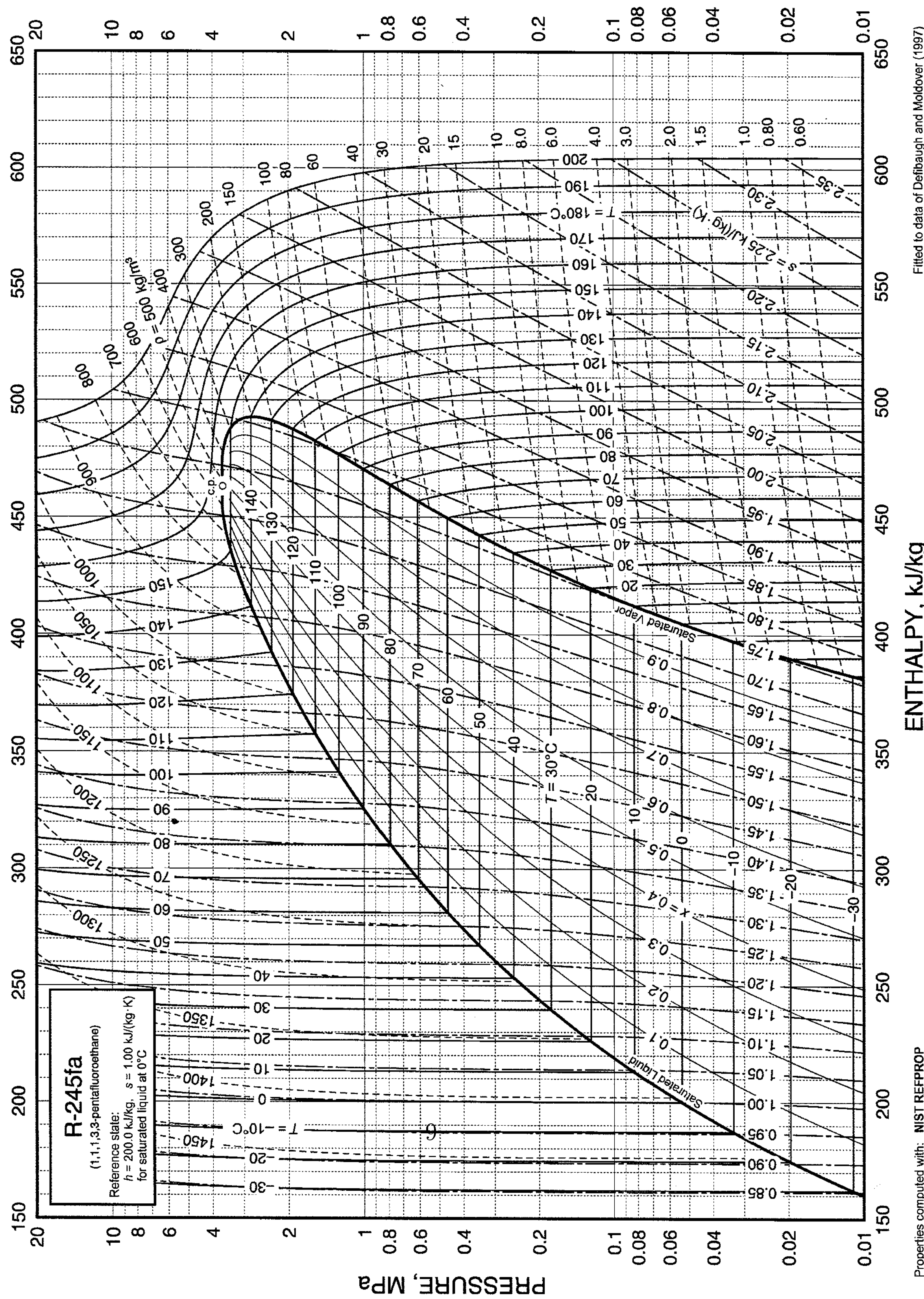

Fig. 11 Pressure-Enthalpy Diagram for Refrigerant 245fa