Design of a facility for testing expansion machines for small scale CSP and first test results

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Abstract

The result of a study carried out by Fraunhofer ISE (MEDIFRES) was that solar thermal power plants in the range of 50 kWel to 1 MWel can be economically viable in countries with high irradiation potential. [1],[2] Especially the combined use of solar heat, cold and electricity could enhance the economics. Industrial sites in remote areas today mostly cover their energy demand by diesel generators and fossil burners. Due to the high prices, substituting fossil fuels with solar polygeneration systems could be economically viable in the near future, even without government incentives. Also small and medium sized enterprises, not having the resources to build large power plants, could implement such systems. Thus smaller solar thermal power plants could lead to a significant increase of solar usage in energy production.
The key components (e.g. middle and high temperature collectors, storages, small expansion machines and absorption chillers) for solar polygeneration are currently at various levels of development. A demonstration of a solar combined heat, cold and power system has not been realized yet. Components that would be suitable for solar polygeneration have not yet been tested or optimized for the dynamic behaviour of solar systems.
In order to test components for solar polygeneration, a gas heated test facility with 250 kW thermal capacity was erected at Fraunhofer ISE. It will be used for measuring the behaviour and advancing components.

Keywords

Solar Polygeneration, Steam Expansion Machine, Piston Engine,

Introduction

Up to now, for technical and economical reasons large concentrated solar thermal power plants starting from a rated electrical power of 10 MW_{el} and more, are to be favoured Small and medium sized projects could have advantages because of flexibility and financing options. Also, the potential benefits of combined generation of heat, cooling and power could be utilized by smaller power stations, if load demands match.
A study financed by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) has shown that also Medium and Small Size Concentrated Solar

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thermal Power (MSS-CSP) plants from about 50 kW_{el} up to 10 MW_{el} can be economically feasible [1],[2].
Solar polygeneration applications in rural areas, where no grid is available, show large potential. Today, in these areas, commonly combustion engines are used to supply small production sites, for example, with heat and power. In India the capacity of industrial in house power plants is about 12 322 MW_{el} which equals 30% of the overall electricity production [3]. Rising oil prices result in increasing electricity production costs.
The key components for solar polygeneration (e.g. medium and high temperature collectors, thermal energy storage, small expansion machines and absorption chillers) are at various levels of development. A demonstration of a solar combined heat, cold and power system has not been realized yet. Many components that would be suitable for solar polygeneration have not yet been tested or optimized for the dynamic behaviour of solar systems.
In order to test components for solar polygeneration with less than 250 kW_{th} thermal input, a test facility was erected at Fraunhofer ISE. It was designed to be as flexible as possible. A gas fired burner allows to emulate the dynamic behaviour of a collector field. The system can be used as a heat source for different applications, such as power generation cycles, thermally driven chillers and sea water desalination units. Various working media can be used in the power generation cycle. It will be used for component development and characterization. The present paper gives an overview on the design of this facility and the current status.

1. Design of the test facility

1.1 General specifications

In order to be independent of solar irradiation, the facility is based on a gas driven thermal oil heater. The oil heater has a rating of250 kW at a maximum temperature of 300°C. The cycle is designed for pressures up to 30 bar and offers the possibility to use water or organic working fluids. A water brake allows for testing a large variety of expansion machines and loading profiles up to 40 kW and 12000 rpm.
The facility provides connections for possible future extensions with the following components:

- thermal storage
- thermal driven chillers (ab-/adsorption)
- desalination units
- heat users simulated by cooling system.

1.2. General Layout

The test facility consists of three loops:

- Thermal oil loop
- Working cycle
- Cooling loop

The thermal oil loop separates the natural gas burner and the evaporator. The gas burner allows for simulating the thermal power generation of a concentrating collector. The thermal oil heater operates with a constant mass flow. In order to manipulate the thermal oil mass flow a bypass is installed. The thermal capacity of the burner is 250 kW_{th}. With the test facility the effect of thermal oil based collectors and direct steam generating (DSG) systems can be studied. For DSG systems behaviour the heater and the evaporator are seen as one unit.
In the working cycle the thermal energy of the working medium is used to generate mechanical work. It consists of the following main components:

- Evaporator
- Expansion Machine
- Friction Brake

- Condenser
- Vessel
- Pump

Evaporator and condenser are designed as tube shell exchangers. This design allows a wide variety of temperatures and pressures to be covered with one system. Therefore, they are ideally suited for this application where different working media should be tested.
The test rig allows great flexibility concerning the integration of different expansion machines. A water brake is used to dump the mechanical work generated by the expansion machine. Sensors for measuring the torque and the revolutions per minute are installed. The generated mechanical power can be derived from these values. A combination of two pumps is used to achieve pressures up to 30 bar and to avoid cavitation problems. The cooling loop is filled with a water glycol mixture. It uses a dry cooling system to work as a heat sink for the system. It cools the condenser in order to condense the working medium.

2.3. Working media

The test facility is designed to be used with different working media. Either water or organic substances can be filled into the system. For the first tests water is used, as it has the advantage of not being harmful to the environment and not being flammable. In a later step organic media like Octamethyltrisiloxane (Si3O2(CH3)8)(OMTS) can be used. According to Drescher [6] OMTS promises the highest efficiencies for high temperature Organic Rankine Cycles. In Table 1 the chemical properties of OMTS and water are compared.

Table 1: Properties of OMTS und Water [4, 5]

Medium	OMTS	Water
Formula	$Si_3O_2(CH_3)_8$	H_2O
Molar Weight [g/mol]	236.535	18.015
Boiling temperature [°C]	152.53	99.97
Melting temperature [°C]	-82	0
Critical Temperature [°C]	290.94	373.95
Critical Pressure [bar]	14.6	220.64
Flammability [°C]	34.4	no

The saturated vapour line of OMTS has got a positive slope. This behaviour classifies it as a dry working medium. The expansion of OMTS steam results in superheated steam. By contrast, the expansion of water generates wet steam as the saturated vapour line of water has a negative slope. If a turbine is used for expansion, wet steam erodes the turbine blades. Figure 1 shows a comparison of both media in the temperature entropy diagram.

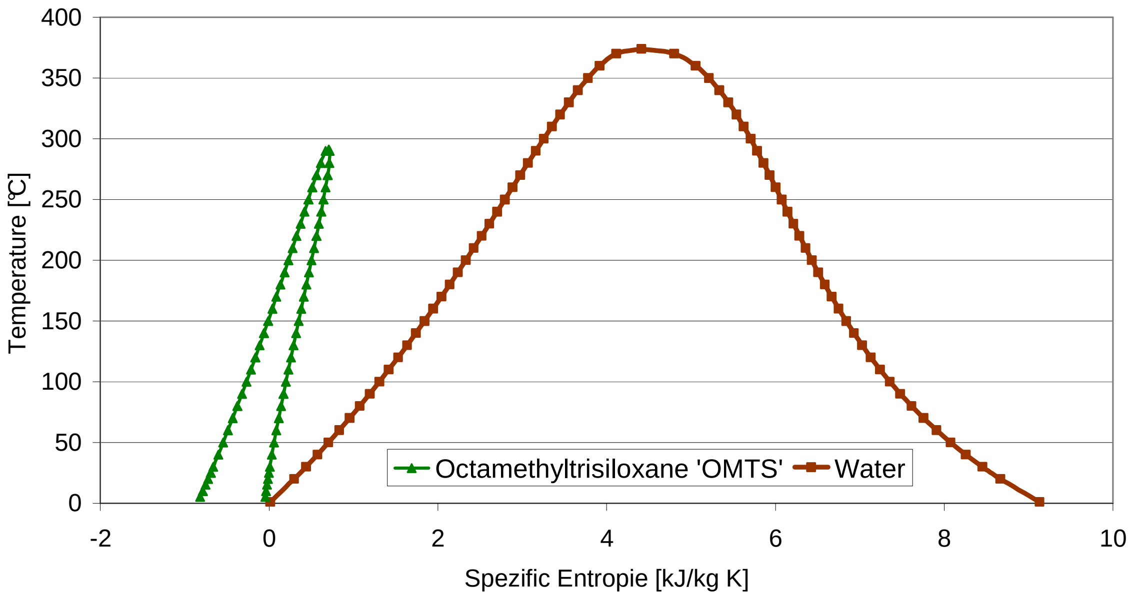

Figure 1: T-s-Diagram of Water and OMTS

2.4. Static Cycle Calculation

In order to design the system a steady state calculation of the steam cycle was performed. For this calculation a simulation tool was implemented containing the properties of OMTS and water. The properties of water at the entrance of the main components (expansion machine, condenser, pump and evaporator) are shown in Table 2

Table 2: Properties of water in the cycle

		EM	CS	P	EVAP
Pressure	[bar]	24.00	1.01	1.01	24.00
Volume Flow	[m³/h]	25.17	595.98	0.32	0.31
Temperature	[°C]	221.80	99.97	99.97	99.97
Enthalpy	[kJ/kg]	2801.54	2801.54	418.96	420.69
Entropy	[kJ/kg*K]	6.27	7.67	1.31	1.30
Density	[kg/m³]	12.01	0.51	958.38	986.66
Mass Flow	[kg/h]	302.41	302.41	302.41	302.41

The calculation results for OMTS are shown in Table 3. It can be seen that the resulting mass flows and pressures for these working media are different. These values had to be taken into account for the design of the facility. For example the heat exchangers, valves and sensors had to be designed to work with both pressures and mass flows.

Table 3: Properties of Octamethyltrisiloxan in the cycle

		EM	CS	CS*	P	EVAP
Pressure	[bar]	7.48	1.00	1.00	1.00	7.48
Volume Flow	[m³/h]	36.34	373.88	305.52	3.23	3.22
Temperature	[°C]	250.00	228.00	152.00	147.00	147.00
Enthalpy	[kJ/kg]	315.00	64.50	151.67	-11.63	-11.40
Entropy	[kJ/kg*K]	0.64	0.66	0.35	-0.02	-0.02
Density	[kg/m³]	60.70	5.90	7.22	682.00	685.00
Mass Flow	[kg/h]	2205.88	2205.88	2205.88	2205.88	2205.88

3. Commissioning of the facility

Figure 2 shows the test facility in the laboratory of Fraunhofer ISE.

Figure 2: Picture of the test facility

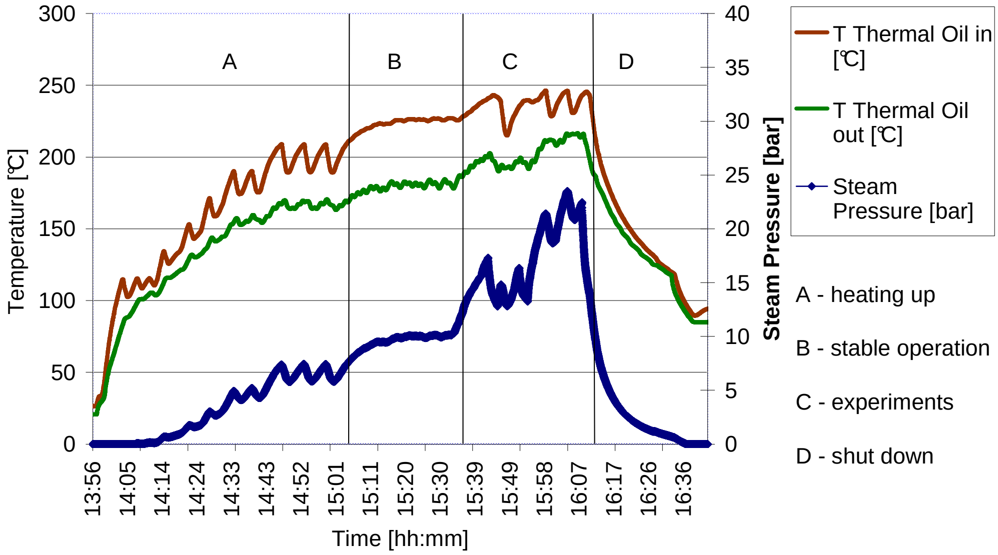

Figure 3: Data plot of the commissioning

Figure 4 shows the measured values for the thermal oil in- and outlet and the steam pressure in the evaporator. In Phase A the system was slowly heated up and checked to be proof. It can be seen that there are still some fluctuations in the thermal oil temperature. Through adaption of the burner controller this problem could be solved. Therefore a step response was recorded in a later experiment to calculate the controller parameters. In phase B stable conditions where reached at 10 bar. After stable operation was achieved the response of the facility was tested for different throttle valve adjustments. Afterwards the facility was slowly cooled down in phase D

4. Conclusion

An experimental facility was designed to emulate the behaviour of concentrating solar collectors. In order to be independent of solar irradiation the facility uses a gas driven thermal oil heater as heat source. Its thermal capacity is 250 kW at a maximum temperature of 300°C. The cycle is designed for pressures up to 30 bar and offers the possibility to use water and organic working fluids. A water brake allows testing a large variety of expansion machines and load profiles up to 40 kW_{el} and 12000 rpm. It will be used to test different expansion machines and working media for small solar polygeneration systems. Additionally the facility may be used for testing and characterization of thermal storage systems, chillers and desalination units. The facility was successfully commissioned and is now ready for testing.

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