NOVEL STEAM ENGINE FOR MULTI PRIMARY ENERGY RESOURCES

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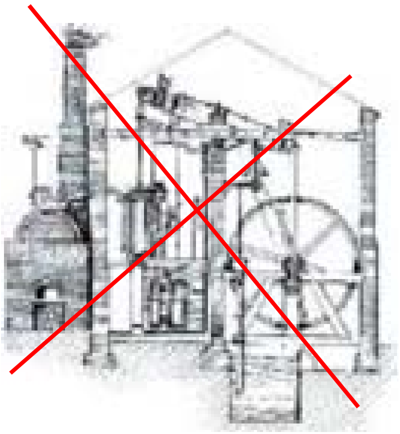
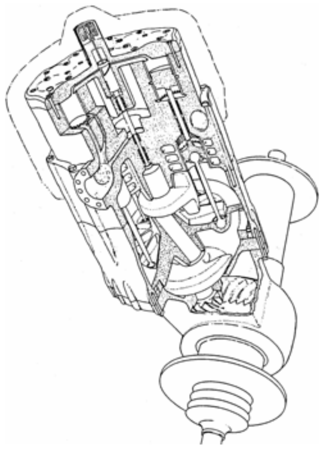




ABSTRACT

In our daily live we are surrounded with different prime mover (power–cycles) as internal combustion engines, jet engines and big power plant that propel vehicles and generate electricity.

The oldest type of power cycles is the Rankine –cycle or as the more familiar name, steam power. Steam power is today mainly used in large power plant generating electricity by burning fossil fuel or splitting atoms in nuclear power plant. When it comes to smaller steam power plant people in general associate steam power with black smoking locomotive or slow boats. However, Rankine power cycles has several inherent unique qualities that makes it very attractive as a future propulsion system in mobile applications as well as small scale electric generation and heat at the same time, so-called CHP (Combined Heat and Power).

The novel high-tech micro Rankine cycle embodied as steam engine is not only a choice of replacing conventional prime movers but may an also be an attractive complement to an internal combustion engine, gas turbine and fuel cell where waste heat is recovered and realising a hybrid power cycles with high efficiency, flexibility and reliability. However, in many applications a self-contained steam engine will offer the best possibility to use different energy sources including solar energy,

This paper gives a brief description of the results from the work on a modern steam engine that has been carried out by the RANOTOR Company and current research work at KTH Stockholm. The figures in this paper is mainly based on computer simulation models but also on certain laboratory tests on specific components

INTRODUCTION - WHY STEAM ENGINE AGAIN-

Among different types of power cycles the steam power cycles (Rankine cycle) unfolds the largest possibilities to use various primary energy resources. As long there is a heat sources above + 400 ºC it is possible to boil water and then generate electricity. At present the dominating power cycles for small-scale power is the conventional internal combustion engine.

External combustion has a more fuel flexible power cycle than internal combustion engine because the fuel doesn’t have to deal with anti-knocking and lubrication issues. Internal combustion is also more sensitive for fouling problem than an external combustion with heat transfer to the working fluid via a heat exchanger.

Steam power is not unique when it comes to external combustion. However, steam power is unique when it comes to external combustion and low temperature. The external combustion in a steam engine starts at ambient temperature whereas a Stirling engine for instance uses a preheating process in order to get acceptable efficiency. That means that the highest flame temperature in a steam power system is low and hence very little nitrogen in the air is oxidize. RANOTOR company has previous carried out testing and evaluation of combustion performance and emissions for a steam engine. The result has been compared with other engines and particular with the Stirling engine. The ability to harness low temperature makes the steam power also able to recovery waste heat from other sources and acting as a so-called bottoming cycle.

Last but not least, the ability to use of low temperature sources makes it possible to harness solar energy by evaporating water or other working fluids in parabolic trough. Stirling engine requires about + 800 ºC to operate which requires high concentrating solar collectors, which in turn means complex and expensive solar collector technology, whereas steam power can accept lower temperature and thus simpler and cheaper solar collectors. When generating electricity from solar energy in this way it is called STP (Solar Thermal Power). Such a solar thermal power system has run for a long time in California dessert but now there is resurgence in this technology and approximately 3000 MW new capacities is under construction.

NOVEL STEAM ENGINE SYSTEM TECHNOLOGY

In Figure 1 the components in a novel steam engine system are illustrated. The components are the same as in big power plant and old classic steam engine system; A burner, steam generator, an expander, a condenser and a feed pump.

Burners will be different depending on fuel. Alcohols can be pre-vaporized with the heat from the condenser and pre-mixed and resulting in very low content of harmful emissions in the exhaust gas [1].

The most costly components in the system are the steam generator (boiler) and the expander. In a typical steam power plant the cost normalised to the electric output for the steam generator is about twice the expander. Due to the high cost and weight for conventional boilers there is a necessity to find a new steam generator design whith high compactness.

In order to realise compact steam generators in terms of volume and specific weight it is necessary to adopt laminar flow on the flue gas side. Heat transfer coefficient is proportional to Nusselt number (*Nu*), heat conductivity λ and reciprocal hydraulic diameter (*d*) according to following equation:

$$\alpha = \frac{Nu \cdot \lambda}{d}$$

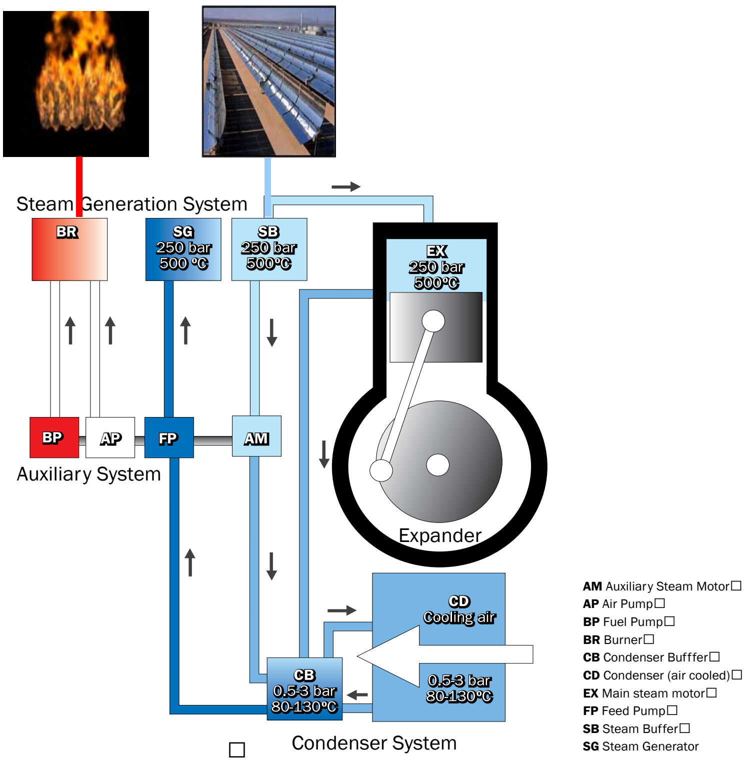


Figure .1 Components in a steam engine system

When operating in laminar flow regime, *Nu* will be constant and with decreasing *d* will α increase. Further more with reducing *d* more heat exchangers surfaces will be possible to package within a certain volume. In figure 2 the micro tubes in the steam generator are shown. Steam generators build up with micro tubes unfolds steam generator with a power to weight ratio (kW/kg) several order of magnitudes higher than conventional boilers.

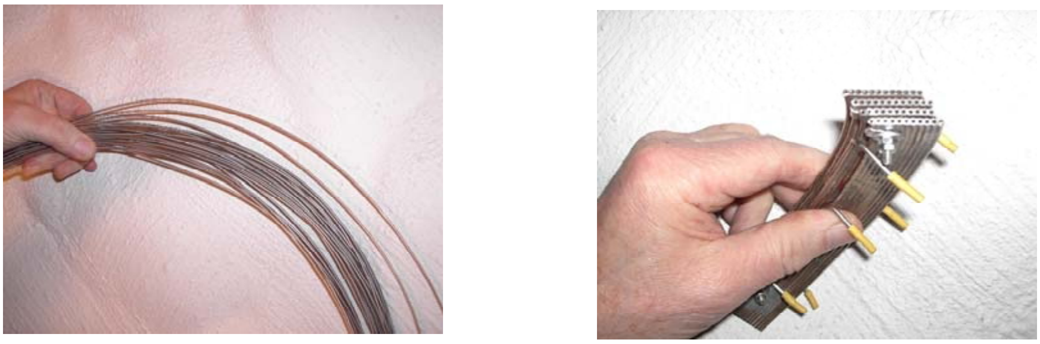


Figure 2. Steam tubes

WHAT KIND OF EXPANDER.

When realising a small-scale steam power there is several possible expander type that could come in questions at a first glance. However, when realising a high performance small-scale steam power that is supposed to compete with internal combustion engine efficiency the expander has to cope with high-pressure ratio and still having a low blow-by (low internal leakage).

In the small- scale power out put range there are several parameters that indicate that a reciprocating piston engine, that is, a steam engine will provide the largest possibilities to offer high efficiency, an attractive torque and shaft-speed and a low price [2].

The modern high performance steam engine should operate without oil because oil will degrade at the high temperature that is needed to obtain high efficiency. Further more, when employing water as a working fluid it will be necessary to deal with high admission pressure and large expansion ratio for high efficiency [2]. Typical expansion ratios for internal combustion engine are 1:10-1:20 whereas the steam engine should have an expansion ratio of 1:100.

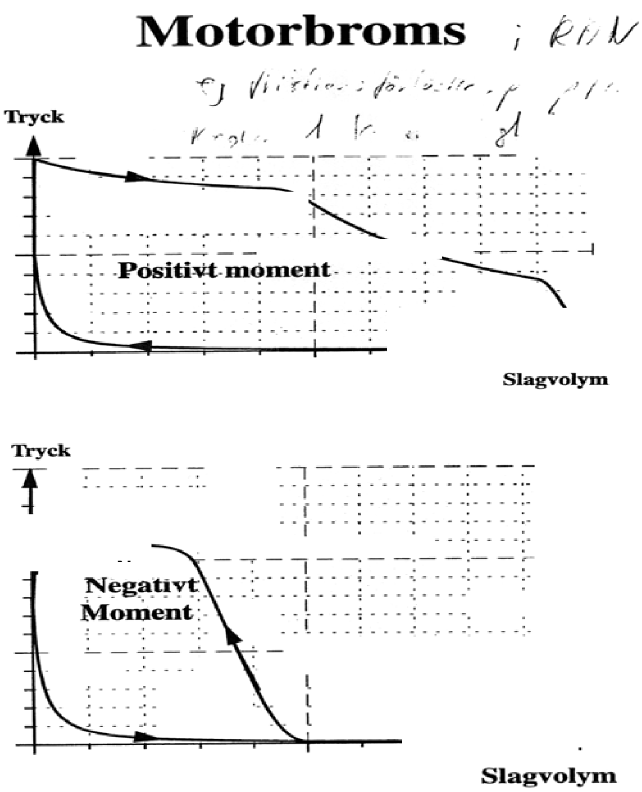
High Pressure means a high-density working fluid, which in turn means a high-speed nature of the engine.

When realising a high-speed steam engine several advantages are possible to achieve. High speed will give reduced internal leakage (Blow-by) and hence, improved efficiency. Further more, high-speed will imply low heat losses and last but not least, high specific power (kW/kg). High specific power is of paramount importance in all utomotive applications, but will also give more cost effective stationary applications.

Steam engine is used to be associated with large and bulky contraption but with modern concept it has an inherent quality to be very compact and having much higher power density than internal combustion engine. This is because it's possible to fill almost all the displacement volume with working fluid before expanding. In figure 3 is a computer simulated pressure volume graph illustrated. It can be seen that the area, which correspond to the work during one power cycle is big, i.e. mean effective pressure is high compared to an internal combustion.

In Figure 3 is also illustrated a computer simulated pressure –volume graph for a steam engine acting in a reversed mode, that is, compressing steam instead of expanding steam and hence providing a negative torque. In such a mode is the steam engine providing a powerful engine braking, which is an attractive feature in automotive applications. When it is possible to operate a steam engine with high shaft speed combine with high torque, very high specific power can be possible to obtain.

In Figure 4 the specific power versus shaft speed is illustrated. It can be seen that specific power of 1200 kW/litre displacement volume should be possible to obtain. That is more than ten times higher power density than a typical internal combustion engine



Pressure – volume graph (Indicator diagram)

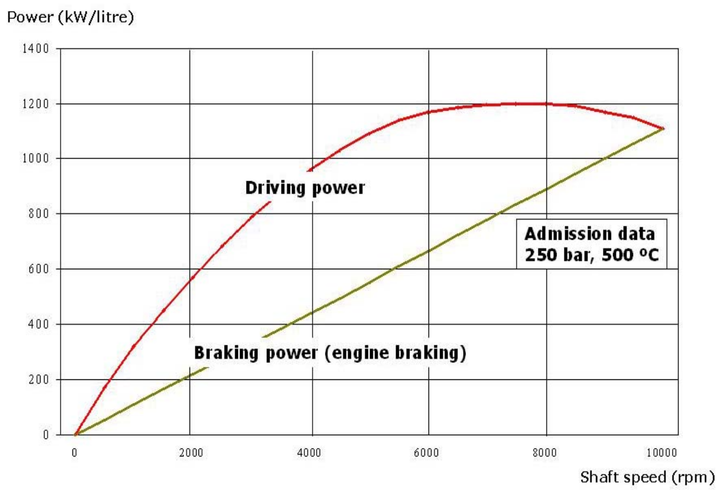


Figure 4. Specific power kW per litre displacement volume

With supercritical steam engine employing a pressure of 250 bar and a mechanical design that can operate at high pressure it could be possible to get very high performance including an torque characteristic that is considered as favourable in automotive applications. In Figure 5 the torque characteristic for an internal combustion engine and a steam engine is schematic illustrated. The torque for the steam engine is very high already from zero shaft -speed and has a torque characteristic that increase with decreasing shaft speed.

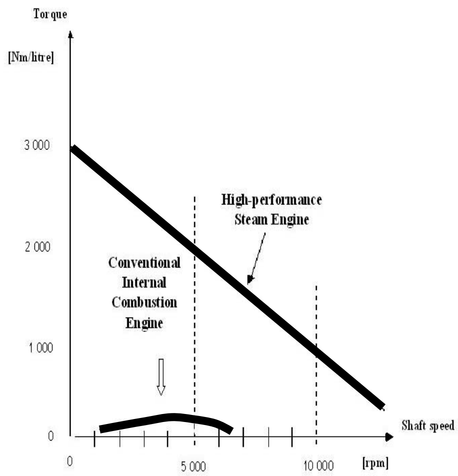


Figure 5. Schematic torque characteristics for a high speed steam engine and an ICE

The internal combustion requires a shaft speed of 500-1000 rpm (idling) before any torque is obtained at all. The torque is then increased until maximum torque is reach whereupon the torque is reduced at higher shaft speed. The steam engine torque characteristic makes it possible to eliminate or at least using a very simple and cheap gear-box in automotive applications.

As shown in figure 4 and 5 is the shaft speed very high compared to old classic steam engines that revs a few hundreds revolution per minute It is clear that a moderns steam engine will benefit very much with high shaft-speed. In Figure 6 the efficiency for a steam engine is illustrated as function of shaft speed and for two simulations cases, one where only friction losses is taking into account and one case where also heat losses and blow-by is taking into account. It can be seen that the efficiency is not affected very much by shaft speed whereas heat losses and blow-by is strongly influenced by shaft speed.

Engines performance can be presented in so-called performance maps. In Figure 7 such a performance maps based on computer simulation is illustrated. The performance maps have shaft-speed on the x-axis and torque on y-axis. The efficiency curve is then plotted in the graph and constant efficiency curves looks more and less like island as can be seen in Figure 7. It is also apparent the highest efficiency is obtained at low loads, that is, low torque. This is the opposite to conventional internal combustion engine which have the highest efficiency at full or close to full load. The efficiency characteristic of a steam engine is very advantages in most applications.

In a typical car the maximum power out put is many times higher than the significant power used during normal driving. There is a desired (need) for high peak power during very short periods but on average is the power out put in the order of 10-20 times lower than peak power. That holds also true in stationary applications where the steam engine is used for combined heat and electricity generation. Normal power electricity output in a typical building is about one tenth of the required peak power.

Figure 6. Efficiency as a function of shaft speed

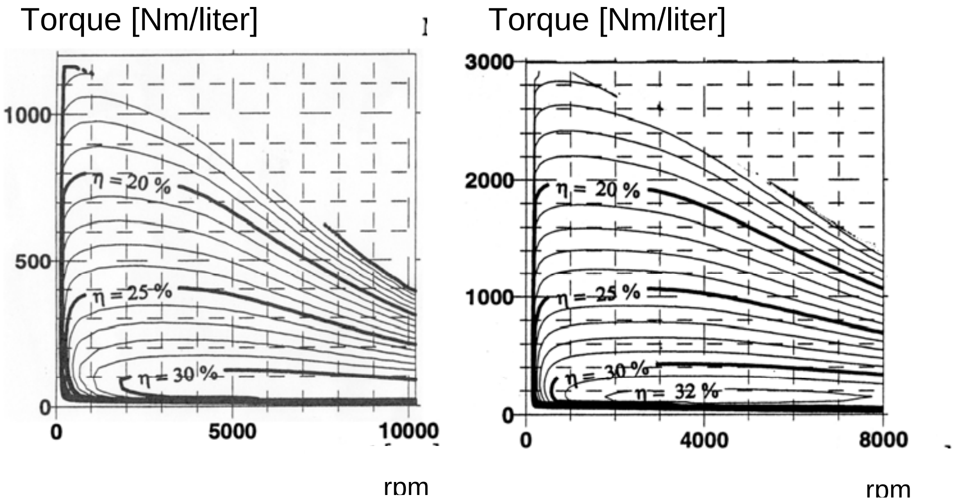


Figure 7. Performance maps for a 100 bar and a 250 bar steam engine.

In figure 7 shows the performance maps for two different admission data (pressure and temperature). One is for supercritical steam at 250 bar and one is for 100 bar. The efficiency for 250 bar machine is slightly higher with the chosen temperature, but torque will differ very much. A steam engine employing high pressure resembles hydraulic motors. However, in the steam engine case should shaft speed be considerably higher. The basic physics that tells us that a modern high performance steam engine should operate with high pressure, high shaft speed and operation without oil as lubricants calls for extraordinary engine design.

One concept that seams to offer the desired requirements is a multi cylinder axial machine with wobble plate (Taumelscheibengetriebe) and a rotating valve as illustrated in Figure 8.

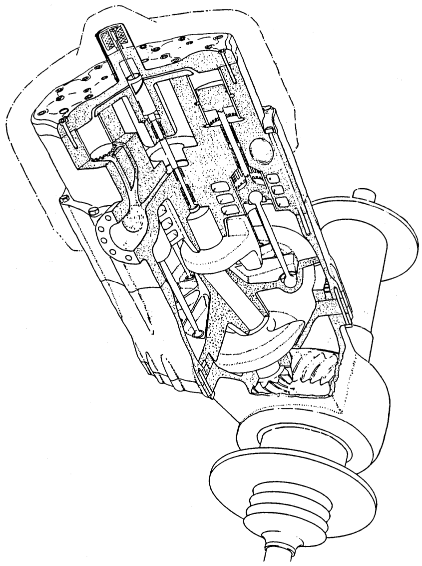


Figure 8 Axial multi piston steam engine

Multi cylinder will give low degree of irregularity of torque and hence a smooth operating characteristic (turbine like). Low degree of irregularity of torque is favourable because it makes it possible to operate the steam engine at low speed without feeling torque pulsation. The wobble plate concept gives several possibilities for attractive balancing solutions and hence free of vibrations. Further more, very low transverse forces on piston, which gives low friction losses. An axial piston engine also makes it easy to implement a rotating valve in the centre, which unfolds very high-shaft speed and hence low blow-by and heat losses (high efficiency) and high specific power. Rotating valve imply a simple cut –off (capacity control) for both forward and backward (regenerative braking). Axial machines with a rotating valve makes it turn possible to built engine with short inlet pipes with equal length that is, a small clearance volume (dead space), which in turns imply high expansion ration and high efficiency.

CO_2 STEAM ENGINE

If temperature sources is below approximately +400 C water as a working fluid will not yield the best thermodynamic characteristic when it comes to high efficiency and so-called ORC (Organic Rankine Cycles) is gaining increasing interest to recover low grade waste heat. Such a ORC is using refrigerants as working fluid rather than water. Due to environmental concern natural working fluids as CO_2, ammonia and propane have been suggested as the next generation working fluid in AC and refrigerators. An interesting concept is to implement a so-called transcritical power cycles employing CO_2 as working fluid [Yang]. If using CO_2 as a working fluid the heat sink has to be lower than for water as working fluid. The schematic different temperature level for a CO_2 and water Rankine cycle is illustrated in a temperature-entropy diagram, Figure 9.-

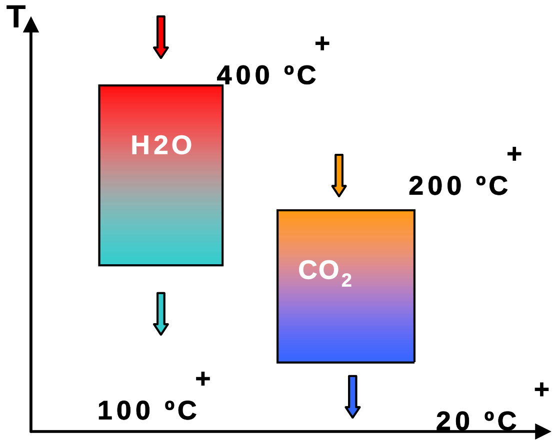


Figure 9. Typical temperature-entropy diagram H_2O and CO_2 Rankine cycle

In Figure 10 is efficiency for a CO2 steam engine illustrated as function of inlet temperature (admission temperature) for different inlet pressure (admission pressure). With a low condensing temperature (+22 ºC) the efficiency can be pretty high even for low admission temperature. The lower temperature the simpler and cheaper solar collectors can be used. Even at as low temperature as +175 ºC the efficiency (electric) is in the same order of a photovoltaic. However, with a solar powered CO_2 steam engine it is possible to burn some local fuel when sun is failing and hence, a solar thermal CO_2 steam engine will be able to offer dispatchable energy commodities.

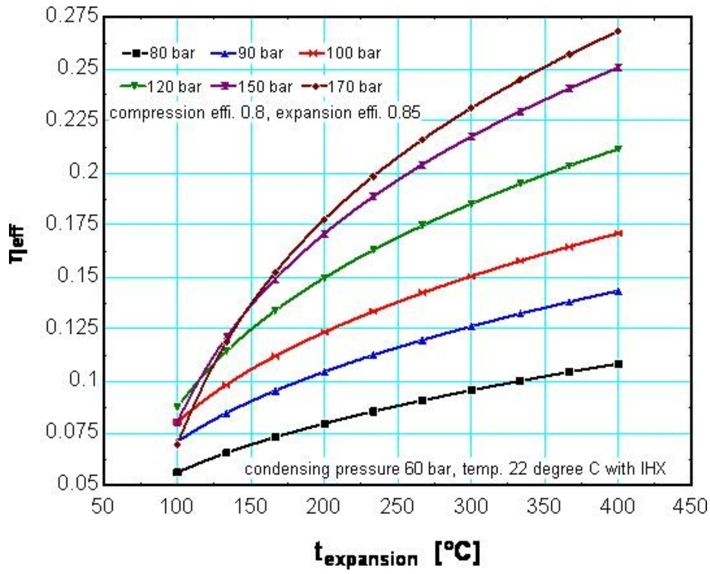
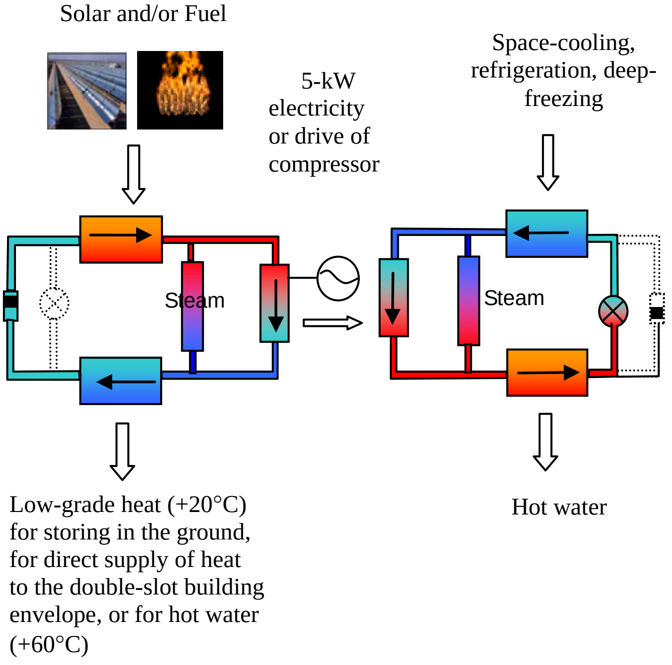


Figure 10. Efficiency for a CO2 steam engine

The CO_2 steam engine also makes it possible to realise an innovative power-heat pump that besides acting as a power cycle and generating electricity and heat it also can operate in the reversed mode as a heat pump. Mostly working fluid is not well suited for operation both in a power cycle and as a heat pump or AC. Heat pumps with CO_2 as a working fluid has been in commercial use in Japan for many years. CO_2 heat pumps offer high efficiency for hot water production if certain condition is present. In Figure 11 is a CO_2 steam engine operating with solar energy or by burning a fuel. The steam engine generates electricity and low-grade heat. Electricity is used to propel the heat pump that produces low temperature for freezing applications and and hot water.



CONCLUSION

The research so far indicates that there are great possibilities to improve cost and performance of steam engine system for small-scale CHP applications. The most attractive expander seams to be the reciprocating piston engine but further development of the high-speed oil-free steam engine has to carried out before a mature and reliable engine is commercial technology for automotive applications. For stationary applications the situation is different because specific weight is not a crucial parameters. Besides the oil-free topic also fast valve mechanism is important to realise in order to obtain the performance described in this paper.

ACKNOWLEDGMENTS

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