Development of Advanced Hybrid Heat Pipe Receivers in Dish/Stirling Systems for Decentralised Power Production

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Abstract

A new low-cost method producing heat pipe capillary structures has been developed in order to reduce one of the main costs in hybrid heat pipe receivers. Controlled open porous layers for new-type heat pipe capillary structures have been produced with radio-frequency plasma spraying (RF-PS). The RF-PS capillary structures show the possibility of low-cost production of capillary structures, not only for heat pipe applications. Refractory metals as well as ceramics have been sprayed using typical heat pipe materials, e.g. nickel based alloys. Porosities of up to 80% have been reached with molybdenum and of up to 50 % with nickel based alloys. Two prototype sodium heat pipes have been built and tested successfully. Up to a capillary height of 400 mm, heat fluxes of more than 100 W/cm^2 could be obtained. With RF-PS capillary structures, costs of hybrid heat pipe receivers could be decreased at least in the range of factor 5 to 10.

A hybrid heat pipe receiver for dish/Stirling systems has been developed, which allows reliable power generation independent on solar radiation. Basic element is a sodium heat pipe, using conventional spot welded screen wick structures with arterial webs. This heat pipe can transfer any power combination from gas and solar input up to 45 kW thermal power with hardly any temperature drop. The power is introduced either through the solar absorber surface and / or over the gas heat exchanger and is transported to the Stirling heat exchanger tubes by the working fluid of the heat pipe (sodium). At the Stirling heat exchanger there is an equal heat flux distribution, improving efficiency and lifetime of the system.

A low emission, high efficiency and high density combustion system for high temperature applications has been developed, adapted to the hybrid heat pipe receiver. It is a lean premix pre-vaporise (LPP) combustor using combustion gas recirculation (CGR) to lower the combustion temperature. To recirculate combustion gases and to mix air, fuel and combustion gases, the system is equipped with an internal ejector driven by the inlet air. For high efficiency an air preheater is used.

An automatic control system has been developed and implemented. Then the hybrid heat pipe receiver has been installed in a dish/Stirling system at Plataforma Solar de Almeria, Spain and tested successfully in all operation modes, solar-only, gas-only and hybrid mode. A total of 360 Stirling engine operating hours have been accumulated.

A study of the market potential for hybridised dish/Stirling units and of adequate sites concerning solar radiation for Morocco, has been performed, showing a huge potential for decentralized power production with hybrid dish/Stirling systems in Morocco.

Partnership

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Objectives of the project

The objective of the project is to contribute to a commercialisation of the dish/Stirling technology that can provide the decentralised power demand of small communities in Mediterranean countries utilising concentrated solar radiation. Key component is the solar receiver which will have to be improved with respect to lifetime and economy, and will have to be hybridised, in order to increase the availability of electric power supply. Therefore, the following three goals are pursued: to develop heat pipe receivers with specially adapted combustion systems for a possible 24 h/d operation; to considerably decrease the investment costs by a new manufacturing method for the wick structure of the heat pipes and to demonstrate technical maturity by a one years routine operation in two dish/Stirling systems at the Solar European Test Centre, Plataforma Solar de Almería (PSA), Spain.

Technical description

WP 1000 / WP 6000 New Type Capillary Structure for Heat Pipes Produced by Radio Frequency Plasma Spraying

Controlled open porous layers for new type heat pipe capillary structures have been produced with radio-frequency plasma spraying (RF-PS) at the DLR-Institute of Technical Thermodynamics. Therefore the radio frequency plasma spray equipment has been adapted to the special requirements of the new process. For the first time a controlled open porous structure with requested pore radii could be obtained with this process. The capillary structures reached are comparable with those of sintered metal powders concerning morphology and porosity. As far as the application of refractory metals is concerned, plasma spraying has several advantages, e.g. higher porosity is possible and sintering becomes very complicated and cost intensive at high temperatures. In comparison with the conventional spot welding of screen metal wicks, RF-PS shows the possibility of low-cost production of capillary structures, not only for heat pipe applications. A cost reduction potential is assumed to range at least from factor 5 to 10.

Refractory metals as well as ceramics have been sprayed using typical heat pipe materials and furthermore, nickel based alloys have been used. Porosities of up to 80 % have been achieved with molybdenum and of up to 50 % with nickel based alloys. Spraying additional filler materials and leaching them out afterwards results in porosities of up to 80 % for nickel based alloys as well. The porous layers sprayed have been characterized with respect to porosity, effective pore radii and permeability.

Two sodium heat pipes have been built up with planar RF-PS structures for the evaluation of capillarity and maximum applicable heat fluxes. Up to a capillary height of 400 mm, heat fluxes of more than 100 W/cm^2 could be obtained. Planar substrates, tubes and tube sections have been coated.

WP 2000 Development of Low Emission High Efficiency, High Density Combustion System for High Temperature Application in Hybrid Dish/Stirling Systems and Co-Generation Units

A low emission, high efficiency and high density combustion system for high temperature applications has been developed at INTERSOL KB, Sweden, in co-operation with Lund Institute of Technology, Sweden. In the beginning of the program, a number of different combustion unit designs were studied. In the final layout it was decided to move the Stirling engine heater tubes to the rear plate of the heat pipe and also having the sodium to flow between the rear plate with the Stirling heater tubes and the rear plate of the solar absorber. This concept had several advantages, the only question was how the different tube length should affect the engine performance. However calculations showed that the minor disadvantage in engine performance was acceptable.

To accomplish the major goal to reach ultra low emissions, the internal and external dividing lines had to be designed in the most leak tight way as possible. Therefore finally it was decided that the only way to get good tightness in the system was to avoid to seal around the hot square Stirling heater tube manifolds. Instead the combustion system was extended with its full outside diameter past the Stirling engines cylinders with holes cut out for the cylinders that could be welded and be completely tight. The preheater studies showed that a circular smaller unit should be the most efficient as well as the most suitable for the design. Experience from earlier reliable units could be used.

A big concern in the combustion system design, is the big heat expansion differences in the material. Between the resting and operation temperatures, the outside diameter at the hottest parts will vary up to 4 mm and even more in the length of the system. When the system is in operation the difference between highest and lowest temperature can be up to 800°C.

The system was first completely built in cardboard and clay, and then full scale in steel. A complete dummy engine was used, to serve as a base for the producing of the combustion system (casting parts without crankshaft, connecting rods, pistons e.g.). A stainless steel water cooled dummy in the heat pipe dimensions was built both to serve as a mock-up unit on the dummy engine as well as a water cooled heat pipe unit at later combustion tests.

- The air preheater is build up of a thin corrugated stainless steel sheet metal band folded to a ring with welded ends and covered on the inside and outside to prevent air from bypassing the unit. Premixing tube length and diameter was based on experience from Lund Institute of Technology. The air-gas ejectors design was not possible to determine completely without testing, they were therefore designed and manufactured in several different dimensions. To get access to, and be able to replace the ejector units easily, the system was designed with a removable plate. The flame holder is built up of different layers of sheet metal arranged so that one layer is waved from a 0.5 mm thick and 10 mm wide band, the waves make the band to be 1,2 mm thick. Next band is flat and to roll these bands 7 layers in each second it will have the opening area that was initial calculated for the actual flow. Also front ducting was changed as a result of the test.

The prototype was tested in the Lund Institute of Technology engine lab substituting the heat pipe with the water cooled heat pipe dummy. Due to the water cooling, system temperatures were considerably lower than expected for the final system, and thus, lacking hot exhausts, the inlet air could not be preheated. This meant that only start-up procedures could be simulated in the prototype rig. However, useful tests of the design could be done, resulting in some combustor redesigning, e.g. it was shown that the annular distribution chamber just upstream the flame holder did not work properly and had to be redesigned to ascertain uniform distribution of fresh mixture to the flame holder. For testing flow distribution in the distribution chamber and in the flame holder, a transparent model was built and a smoke generator used for visualisations, and LDV (Laser Doppler Velocimetry) techniques were used to measure velocity profiles at the flame holder outlet. Also the model was used to test flame distribution on the flame holder in free-burning tests.

WP 3000 Development of Hybrid Heat Pipe Receivers with Conventional Capillary Structure

A hybrid heat pipe receiver has been developed by DLR together with IKE, University of Stuttgart. The development has been based on experiences gained through the development of two solar heat pipe receivers and the manufacturing process and testing of a first generation hybrid heat pipe receiver, which had been developed in a preceding project, funded by the German Ministry of Education, Science, Research and Technology (BMBF). Basic element is a sodium heat pipe, using conventional spot welded screen wick structures with arterial webs. The heat pipe had been designed for a maximum thermal power of 45 kW, it can handle any power combination from gas and solar input, as long as the sum doesn't exceed the maximum power. At the Stirling heat exchanger there is an equal heat flux distribution.

Various concepts have been investigated. In the final concept the power is introduced through the solar absorber surface, which is a cylinder with 210 mm diameter, closed at the bottom by a flat plate. The gas heat exchanger is made up of 400 fins (200 mm long), embedded into the outer heat pipe mantle with a diameter of 360 mm. The heat is transported to the back of the heat pipe, a flat plate at the bottom of the outer mantle, where the Stirling heat exchanger tubes are embedded. Heat transfer calculations for the gas heat exchanger have been performed for different fin shapes, λ-values and CGR-rates. With a λ-values off 1.8 and a CGR-rate of 50% a total power of 30 kW can be transferred through the heat pipe into the Stirling heater tubes at a heat pipe temperature of 800°C and 700°C helium temperature.

The stresses in this new heat pipe container due to thermal and pressure load have been a critical point, where a 2-dimensional finite element stress analysis proved to be not sufficient. Therefore a 3-dimensional analysis has been performed for all load cases, solar-only mode, gas-only mode and parallel mode. Finally a design has been chosen with fins between the two flat plates - absorber bottom plate and Stirling heat exchanger plate - to support them against deformation from thermal stresses and under pressure in the heat pipe.

The connection between engine heads and heat pipe must be able to take up the thermal expansion of the heat pipe at operation temperature. Most of the thermal expansion of the heat pipe will be covered by the flexible gas cooler of the SOLO Stirling 161. The rest will be covered by the connection on the regenerator side, which will be via 20 tubes that lead in two rows into the manifold at the Stirling heat exchanger plate and are equally distributed onto the top of the regenerator housing. The expansion cylinder is stiffly connected to the manifold by one thick duct.

WP 4000 Modification and Fabrication of Electronic Control System for Fully Automatic Operation

The large experience with the different controls developed in the past could be used for the design of a control system for the hybrid heat pipe engine. The SOLO solar Stirling 161 with the PC was used as a basis for the new development. The control system's main parts are a microprocessor controller board located in the stirling unit and a remote PC in the plant control and operator room. Both communicate via the InterBus-S field bus (the dish motion control uses the field bus also). The controller board serves as an intelligent input/output, it transmits motor analog and digital data to the PC and executes the commands from the PC. The heat pipe receiver as well as the new gas burner need some additional and different sensors which require modifications and supplements to the controller.

The factual engine control is performed by the Stirling program code which is executed under a multitasking system in the PC. The burner control including finite state machines and control algorithms had to be developed completely new. For this purpose, the available measurement data and operation experiences from previous heatpipe tests had to be analyzed. Also data from the burner test version at Lund Institute of Technology were used to create the burner control.

The controller board in the stirling unit has to be programmed in assembler due to the restricted resources of the hardware. Main tasks are the communication with the host, acquisition of analog and digital sensors and execution of the host commands. Time critical functions as the helium pressure control are implemented in the controller, they can still be used in the new design. For the case of communication loss an emergency shutdown routine and a simplified solar controller are implemented. The shutdown routine and all I/O functions for the new sensors and actors had to be developed or reprogrammed. The complete host program code is written in Turbo Pascal 7.0.

During acceptance tests at PSA the new flame supervision by thermocouple was successfully implemented in the burner control software. The dish control had to be modified in serveral points to meet the special requirements of the heatpipe receiver. During the first part of the tests, hybrid operation was executed with preset gas mass, the engine pressure was controlled to keep a constant heat pipe / helium temperature (solar operation mode). To run the system in a real hybrid operation with constant power output the gas pressure is kept constant by the pressure controller and the burner has to be modulated to maintain the helium temperature on the preset value. The engine and burner control software had to be modified for this operation mode. Finally, the full hybrid operation could be successfully implemented and tested.

WP 5000 Study of the Market Potential for Hybridised Dish/Stirling Units and of Adequate Sites Concerning Solar Radiation for Morocco

From the presentation of the energy situation in Morocco, the following conclusions have been drawn: the proved national reserves of used classical fossil resources are derisory or already exhausted. So, the role of the national production of these resources, which covers currently 4% of the demand, can only decrease in the future. The Moroccan non-classical fossil resources, that are abundant, that is oil shales, presents economical and ecological obstacles for its valorisation. The reserves of uranium (from phosphates) are important, but their exploitation is hindered by political, ecological and economical conditions. The valorised renewable resources (hydraulic and biomass) are limited, the production potential of hydraulic electricity (for a year with good precipitations) is 4000 GWh, the present demand is about 11000 GWh (1996) and should increase from 5 to 7% a year in the future, because of the current weak consumption by inhabitant, weak rate of territory coverage and the high demographic increase. A more rational utilization would improve the efficiency and output of hydraulic resources, but could not change fundamentally the production capacity.

The sustainable offer of firewood is estimated, under the present conditions, to 1.8 millions of tons (0,75 Mtep). An adequate policy of reforestation and a more rational cut would allow to considerably increase this offer and can even exceed the present demand in forest firewood. The consumption by inhabitant, either primary or electric energy, is derisory and could not allow the wished development. The load curve at its present state, requires an expensive composition of electricity production plants. A rural electrification by network would amplify this characteristic.

On grounds of a national economical balance and of the environmental protection, it is necessary to mobilize the country-abundant resources in renewable energies (solar and wind energy). In order to fulfil the requirement of social equity and of national development, the electrification of rural areas is imperative. In order to avoid increasing again the ratio (peak-load / minimum-load) already too high and not to be limited in this rural electrification to the regions where the extension of the network would be economical, it is necessary to call on the technology of decentralized electricity production.

Depending on the importance of the solar and wind energy mobilization, an adequate impact will occur on energy-imports of Morocco. Taking into account some features of the dish/Stirling technology, the production transfer of a part of the components in Morocco is feasible for the first units. The state of the metallurgical, mechanical, electric and electronic industries in Morocco present good conditions for the realization of a good part of the components in the country. The realization of components in Morocco would reduce transport and production expenses. This transfer will permit the creation of a new job domain in the country. The substitution of a part of the fuels and of equipment imports for the electricity production through national resources and products, will contribute to a commercial balance improvement and will permit to import other products that are also of a big utility to the development of the country. Under these conditions, the modular technologies for the valorization of renewable energies present a promising answer for energy problems in Morocco.

WP 7000 System Integration

Two packagings have been set up completely at DLR. The packaging is divided in the cooling unit on the back side and the main packaging which consists mainly of outer frame of aluminium profiles, engine frame of welded steel sheets, hybrid receiver suspension out of stainless steel profiles, front window frame for ceramic front protection shield and two switch cases for data acquisition and control devices.

The aperture is composed of two ceramic rings and an in-between hold 3mm thick quartz glass window which closes the heat pipe cavity against the ambient to reduce heat losses. The quartz glass window can be removed without making any adaptations. In addition a small shutter will be integrated in the front protection. This shutter can be closed in case of gas only mode to reduce the losses more effectively.

To prevent failures caused by dampness all electric and electronic devices are build in switch cases. The data acquisition switch case (DAS) and the control device switch case (CDS) are completely integrated in the packaging.

After all parts have been tested as far as possible individually, the first hybrid heat pipe receiver has been mounted on the Stirling engine in the packaging. Then the unit has been installed in the test cell at a lab of DLR, where a Propane gas supply had been installed. All necessary connectors as well as security installations had been prepared. 66 sensors have been installed on the receiver/engine unit.

Function testing of the unit in the lab at DLR has been done between June and November 1998. The combustion system has been operated for approx. 110 hours in the lab, with 85 hours of engine operation and 140 hours with heat pipe temperatures above 100°C. The burner power could be controlled between 3 kW and 27 kW. System efficiency of 17% has been reached at 4,1 kW gross power output.

During lab tests in Stuttgart several investigations and modifications have been done, like the determination of an air/fuel parameter field for combustion system control, determination of start-up procedure and emission measurements.

As preparation for field testing a flap has been installed infront of the aperture, to reduce heat losses in gas-only mode, a melting wire has been installed into the aperture, to avoid any damage to the receiver in case of tracking problems, a preheater by-pass has been installed for excess heat rejection at insolation levels higher than 800 W/m² (dish is oversized for higher yearly output), and all parts related to the gas supply system have been included in the gas switch case.

WP 8000 Assembly and Installation on PSA

A small cabinet has been installed beside the Dish to have a better view and control of the system. Because of the elevated length of the power conversion unit and it´s positioning at a longer lever arm, the structure of the ‘dishes’ had to be reinforced by welding counter weights at the opposite side of the concentrator. Additionally the ‘dishes’ were equipped with a more powerful servo motor for the elevation axis.

A gas supply system has been installed by a local company, implying a tank with a capacity of 2450 l and a distribution system of copper tubes from the tank to the switch cases at the north side of each dish. New cables had to be installed to connect the ‘Integrated Measurement Pods (IMPs)’ to a new data acquisition computer, which is used for the heat pipe testing. The necessary signals from GPS and meteo station were attached and proved.

A second control system for two dish/Stirling systems had been installed and operated in parallel to the existing system of DISTAL II. The dish’s security system had to be adapted, to avoid immediate stowing of the dish after a detrack, which is not allowed because of the high thermal inertia of the heat pipe receiver.

WP 9000 Demonstration Testing of Two Systems

After lab tests have been finished on November 2, 1998, the packaging including the data acquisition and control PC has been prepared for transport and was transported to the PSA. Installation of the system and start-up procedures have been performed by DLR with support by CIEMAT.

During gas-only start-up the system was still operated with „semi automatic“ burner operation, where the gas mass flow had to be pre-set at the control PC and the control uses the air/gas parameter field to control the respective air flow.

Tests in solar-only mode started Dec. 4, 1998. During the first tests in solar-only mode the tracking position still had been adapted. Then the by-pass control for high solar insolation levels had been tested and control parameters adapted. The maximum power output was 7.6 kW at 600°C operating temperature of the Stirling and a maximum engine pressure of 150 bar. Total efficiency was 15,5%.

First test in hybrid mode was done on 24th of January 1999, where the combustor was still controlled with pre-set gas mass and the engine pressure was controlled to keep a constant heat pipe / helium temperature (solar operation mode). Then the hybrid control was implemented, where the burner power has to be modulated to maintain the engine pressure and with that the power output on the pre-set value at constant helium temperature.

Fully automatic routine operation was not possible, due to flame instabilities in the combustion system. After lab tests the burner operation looked very promising. Stable operation was possible over several hours, occasional flame losses caused no problems, because the system could be started again without problems. During start-up period at PSA, though, burner operation deteriorated and the following problems occurred: Air/gas ratio has increase probably due to leaks in combustion system, flameholder was getting too hot at certain loads, flame was uneven over circumference of flameholder.

Nevertheless the combustion system has proven its function in all modes and all problems seem solvable. Further extensive tests in the lab and several hardware adaptations would be necessary though, which were not possible to do during the course of the project.

WP 10000 Evaluation and Documentation

On the Plataforma Solar the system has been operated on 76 days between Nov. 14, 1998 and June 21, 1999. Total operating hours for the engine are 265 hours, wherefrom 92 hours were gas-only mode, 117 hours were solar-only mode and 56 hours hybrid mode. The combustion system has been operated for 397 hours including start-ups. Including lab hours the total operation hours on the engine are 360 hours and on the combustion system 507 hours. In gas-only mode maximum power output was 4,1 kW. System efficiency of 17,7 % has been reached with helium temperature of 640°C and 16,6 % with helium temperature of 600°C. In solar-only mode maximum power output was 7,8 KW, maximum efficiency 16%. In hybrid mode the highest hybrid efficiencies lie between 15 and 16%.

During field testing at PSA, operation temperature of the Stirling engine was always kept at 600°C instead of 700°C, because of a damage that occurred during lab testing, where an aluminum ring around the quartz glass window had molten and flown onto the absorber surface, attacking the material. As a precaution, the maximum temperature had been limited afterwards, reducing of course Stirling engine performance and therefore total efficiencies.

Heat pipe temperatures where no heat flux is applied are approx. 110°C above Helium temperature. At the combustor flameholder temperatures have been between

650 and 750°C,. premixed gases in the premixing tubes lie between 550 and 600°C. Flame temperture right behind the flameholder was approx. 800°C, combustion mantle temperatures behind the flameholder were between 800°C and 950°C. In solar-only mode absorber temperatures are approx. 220K above He-temperature (820°C).

Stirling parasitics are made up of control unit, cooling water pump, cooling fan, burner ventilator and ventilator for by-pass control in solar-only mode. For gas-only mode this sums up to 674 W parasitics at 24,7 kW burner power. The gross power output is 4,1 kW, resulting in a total gross efficiency of 16,6 % and a total net efficiency of 13,9 %. For solar-only mode parasitics are 374 W without by-pass and 424 W at maximum solar insolation. Approx. at gross power output of 7,3 kW the by-pass is opened. At that point the total gross efficiency is 15 % and the total net efficiency 14,3%. In hybrid mode the maximum burner ventilator parasitics are 400 W. Dish parasitics (drives and vacuum pump) are approx. 250 W average value over a day.

Dish reflectivity before cleaning on 25.02.99 was approx. 80%, after cleaning approx. 90%. Reflectivity has been measured again on 22nd of June 1999, showing still a value of approx. 87,5%. With this the dish efficiency was approx. 67% before and 75% after 25.02.99.

The receiver efficiency has been determined with and without the quartz glass window infront of the aperture. Assuming 28% Stirling efficiency and 90% generator efficiency, the receiver efficiencies are $\eta_{Receiver}$= 90% with window and $\eta_{Receiver}$= 81% without window.

Cooling water inlet temperature into the Stirling engine was approx. 25 K above ambient temperature at full load. Temperature between cooling water outlet and inlet of engine was typically between 10 and 12 K. Oil temperature was around 80°C. A difference of 10 K in cooling water inlet temperature makes a difference of 1,5 percentage points in efficiency.

Performance characteristic of the preheater is 83%. Exhaust outlet temperatures after the preheater are only up to 140°C, the air is preheated to approx. 570°C.

Over night the flap was always closed, to reduce heat losses. Therefore after 12 hours non-operation, the heat pipe temperature was well over 100°C the next morning, unless there was no operation the day before. Therefore start-up procedure to melt the sodium was not necessary.

Several minor failures occurred during the test period. One major failure occurred after a grid failure around noon, where the system was running at full power in solar-only mode. This caused overheating of the engine, because cooling water evaporated very quickly, and the vapor was blocking the cooling flow after the pump was working again. For repair several seals at the engine cylinder had to be exchanged.

Results and Conclusions

Result No. 1: Dish/Stirling system 10 kW_{el} with metal membrane concentrator and advanced Stirling engine - owned by SBP

A Dish/Stirling for decentralised solar power generation was developed over a period of 10 years. The main features are:

- stretched metal membrane concentrator 8.5 m in diameter with high optical quality and durable thin glass mirrors as reflective surface.
- Turntable suspension for maximum stability at high wind load.
- Highly reliable 10 kW_{el} kinematic Stirling engine which has matured during 15 years of development.
- Tube type standard receiver available, hybrid heat pipe receiver under development.
- Fully automatic system operation using industrial field bus technology, remote control via WWW under development.

3 generations of 10 kW_{el} Dish/Stirling systems have been developed and tested. More than 34,000 operation hours (1/99) have been accumulated, being the most extensive operation experience in Dish/Stirling world wide. The system development is going on with the target of further cost reduction and the implementation of a remote control via WWW. The 10 kW_{el} Dish/Stirling system is currently undergoing a last development step to reach maturity for small series production and to reduce system costs.

Result No. 2: Hybrid Heat Pipe Receiver for collection and transfer of solar and/or combustion heat and heat exchange to Stirling engine - owned by DLR.ITT

The hybrid heat pipe receiver is a key component of dish/Stirling systems, which makes them operable independent of solar incidence. It allows

- utilisation of solar and /or combustion heating for electricity generation, thus improves system availability
- independent design optimisation of solar and combustion heating, and engine heater head, thus improves system efficiency and lifetime.

World-wide, as known, all work on hybrid heat pipe receivers is at R&D and prototype level, like our own work.

The second generation hybrid heat pipe receiver developed and manufactured within this project has been tested extensively on a SOLO Stirling 161 engine in the laboratory and in the field in a parabolic dish system. It has demonstrated successfully all operation modes - solar-only, combustion-only and parallel mode of solar and combustion. Even cloud passages could be covered without problems, producing a smooth and constant electric power output.

Result No. 3: Low emission combustion system with high density and high efficiency for high temperature application - owned by Intersol

A low emission, high efficiency and high density combustion system for high temperature applications has been developed. It is a lean premix pre-vaporise (LPP) combustor using combustion gas recirculation (CGR) to lower the combustion temperature. To recirculate combustion gases and to mix air, fuel and combustion gases, the system is equipped with an internal ejector driven by the inlet air. For high efficiency a preheater is used. The potential of the system is for world wide use of small scale energy production not only in combination with solar energy but also for co-generation with various fuels.

The concept was tested on a United Stirling V160 engine. It has been proven to work well, and emission data are encouraging. NO_x emissions can be held well below 0.5 g/kg fuel, with methane equivalent hydrocarbon emissions between 0.1 and 1 g/kg-fuel. One remaining task is to lower carbon monoxide emissions, which now are in the range 5 - 10 g/kg fuel.

A prototype for the hybrid heat pipe receiver has been manufactured and both lab tests and field tests have been performed with the heat pipe. The low-emission combustor has been tested in gas-only as well as hybrid mode.

Result No. 4: Control system for a hybrid stirling engine including motor management and burner control - owned by SBP

A microprocessor based control system was developed with the following features:

- single board controller with additional inputs located in the stirling engine.
- ability for remote control by PC via InterBus-S.
- stirling motor management with working gas temperature and pressure control.
- gas burner operation with gas and air control.
- error detection and treatment for all components.
- comfortable and flexible control software using finite state machines.
- integration into the complete Dish/stirling control system which is able to run up to 16 units from a single PC.

The present development was extensively laboratory tested. One unit was installed on the Plataforma Solar de Almeria and was under test operation from Nov. 98 until June 99. Adaptations and improvements during the test phase resulted in a stable and reliable function of the control system satisfying all requirements.

Result No. 5: New type capillary layer production - owned by DLR.ITT

By using of adapted equipment production parameters and powders it became possible to produce controlled open porous capillary layers and structures by means of RF-plasma spraying (RF-PS). The method has a high potential for the automatic production of porous and also dense components at very low costs, provided the design of the product is laid out corresponding to the properties of the manufacturing process.

The principal suitability of the RF-PS method to produce capillary structures was demonstrated with samples of simple geometry. Now, porous layers for geometry's more relevant to heat pipes have to be developed.

Conclusions

Feasibility of producing heat pipe capillary structures by radio-frequency plasma spraying (RF-PS) has been proven. Controlled open porous layers for new-type heat pipe capillary structures have been produced and first heat pipe prototypes built and tested. The results are very promising. This production method is also suitable to produce porous structures for other applications, like gas distributing substrates for solid oxide fuel cells. Further development is necessary to get sufficient information performance of different stuctures.

The combustion system functioned well in the beginning, proving feasibility. NO_x-emissions were very low, but other emissions are still too high, which is probably just a consequence of some geometric discrepancies. Further development is necessary to improve flame stability and emissions, and to avoid degradation problems.

The heat pipe function has been demonstrated in all operation modes without problems.

Sucessful testing of the complete hybrid dish/Stirling system could be performed in all operation modes, though not in the intended scope due to problems with the combustion system. Nevertheless sufficient test data has been collected, and the points for improvement could be identified. Automatic control system functioned very well.

Exploitation plans and anticipated benefits

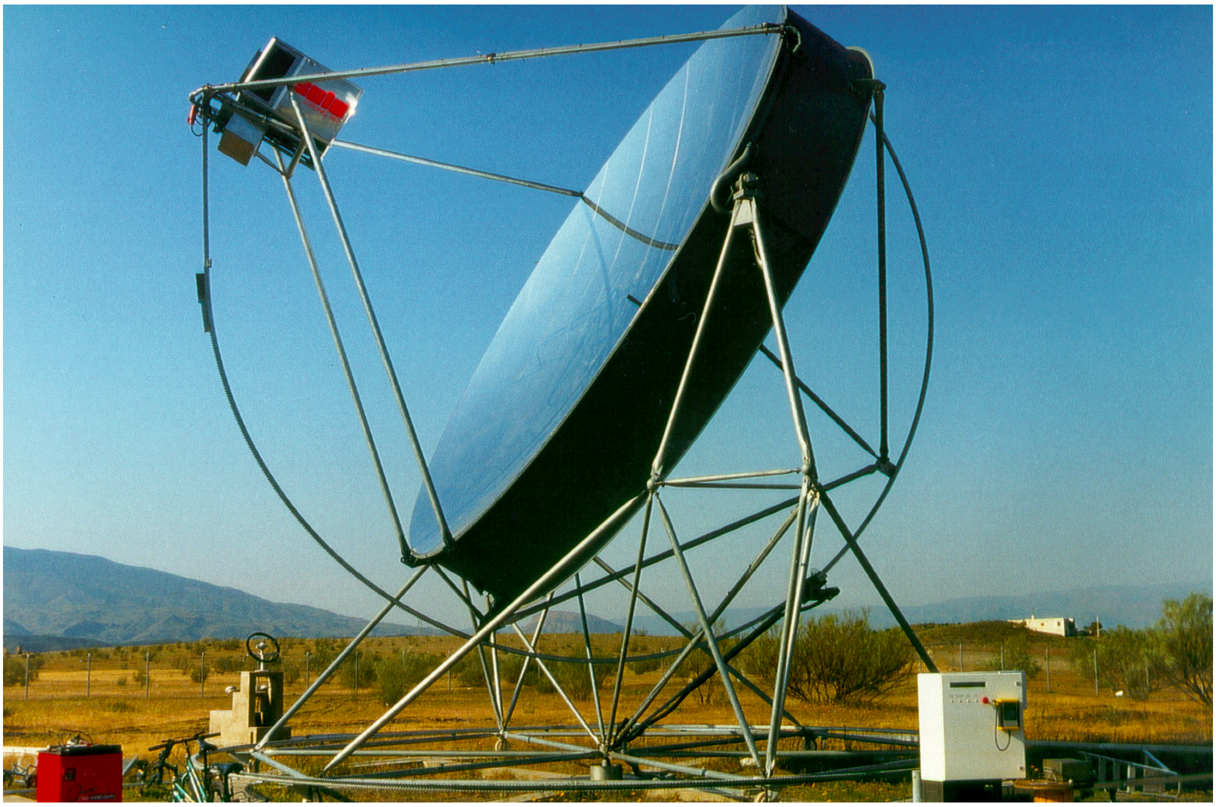
The industry involved in this project intends to commercialise hybrid dish/Stirling systems for decentralised power production in the sunbelt. A potential market are Mediterranean areas like Morocco, as there are many small communities without any connection to the electric grid. Substituting Diesel engines for electricity production or animal-powered water pumping, the total required power will amount to at least 5 GW for the Southern Mediterranean countries. Assuming 5000 hours (hybrid) operation per year, this will result in a considerable reduction of CO_2 (20 million to per year) corresponding with avoiding costs between 500 million and 1,5 billion DM. The economic forecast is reliable, as 9 dish/Stirling units have been built in Germany and operated for several years. The operating hours for DISTAL 1 and 2 (6 parallel running dishes at the Plataforma Solar de Almería) accumulate to nearly 30 000 hours. The expected forecast for the costs of the first 100 items are 14 000 DM/kW, decreasing to 3 200 DM/kW for a series of 10 000/year.

One important social goal for Morocco (and this is valid also for many other North African states) is to extend and update the agriculture. Hybrid dish/Stirling systems could replace old Diesel engines and the new ones which have to be installed. They will become competitive when 1000 items/a (10 kW) are produced.

There exist two further important applications which can be utilised in all countries: low emission burners for co-generation units and new and cheap capillary structures for heat pipes produced automatically by the high frequency plasma spray technique for heat pipes which are used for space crafts, nuclear power plants and industrial process heating. This technique has also been developed within this project.

The low emission burner for different fuels coupled with a Stirling engine developed in this project is a key element for a future increasing market of co-generation industries. There are already 7 demonstration units (10 kW each) being operated in Baden-Württemberg/Germany, with approx. 50.000 accumulated operating hours. Further 13 items will be installed in Germany. Also big electric power suppliers show interest, as these units can also be used in the gas off-take stations of pipelines to provide heat to prevent the gas cooling down due to the gas pressure expansion from 160 to a few bars. A first demonstration unit has well proven at the RHENAG (Rheinische Energie Aktiengesellschaft). The market potential[1] of co-generation units even in Baden-Württemberg until the year 2010 is more than 20% of the expected electricity consumption (> 60 TWh/a) what results in an approximate 7% saving of primary energy and an avoided emission of CO_2 by some million t/a.

Photograph



[1] Wirtschaftliches und ausschöpfbares Potential der Kraft-Wärme-Kopplung in Baden-Württemberg Study on behalf of the Ministry for Economy, co-ordinated by the division „System Analysis and Technology Evaluation", DLR, Stuttgart (1991).