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DESIGN AND OPTIMIZATION OF A CERAMIC SOLAR HEAT EXCHANGER FOR OPEN BRAYTON CYCLES

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ABSTRACT

Design, optimization and technology of a ceramic solar heat exchanger are presented, with regard to three basic points : optimal working conditions for the thermodynamic cycle, optimization of a jet type air ceramic heat exchanger and basic features of the final ceramic design.

KEYWORDS

Solar heat exchanger, ceramic heat exchanger, high temperature heat exchanger, Brayton cycles.

1. INTRODUCTION

Previous solar energy conversion system studies, carried out by BERTIN & Cie (1) and other laboratories (2) (3), concluded on the necessity of using gaseous thermodynamic fluids in Stirling or Brayton Cycles ; that means novel heat exchanger technologies which can withstand both elevated temperatures and thermal fluxes.

The present paper deals with a new high temperature solar heat exchanger (HT SHE) designed by Société BERTIN & Cie. Two original features allow maximum heat transfer efficiency :

- the use of a new ceramic material, made by Société CERAVER, viz. Silicium Carbide α (SiCα),
- the obtention of high heat transfer conductance through the optimal design of impingement convective heat transfer systems (6).

The paper concludes with the prototype development program which was jointly prepared by CERAVER and BERTIN & Cie.

2. THERMODYNAMIC OPTIMIZATION OF THE SOLAR CONVERSION SYSTEM

This study is described in details in Ref. (1) and (4). Because of its lower technological complexity, an open air Brayton cycle was retained for the design study with a 30 kW HTSHE unit ; the focusing system could be an extension of the paraboloid module developed by CREUSOT-LOIRE and BERTIN & Cie (5).

3. HEAT EXCHANGER DESIGN

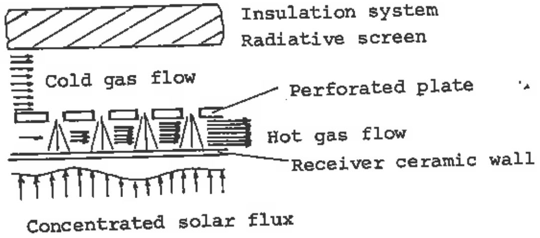
3.1. Basics

The design of the HTSHE is based upon two basic principles :

- to minimize heat exchanger surfaces and therefore mechanical problems related to ceramic technology,
- to minimize local heat exchange coefficients so as to increase overall heat conductance.

Fig. 1 describes the proposed system. It uses both radiative and convective heat exchange modes. The ceramic walls of the receiver system radiate toward perforated plate(s) placed around the receiver. The gaseous fluid entering the heat exchanger is progressively heated up through successive impingements on the various perforated plates and the receiver ceramic wall. After passing through the whole receiver unit, it is sent toward the turbine to expand and thus to provide net shaft power.

Fig. 1
HTSHE detail



3.2. Sizing methodology and results

A mathematical model of the above unit, described in (1), is used to study the influence of the main parameters. Ref. (1) and (4) give a full description of the results obtained today. To summarize, one must retain the following conclusions :

- overall efficiency can reach 0.25 to 0.35 depending upon maximum cycle temperature and allowable pressure drop,
- at a given pressure drop, the most important parameters are the open area of the perforated plates and the impingement distance.

4. SOLAR HEAT EXCHANGER TECHNOLOGY

4.1. Basics

The basic HTSHE is made of the following subsystems :

- a spherical receiving dome,
- a perforated spherical dome which allows for air jet distribution prior the impingement heat transfer,
- an upper module which distributes "cold" air above the perforated spherical dome,
- a cold air distribution system,
- a hot air collector system,
- an annular support module which allows for assembling of the various modules.

4.2. Functional assignments of the various modules

4.2.1. Receiver dome

It insures heat transfer by conduction of the concentrated-solar incident flux. It is the mechanical element which is by far the most stressed, both mechanically and thermally :

- maximum surface temperature around 1 400 °C (to take care of possible overheating problems due to errors of the solar flux control system),
- low material thickness (a few millimeters) to minimize heat conduction losses,
- very high differential pressure (around 3 bars) between the inside module and the outside,
- minimum leak-off flow rates.

4.2.2. Perforated dome

This subsystem is much less mechanically and thermally stressed (temperature around 1 200 °C, differential pressure around 0.5 bars). It is aimed at distributing air jets around the receiver dome : open area around 1 % have been chosen so as not to interfere much with its mechanical integrity. Furthermore, it yields good jet density with no side effects. Finally, jet diameters around 2 mm are taken to obtain initial subsonic velocities for the jet and to allow for an easy fabrication process.

Potential leakage problems must be stressed when coupling the receiver dome with the perforated and insulation dome. In the present design, it is thought that the use of ceramic wool (like ICI alumina fibers) could be helpful to keep local tensile stresses at a low level.

4.2.3. Insulation dome

This piece of equipment supports high differential pressures, viz. 3 bar. Its thickness is not however a critical parameter, since insulation properties of the heat exchanger upper part must be good. A comparative study of metallic and ceramic insulation dome was carried out : the ceramic version was retained to minimize thermal expansion problems between the various domes.

4.2.4. Annular support module

This piece of equipment allows assembling of the various dome bases, with sufficient rigidity and minimal flow rate losses. Furthermore large temperature gradients are present within the support because inner portions are tied to hot parts of the heat exchanger, whereas outer parts lie in ambient air. The chosen material should therefore be characterized by expansion properties compatible with other dome materials.

4.2.5. Flow arrangements

Cold air is introduced through separate piping systems which are positioned around the dome structure. This system allows for correct air distribution within the upper dome volume with no preferential trajectory.

Hot air is picked from a unique pipe at the top of the heat exchanger. Such a configuration minimizes heat losses from the hot air collector system.

4.3. Material choice procedure

4.3.1. Ceramic parts

Preliminary calculations carried out by BERTIN & Cie and CERAVER corroborate other studies (2) (3) : Silicium Carbide is the best present ceramic material which can be made within a quasi industrial environment. CERAVER SiCα is characterized by :

- very good mechanical properties at elevated temperatures (1 500 °C),
- no oxidation risks with air at high temperature,
- good thermal shock resistance,
- almost proof-leak material (98 % of theoretical density with vitrified surfaces),
- good thermal conductivity and emissivity,
- good overall fabrication energy balance (by comparison with, say, Silicium Nitride),
- full availability of raw materials needed by CERAVER within the fabrication process.

Finally, it must be pointed out that the insulation dome can be made of standard refractory alloys which can withstand temperature around 1 000 °C in quasi stressless environments.

4.3.2. Prototype design and fabrication process

The final BERTIN & Cie-CERAVER design is shown on fig. 2. Original fabrication steps are proposed by CERAVER. For all the modules involved, they are :

- isostatic pressing followed by nitriding : this latter step is facilitated by the spherical geometry (16 % loss on radial sizes)),
- leak proofing improved by machining the pressed modules before nitriding on the annular surfaces. A better surface aspect should minimize leakage problems. However, a leak behavior study in hot environment is still needed to take care of eventual prohibitive flow rate losses.

The front face insulation system was not extensively studied. Complementary works are needed to model radiative balances within the black body like cavity and to develop low weight insulation systems.

Last, but not least, it must be stressed that the present design comes from a compromise taking account of :

- actual CERAVER fabrication capabilities,
- the deliberate choice of using parabolic dishes as focusing systems,
- the flux distribution that can be expected from them,
- the existence of both compressor and turbine that have good mechanical efficiencies.

Any change in the above criteria would necessarily lead to different designs, both in terms of resulting mechanical power and/or heat exchanger configurations.

5. CONCLUSIONS

A complete iterative analysis of a high temperature ceramic solar heat exchanger is presented. It is the result of cooperative work between CERAVER (the ceramic manufacturer) and BERTIN & Cie. A prototype design is described with respect to the major constraints which are considered, viz. CERAVER fabrication capabilities, the solar focusing system and its induced unit thermal power (30 kW). Overall efficiencies between 0.25 and 0.35 can be expected.

A prototype development program has been set up which includes :

- final optimization study,
- fabrication of a cold ceramic module to test leakage properties, mechanical behaviour under pressurized cold air flows,
- fabrication of hot ceramic heat exchangers to extensively test their properties in solar environments.

CHAUDIERE SOLAIRE CERAMIQUE

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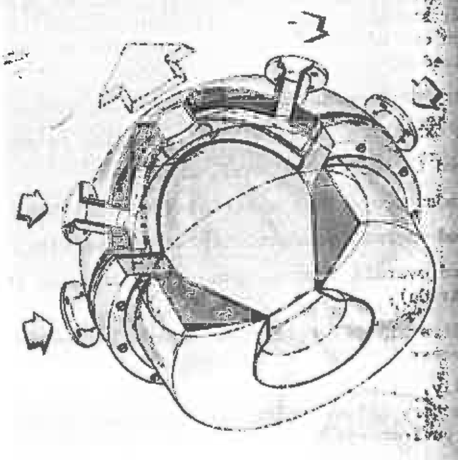

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PHASE-CHANGE THERMAL STORAGE FOR SOLAR ELECTRIC POWER GENERATION

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ABSTRACT

A computer model has been developed to describe the dynamic response of a thermal energy storage unit operating in the range 516 - 584 K using a solid-liquid phase-change storage medium, and a passive tube-intensive heat exchanger. A sub-scale research experiment has been designed, constructed, and tested with two non-phase-change heat transfer oils for charging and discharging heat. Experimental data have been obtained for several charging and discharging modes including repetitive cycles which simulate a solar cycle. Correlations of data with predictions of the computer model show the latter to be a useful tool for the design of thermal storage units of this type.

KEYWORDS

Solar power generation; solar total energy; energy storage; thermal storage; phase change storage media; computer model; research experiment; data correlation; heat exchanger.

INTRODUCTION

Solar total energy systems whose purpose is the delivery of heat for electric power generation and other end uses, such as space and water heating, and air conditioning, usually require thermal storage to make them independent, to some degree, of the solar insolation.

Many concepts for thermal energy storage (TES) using PCM have been proposed. For example, Ref. 1 lists more than forty, including the tube-intensive passive heat exchanger, encapsulated PCM, direct contact heat exchange between a heat transfer fluid and the PCM, and active heat exchangers which scrape solid PCM from heat exchanger surfaces. None has yet been carried to the stage of commercial demonstration. The tube-intensive passive heat exchanger is expected to be among the most cost-effective and to entail the least developmental risk.

The work reported here describes a "sub-scale research experiment" on a tube-intensive passive TES subsystem for use in a solar total energy system operating in