

A COMPARATIVE STUDY OF THE ENERGY MACHINE AND A CONVENTIONAL HEAT PUMP SYSTEM

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ABSTRACT

This master thesis has been made on behalf of *Energy Machines*, a company who is developing and designing energy efficient solutions for heating, cooling and ventilation. The company has its head office in Sliema, Malta, and branches in Gävle and Stockholm, Sweden.

The company's main business is to develop and design heat pump systems for heating and cooling of buildings. The main product is a patented system solution called the *Energy Machine*.

The heat pump technology's main drawback has for long been low efficiency occurring during domestic hot water production. The problem is the high condensation pressure needed to reach high temperatures. To produce domestic hot water, the system need to deliver a supply temperature of about 60 °C, to be compared with a supply temperature of around 30-50 °C when heat is delivered to a radiator circuit. This drawback has for long held the heat pump technology back and instead gave room for alternative technologies, like district heating. (Hans- Göran Göransson, 2013)

Energy Machines has found a solution to the problem, and thus made the heat pump technology competitive on the market. The solution is to use a separate heat pump to produce domestic hot water and let the main heat pump deliver heat to the radiator circuit. A subcooler in the main heat pump delivers reject heat to the evaporator in the additional machine. This enables a high efficiency even during domestic hot water production.

The technology has been ready for the market for some years now and about thirty systems have been installed so far. (Hans- Göran Göransson, 2013)

1. Project goal

To design a model of the *Energy Machine* and calculate the annual coefficient of performance (COP-factor) of the system. This COP- factor is to be compared with the COP- factor of a conventional heat pump system, which is also being modeled.

where $Q_{\text{delivered}}$ is the heat delivered by the system during one year and E_{consumed} is the electric energy consumed by the system during the year.

2. The basic heat pump circuit

The basic heat pump circuit is built up by four separate processes: Evaporation, compression, condensation and expansion. Each of these processes can be seen in the pressure- enthalpy diagram in figure 1. The evaporation occurs between point one and two, the compression between two and three, the condensation between three and four and the expansion takes place between point four and point one.

In theory, the evaporation and the condensation are often assumed to be isobaric, whilst the compression is assumed to be isentropic and the expansion is assumed to be isenthalpic, as can be seen in figure 1. (Ekroth and Granryd, 2006, 339)

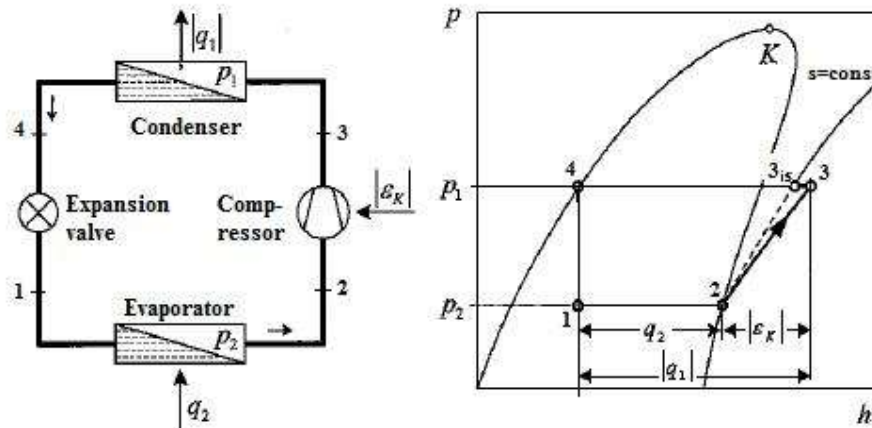


Figure 1. To the left: A schematic of a heat pump showing the four components of the machine; Evaporator, Compressor, Condenser and Expansion valve. To the right: A pressure- enthalpy diagram showing the heat pump process. (Ekroth and Granryd, 2006, 338)

The basic idea of a heat pump is to move thermal energy from a low temperature heat source and deliver it at a higher temperature. As the second law of thermodynamics states that heat cannot by itself go from a low temperature- to a high temperature body, work has to be added. This work is performed by the compressor, which raises the pressure from p_2 to p_1 . (Ekroth and Granryd, 2006, 339)

In the evaporator, the refrigerant is fed with low temperature heat, q_2 , at low pressure, p_2 , why it evaporates as the temperature rises. This can be seen to the right in figure 1.

The refrigerant is then compressed by the compressor to a resulting pressure of p_1 . During the compression, additional energy is added to the refrigerant as it absorbs the power added by the compressor engine. The pressure increase also results in an increase in temperature.

From point 3, the super heated steam is then cooled down in the condenser at constant pressure, p_1 . This makes the gas condensate, i.e. emit the thermal energy it holds. The heat sink is typically a radiator circuit or a domestic hot water circulation circuit.

The refrigerant then undergoes an expansion through an expansion valve whereon the resulting pressure is brought back to p_2 . During the expansion, some of the liquid is vaporized whilst the rest is vaporized in the evaporator. (Ekroth and Granryd, 2006, 339)

2.1 Compression and isentropic efficiency

The compression process can be described in many different ways. Two commonly used theoretical compression processes are the isothermal compression, where the temperature is held constant, and the isentropic compression, where the entropy is held constant. Neither of these processes can actually be realized, but are used as approximations of real compression processes. (Ekroth and Granryd, 2006, 103-106)

One way of measuring the efficiency of a compressor is the isentropic efficiency. This is a measure of the efficiency of the compression process compared to an isentropic compression process. The isentropic efficiency is defined as:

where $E_{\text{isentropic process}}$ is the work required by the compressor to raise the pressure from p_1 to p_2 in the case of an isentropic compression process. $E_{\text{real process}}$ is the work required in reality. (Ekroth and Granryd, 2006, 193)

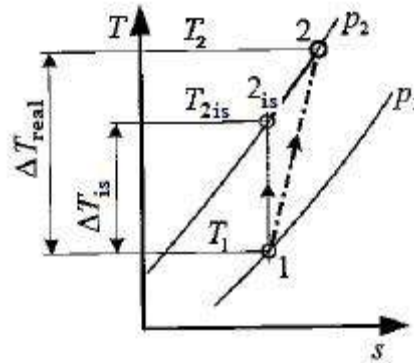


Figure 2 The compression process in a temperature- entropy diagram. An isentropic compression is shown between 1 and 2_{is} whilst a real compression process is shown between 1 and 2 (Ekroth and Granryd, 2006, 192).

Figure 2 shows a temperature- entropy diagram describing a compression process. The line between point 1 and point 2_{is} describes an isentropic compression process, where the entropy is held constant. The line between point 1 and point 2 describes a real compression process.

The difference between the isentropic compression process and a real compression process can also be seen in the pressure- enthalpy diagram of figure 1. The line between 2 and 3_{is} shows an isentropic compression whilst the line between 2 and 3 shows a real compression process. The curvature of the line between 2 and 3 is depending of the isentropic efficiency.

The isentropic efficiency is depending not only by p between p₁ and p₂, but also by the pressure level, i.e. the absolute values of p₁ and p₂ as well as the type of compressor etc. (Kjell Pernestål, 2013)

2.2 COP-factor

The COP- factor is a measure of the efficiency of a heat pump. It is defined as

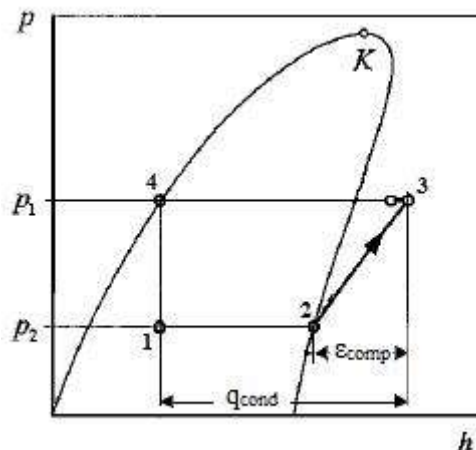


Figure 3 The heat pump process shown in a pressure- enthalpy diagram. The work done by the compressor and the heat delivered by the condenser are shown. (Ekroth and Granryd, 2006, 338)

2.3 Subcooling in heat pumps

In some applications, it is possible to sub cool the condensate to a temperature below the condensation temperature. This increases the heat delivered by the heat pump without affecting the power consumed by the compressor, i.e. the COP- factor of the heat pump increases. The subcooling process is shown between point four and five in figure 4. (Ekroth and Granryd, 2006, 350)

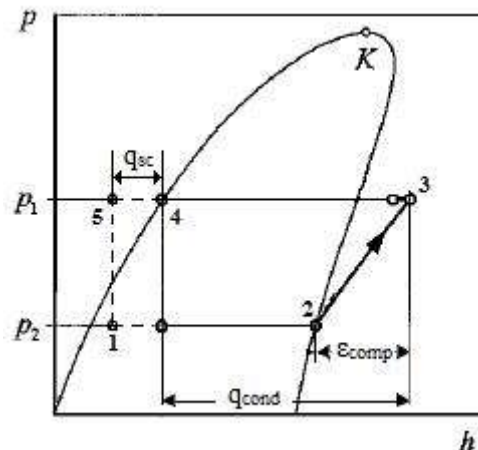


Figure 4 The heat pump process with subcooling shown in a pressure- enthalpy diagram. The heat delivered by the subcooler is shown between 4 and 5. (Ekroth and Granryd, 2006, 338)

The COP- factor can in this case be expressed as:

$$\text{COP} = \frac{q_{\text{cond}} + q_{\text{sc}}}{\dot{W}_{\text{comp}}} \quad (5)$$

where $q_{\text{condenser}}$ is the heat delivered by the condenser, q_{sc} is the heat delivered by the subcooler and $\dot{W}_{\text{compressor}}$ is the power consumed by the compressor. (Ekroth and Granryd, 2006, 350)

2.4 The Energy Machine

The *Energy Machine* is a heat pump system designed to achieve high COP- factors not only during heating operation, but also during domestic hot water production. The system is built up by two heat pumps working together. The main heat pump, called EM01, delivers heat to the heating system, whilst a second smaller heat pump, called EM02, is used to produce domestic hot water. As the evaporator of EM02 is fed with reject heat from a subcooler in EM01, it works at high evaporation temperature. This results in a very high COP- factor, even though the condensation temperature is high. (Hans- Göran Göransson, 2013)

This solution enables the system to deliver heat at very high COP-factor even when delivering domestic hot water, unlike a conventional heat pump which suffers from very low efficiencies during domestic hot water heating.

A simplified schematic of the *Energy Machine* is shown in figure 5. The evaporator of EM01, shown to the left in the figure, is usually fed with heat from a geothermal ground source. The evaporator of EM02 on the other hand, is fed with reject heat from the subcooler in EM01, as described above. The subcooler circuit that is feeding EM02 also pre heats the ingoing domestic cold water, as seen at the top of the figure. The final heating of the domestic hot water is then done by EM02, as can be seen in the bottom right corner of the figure.

Just like EM01, EM02 is also equipped with a subcooler, as can be seen in the figure. This subcooler pre heats the return of the heating water before EM01 performs the final heating. This is not shown in the figure though. Another function that is not shown in the figure is that EM02 is able to deliver heat to the heating system when domestic hot water heating is not required. Since EM02 operates at much higher COP-factor than EM01, this function increases the system COP also in heating operation. (Hans- Göran Göransson, 2013)

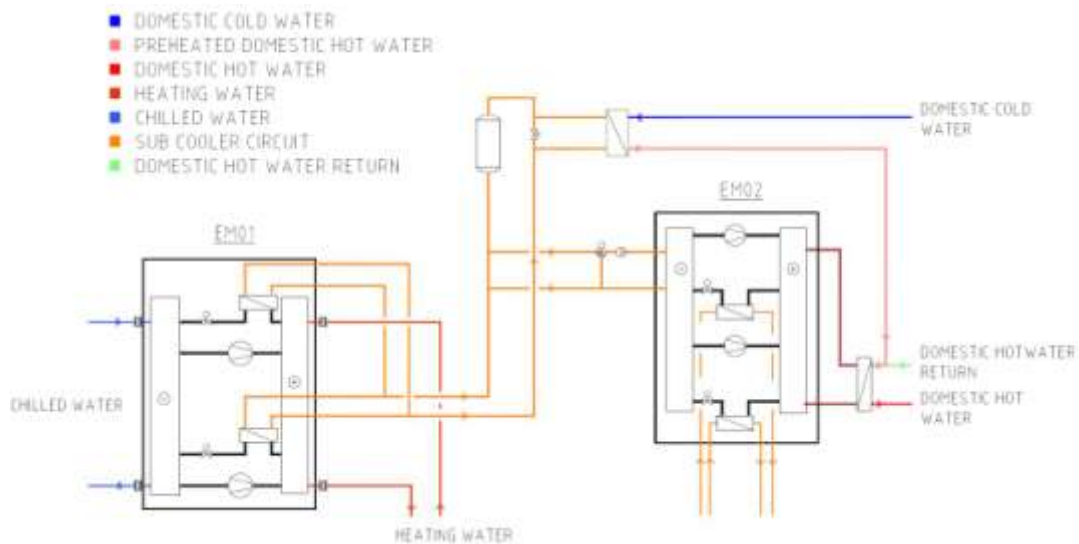


Figure 5 Simplified schematic of the *Energy Machine*. EM01 is shown to the left and EM02 to the right. The subcooler circuit feeding EM02 can be seen in orange between the two machines. (Patrik Ross, 2013)

The subcooler circuit of EM01 is actually also connected to the return of the heating water, although, this connection has been removed from figure 5 in order to make it simpler to understand. The connection in question enables the system to retrieve heat from the heating system to feed EM02 in case the heat from the subcooler is not sufficient. This is of course not desirable since it lowers the system COP significantly, but cannot be avoided at all times. (Hans- Göran Göransson, 2013)

Both EM01 and EM02 consist of two compressors working in parallel, as can be seen in figure 5. This gives two main advantages; the first is that the working range of the machines gets wider since the two compressors is used in steps when the heating demand grows. The second advantage is the redundancy achieved from two compressors in case one breaks.

3. Discussion

3.1 Impact of simplifications

It is important to be aware of the simplifications that have been made in the model in order to get an accurate picture of the results it is producing. The most important parameters are discussed in this chapter.

The parameter affecting the COP- factor of the individual heat pumps most is the isentropic efficiency. The isentropic efficiency is the parameter that separates the isentropic compression process from the real compression process. It is therefore important that this parameter is approximated with sufficient accuracy. The model validation was made in order to ensure that this is the case, which it proved to be. It would have been a good idea to actually measure the hot gas temperature of a real heat pump process as well. But as it was hard to arrange such a measurement with enough accuracy, it was decided that it was better to ask people with a lot of practical experience to validate the calculated efficiencies instead.

One parameter that has been neglected in the models is the compressor efficiency at part load. A real compressor has a maximum efficiency at a certain operation mode, which thus have been ignored in this project. The performance of both modeled systems would of course decrease if this parameter were taken into account. It is though hard to say how the ratio between the COP of the conventional heat pump system and the *Energy Machine* would be affected. But it would probably not change much since EM02, which would make the difference between the two systems, normally delivers quite small amounts of heat compared to EM01.

The efficiencies of the compressor engines have been neglected in the models as well. This parameter would of course have decreased the system COP of both systems. It would also affect the ratio between the annual COP-factors of the two systems slightly. How much is hard to say, but it would probably not change much since EM02, which would make the difference between the two systems, normally delivers quite small amounts of heat compared to EM01.

The fact that the evaporation pressures in EM01 and the conventional heat pump is set to be constant is a major simplification that needs to be considered when looking at the results. In reality, most installations are connected to a geothermal ground source, whose temperature varies during the year. How it varies depends on the conditions at the specific installation, like the number of boreholes and if the installation is used to produce cooling or not.

Another concern about the evaporation is the fact that the temperature drop in the evaporator of EM02 is set to be constant, 17 °C. In reality, the temperature drop would increase with increasing condensation temperature of EM01. This, in turn, results in an increase in the heat retrieved from the subcooler circuit as a greater temperature drop results in more heat. As the temperature drop increases at the same time as the heat delivered by EM01 increases (in most cases), the available sub cooler heat increase exponentially when the power demand rises. As the temperature drop in the evaporator of EM02 is set to be constant, the heat exponential trend is erased, as can be seen in figure 30.

It should also be said that the heat available from the subcooler of EM01 is highly dependent of the temperature drop in the evaporator of EM02. It should be further investigated how big this temperature drop should be in order to get the most profitable operation of the system.

In reality almost all *Energy Machines* installed is used to produce both heating and cooling, whilst the model created in this project only takes the heating into account. This lowers the annual COP- factor of the system very much since the cold circuit of the heat pumps can never be used and is instead treated as a reject. Another aspect of this is that cooling during summers enables the system to heat the geothermal ground source, which makes it warmer when winter comes and the system is to produce heat again.

The fact that the ratio between preheating and final heating in the *Energy Machine* is constant is a simplification which gives the *Energy Machine* a disadvantage when compared to the conventional system. The ratio which has been applied in the model is not optimal at all operating modes, why the system COP is slightly lower at some operating modes than in reality.

The model of the *Energy Machine* has no storage tank, which means that the heat to/from the components of the system has to add up to zero at each time step of the simulation. In the operating mode "*Heating and domestic hot water production 1*" there is more heat available from the subcooler of EM01 than needed for preheating and final heating of domestic hot water. Still EM02 is forced to deliver only the amount of heat to cover the heating of domestic hot water. This means that some of the potential subcooler power from EM01 is lost because there is nowhere to store it. This of course makes the annual COP- factor of the *Energy Machine* slightly lower than it should be.

The domestic hot water heating in the models differs from reality in the way that it follows a constant heating pattern, as described in 6.3.1.1. This does of course not mach reality completely as the demand for domestic hot water usually varies during the day. What is most important for the result though is that the ratio between the time that the system is heating domestic hot water and the time that it is just delivering heat to the heating system agree fairly with reality; otherwise the resulting annual COP-factor will be misleading. This ratio is of course dependent of how the system is designed, why it can differ a lot, but it should be further investigated how the results are affected by this parameter.

4. Result

It is important to check that the definition of the model parameters is mathematically correct and behaves as expected during simulations.

As the subcooler in EM02 is feeding the return circuit of the heating system, it is important that the temperature of the subcooler circuit is always higher than the temperature in the return circuit itself. Otherwise, the subcooler circuit would actually cool down the return circuit which means that EM01 would have to deliver more heat than the model actually calculates. Of course it have been verified that this is not the case. The subcooler circuit is actually supplying a temperature that is much higher than the return circuit at most operating modes.

Another parameter that is important to verify is the heating demand. It is of course important to check that the modeled systems actually deliver the amount of heat that the *Regulator* demands. It have been verified that this is the case as well.

5. Conclusions

Two major conclusions can be drawn from this project.

First of all, the simulations that have been performed with the models shows that the *Energy Machine* actually is performing better than a conventional heat pump system with the conditions defined in the simulations.

The second, and maybe the most important conclusion that can be drawn, is that the *Energy Machine* model has proved to be very useful for analyzing and develop the *Energy Machine* technology. The model can be used both for testing the system in different operating conditions in a very cost efficient way. It can also be used to simulate how different system parameters affect the system performance in order to optimize the system. The model gives an opportunity to simulate different conditions instead of installing expensive installations to run tests with.

The *Energy Machine* model is also a very powerful tool in feasibility studies done together with customers in order to calculate the costs and savings in individual projects.

6. References

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