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ACTIVELY-COOLED GRAPHITE TITES SOLAR THERMAL ENERGY COLLECTOR

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ABSTRACT

A conceptual design of an alternative thermal solar energy collector is discussed.
This envisages a collector design with actively-cooled form-locked graphite blocks (or tiles).
In this paper as an example of a mathematical analysis has been carried out for the use of such collectors in solar power plants.
The concept has been thermally analyzed with a finite element model exposed to a high intensity of radiant surface heat flux. Water is seen as the coolant. Results are presented.
Preliminary feasibility analysis demonstrates that the actively-cooled form-locked graphite tiles collector could be an attractive alternative to other commercially-available solar thermal collectors.
It offers the opportunity to perform as a thermal energy generator in solar power plants. It is also equally suitable to serve as a solar thermal energy absorber to warm up any fluid, e.g. water for domestic and/or industrial applications

KEYWORDS: Nuclear fusion, Actively-cooled, Graphite tiles, Form-locked, Finite element, Efficiency

1. INTRODUCTION

An alternative solar thermal energy collector concept is shown in Fig. 1. The concept was originally introduced for application as heat shields in thermo-nuclear fusion experimental reactors [1, 2].

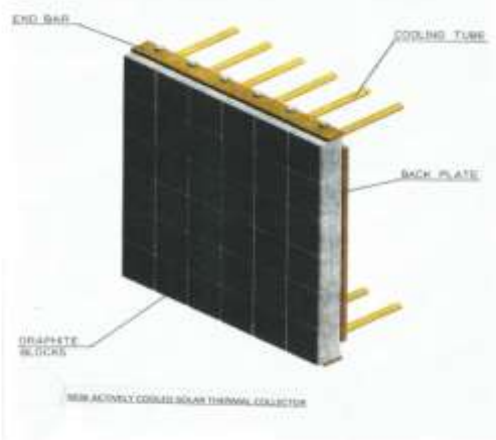

Fig. 1: A radically new solar thermal collector concept

It consists of fine-grained graphite blocks or tiles. Each tile has a shaped semi-circular slot. The tiles are assembled by sliding them over cooling tubes, welded onto a steel back plate, thus forming a complete plane wall.

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In older designs, as shown in Fig. 2, the graphite tiles were mounted onto a water-cooled steel plate, using spring and bolt mechanisms to give the initial contact pressure. The tiles were thus indirectly cooled.

During incoming heat load, the tiles tended to separate from the plate due to their respective thermal expansion mismatch. The gap to the contact surface thus increased, and so the thermal resistance. This resulted in high temperature rise in the tiles and radiation heat losses.

However, in the design proposed here, detailed in Fig. 3, since the individual rectangular tiles (or blocks) are mounted right on the cooling tube the tiles are now directly cooled.

The contact pressure between tile and tube is created by the combination of inward thermal deformation of the tile (due to differential thermal expansion within the tile due to the temperature gradient across the tile), under the penetrating single sided surface heat flux, and of thermal expansion of the cooling tube. This locks the graphite-tile in place -a configuration known as "form locking", as shown in Fig.4. The graphite-tile is thus actively-cooled once the configuration is exposed to the heat flux.

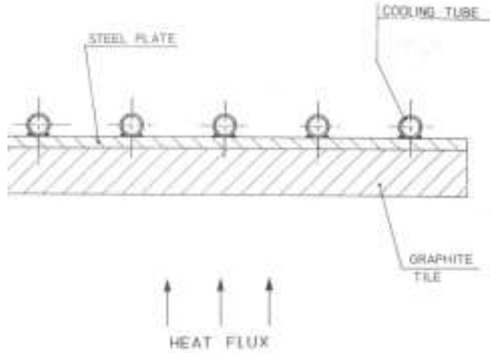

Fig. 2: Older design - indirect cooling of graphite tile

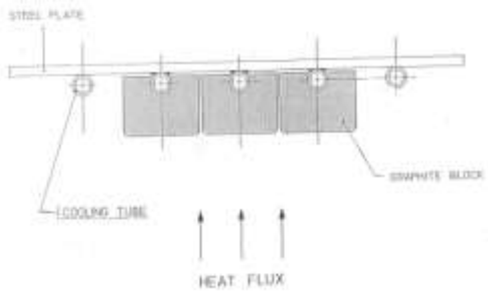

Fig. 3: New proposed design - direct or active cooling of graphite tile

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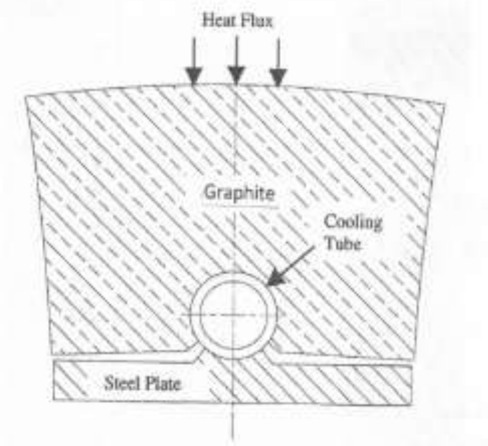

Fig. 4: A form-locked graphite tile (exaggerated thermal expansion)

The higher the surface heat flux, the more effective will be the "form-locking" with reduction of gap resistance at the interface between the tile and the tube. This is a self regulating system, depending on surface heat loads on the tile.

For power generation, the radiant flux density on the solar panel surface can be boosted. The operating limit for fine grain graphite tiles is below 2200 ˚C.

This actively-cooled graphite tiles solar thermal energy collector should be useful
- to produce warm water for industrial or domestic use
- to produce distilled water out of sea (or waste) water
- to generate high temperature steam for power plants.

A modified version of the actively-cooled tiles have already been experimentally tested with ultra-high intensity loads. For the tiles, CFC (Carbone Fibre Composite) material was used. The cooling tube was made of pure copper (OFHC). Water was used as a coolant. The experiment was successful, and the results have been published [3, 4].

The confidence given by this experimental evidence now makes it ripe for development for use in the solar energy field.

2. MATHEMATICAL MODEL

The schematic of the Finite Element model is shown in Fig. 5. All numerical computation is performed with the ANSYS code [5] in 2D geometry, using 8-node thermal solid elements (PLANE77).

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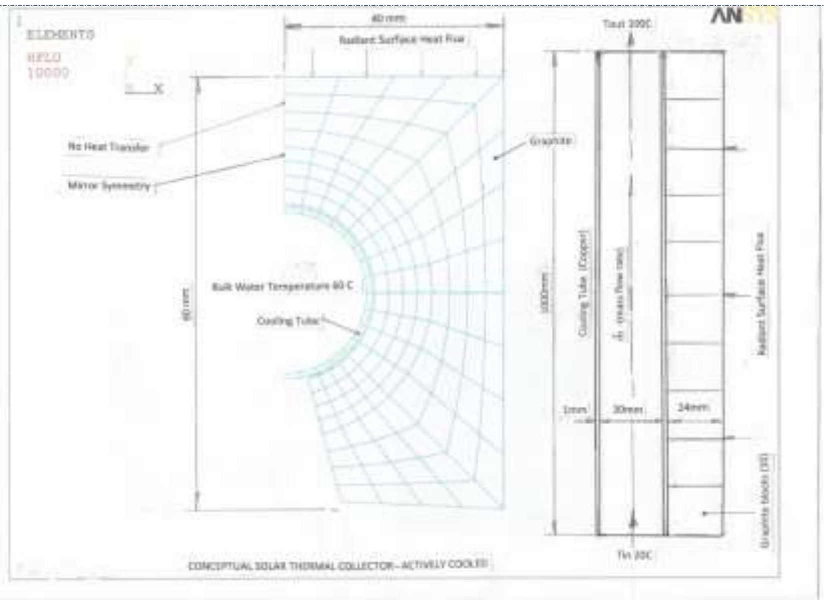

Fig. 5: Mathematical model for thermal analysis of an actively-cooled graphite tiles collector

In the model the properties of high-temperature fine-grain graphite tiles, IG-43, are used with temperature-dependent thermal conductivities.

For the cooling tube, the properties of pure copper, OFHC (Oxygen-Free High Conductivity), are used with temperature-dependent thermal conductivities as well.

Sliding contact is assumed at the tile-tube interface. Link elements (LINK32) for 2-D Conduction Bar are used to simulate the gap between tile- and tube. The conductivity of a link element is so chosen- as to give an approximated value of gap heat transfer coefficient of 500 W/m²K [6] for this conceptual feasibility analysis.
Water is taken as a coolant in the analysis. But any other suitable fluid can eventually be considered as an alternative coolant in the application listed in section 1.

To estimate the amount radiant surface heat load the following assumptions are made:

- The surface of the graphite tiles collector remains flat for any operation. All incident solar rays are normal to the collector's surface
- No thermal radiation heat lost from the surface of graphite tiles (this is an ideal, whose effectiveness will be discussed below)
- The sky is cloudless and no wind is blowingInitially the temperature of the solar thermal collector is
- uniform at 20° C; i.e. the tile is not initially form-locked to the cooling tube
- As shown in the conceptual model (Fig.5) the cooling tube is 1000 mm long with inlet water temperature is 293 K (20 °C) and the outlet temperature is taken as 373 K (100° C), (although it could be higher for the other applications mentioned)
- With the ambient air pressure of 1.0 bar, there should be no pressure drop of the coolant within the tube due to friction
- Suitable-sized reflectors can be used to boost the radiant surface heat flux by multiple factors

Using the above mentioned assumptions, a heat load of 10,000 W/m² on the collector surface is then chosen for thermal analysis.

A convection heat transfer coefficient (h_f) from tube to water is calculated from the Nusselt numbers (Nu_o) [7]:

$Nu_o = 4.364+0.0722$ Re Pr D/L, for developing laminar flow with Reynolds number (Re) < 2300 and this gives
<u>h_f = 126.13 W/m²K</u>.

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3. RESULTS AND DISCUSSION

A steady-state thermal analysis has been carried out for the actively-cooled graphite tiles collector at an average position where the bulk water temperature is 333 K (60° C).

Fig. 6 shows the temperature distribution through the collector with a radiant surface heat flux of 10,000 W/m².

Although the radiant loads are transient in nature, from sunrise to sunset, an entire time-dependant analysis is beyond the scope of this paper. Since the sun is radiating quasi- constant energy when it attains its peak position, and stays there for a while, a steady-state analysis gives a good indication for feasibility purposes.

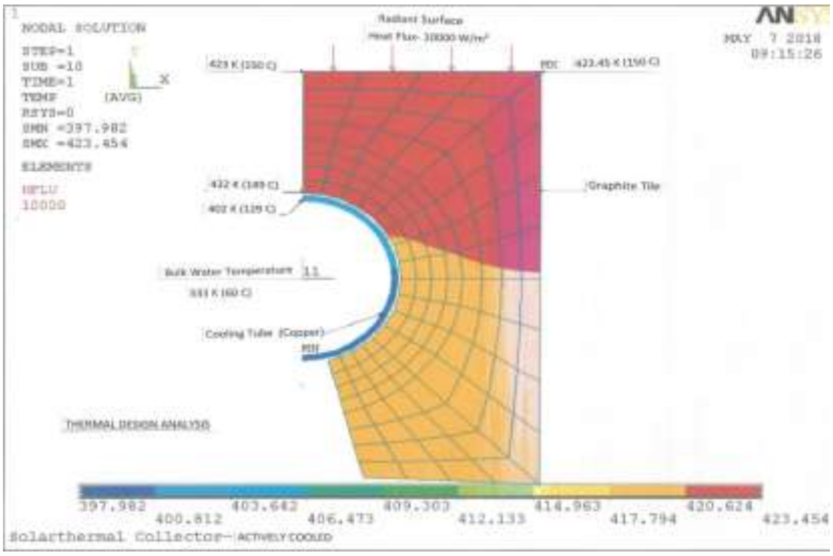

Fig. 6: Temperature distribution along the collector when the water is flowing with Re < 2300. The scale below shows the nodal temperature gradients along the elements; around the middle of the scale are for link elements connecting the tile and the tube. For assessment of results, however, the actual values (not average) of nodal temperatures are obtained from the output list

Since in the steady-state the graphite tile is actively cooled, the surface heat load is directly passed through the copper tube into the water. The thermal resistance is minimum from the apex of the tile (temp. 423 K) to the front of the cooling tube (temp. 402 K). Therefore, heat flows into the coolant mostly along the symmetry line, and relatively less from the sides.

This apex temperature of the tile reaches to 463 K (estimated) where the water temperature at the outlet (Tout) is 373 K (100 °C).

For a solar thermal energy collector the overall thermal resistance, from the surface of the receiver to the coolant, is crucial to system performance.
The lower the overall thermal resistance, the more heat will flow into the coolant.

With increasing thermal resistance, the heat flow into the coolant will worsen. The receiver surface will become hotter and hotter with incoming radiant heat flux, leading to heavy thermal radiation loss into the surrounding air, thus resulting in decreasing collector efficiencies.

In the solar thermal collector discussed here, the graphite tiles are actively cooled. The incoming heat load will face a minimum thermal resistance to the coolant. This will cause a reduction of radiation loss, thus high system efficiency can be expected.

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Using an average temperature distribution on the tile's surface, Fig. 6, the thermal radiation heat loss can be estimated (emissivity of graphite is taken as 0.78 [8]). This gives a thermal efficiency of the system of about 89%, which is considerably higher than other commercial collectors.

4. APPLICATIONS

This actively-cooled graphite tiles solar thermal collector would be suitable for producing hot water through a natural circulation (thermosyphon loop) system [8].

There are already several types of flat plate solar thermal collectors commercially available to produce hot water, air or other coolants [8, 9, 10, 11].

A straight forward example is given in MIT OpenCourseWare [12] in which a flat plate collector with an area of 5.1m² under radiant heat flux of 1000 W/m², outlet/inlet temperatures of 60 °C and 15 °C respectively, warms up 80 gallons (ca. 303 liters) of water in 5.5 hours/day with a thermal efficiency of 60%.

Using the same parameters, an actively-cooled graphite tiles collector should produce more hot water with its efficiency of 89% (mentioned above).

The efficiency of a flat plate collector, in general, goes down almost linearly with the increasing surface temperatures of the plate (due to higher radiation loss). As shown in [10], Fig. 12.7 (p. 427), for a water-cooled collector the efficiency is almost zero at the plate's surface temperature of ca. 160 °C proposed for the design.

For application as a high radiant heat flux thermal collector this actively-cooled graphite tile design also suffers from decreasing efficiency with increasingly high-intensity surface heat flux. But this reduction can be compensated by lowering the overall thermal resistance of the collector, such as by adjusting the graphite tile's dimensions relative to the cooling tube, and/or choosing the material with a higher conductive value, changing the cooling tube diameter, etc., during a design optimization phase for a particular specific case.

Details of different (commercially available) concentrating solar thermal collectors for use in power plants, such as parabolic trough collector, central receiver collector (solar tower) etc., are discussed in [11].

For parabolic trough collectors [13] the efficiency is above 70% at a radiant heat flux of 1000 W/m². This heat load is similar to that for flat plate collectors. Furthermore, a parabolic trough collector occupies a substantial space [11] when used for a power plant.

In comparison, if several actively-cooled graphite tile collectors (each constituting a module , Fig. 1), were arranged in matrix format, they should require less space because of their higher efficiency (89%). Also, they can work with a factor of 10 higher (or even more) heat loads (Fig. 6) for power generation.
As discussed in [14] for concentrated solar power, in all cases where the variation of thermal efficiency as a function of receiver temperature with heat loads varying from 0.01 MW to 5.0 MW, the maximum efficiency lies below 80%.

This actively-cooled graphite tiles thermal collector having also been tested as a heat shield (modified version) with a radiation energy over 10 MW [3,4], could significantly reduce these investment and space requirements.

5. DISCUSSION AND CONCLUTIONS

The results from this feasibility analysis demonstrate that actively-cooled form-locked (Fig.4) graphite tiles solar thermal energy collector could be an attractive alternative to other commercially- available solar thermal collectors.

This paper has demonstrated, through a thermal analysis for the alternative collector concept, that the system could be better than those systems at maintaining high efficiency due to its retention of active-cooling at high temperature.

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In a more detailed design phase a thermo-mechanical analysis has to be done, to determine stresses at the critical zone of the tile (temp. 422 K, Fig.6) which comes into contact with the apex zone of the tube (temp. 402 K, Fig. 6) during form-locked conditions.

The gap tolerance for sliding the tube through the tile must also be so determined, that for maximum thermal expansion of the tube the induced stresses at the critical zone of the tile do not exceed its fatigue limit.

While operating as part of a solar thermal power plant, this graphite tiles collector may be subjected to very high radiant surface heat fluxes. In this case the tile material may be replaced by a Carbone Fibre Composite (CFC) which have higher thermal conductivities and material strength than fine grain graphite.

In general, this actively-cooled graphite tiles collector is simple to make and robust but non-trivial. A low-cost prototype test should reveal its effectiveness.

It is probable that the actively-cooled graphite tiles collector will be immune to any dust deposition on its surface. The solar heat transfer efficiently into the coolant should not be impaired under all operating conditions. This can be easily verified in an experiment.

A simple rig can be conceived, as shown in the mathematical model of Fig. 5, consisting of a cooling tube assembled with armour materials only and no back plate. This rig can then be tested with high surface heat flux.

In conclusion, what is needed now is a more extensive phase of prototype building and testing of this concept in order to verify its promise.

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*Ex- Manager of European Project Office for JT-60SA at Fusion for Energy.

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