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LOW COST SOLAR COLLECTOR OF A PACKED
BED DESIGN

By
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July 29, 1977

Work Performed Under Contract No. EY-76-S-02-2972

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U.S. Department of Energy

Solar Energy

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OF A

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Final Report

Dale R. Simpson

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Under Contract No. EY-76-S-02-2972.*000

Prepared for
Energy Research and Development Administration

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ABSTRACT

Two solar collectors using a pebble bed design were constructed and tested using air as the heat exchange media. One collector had pebbles of metallurgical grade coke, and the other had a frothy volcanic material called scoria. The highly irregular surface of such vesicular material should increase the path distance for the air and the surface exposed cavities should give some honeycomb effect. Both should yield greater efficiency. Actual testing shows the efficiencies to be comparable with other air collectors. Thus the advantages of the pebble bed lie in the availability of the bed material, its thermal and radiation stability, and its shielding of underlying collector materials from ultraviolet radiation.

Several pebble bed collectors using water as the heat exchange media were constructed. However, basic problems prevented effective testing, and it is concluded that pebble bed collectors using water are impractical.

Low Cost Solar Collector of a Packed Bed Design

Introduction

The development of alternate energy and conservation of fossil fuels are pressing national needs. Solar energy for space heat and drying has obvious advantages over other alternates in regard to pollution, environment, and availability. Numerous studies bear on the economic feasibility of using solar energy as a replacement of other fuels; however some of these studies are based on unrealistic collector costs in the current market. It seems unlikely that increased mass production of commonly used collectors will effect major cost reduction. This is because of basic material costs and the many steps involved in the manufacturing process. Although there is widespread interest in solar energy useage, the lack of wide adoption of systems indicates the reluctance of individuals to make a large capital commitment requiring years for amortization. Since solar collectors are a major part of the total commitment for a solar energy system, it is imperative that the cost of solar collectors be sharply reduced so that the viable option of solar energy for space heating is economically attractive.

The cost of solar collectors relative to the rest of the solar system or other heating methods can be reduced

by 1) increasing the efficiency of the solar collector, and 2) reducing the costs for materials and fabrication. This study bears on both. It involves the development and testing of a collector constructable from low cost materials with increased efficiency from a packed-bed design.

A typical collector involves several sheets of glass overlying a metal sheet to which is attached tubes for transmitting a heat exchange material. The metal sheet is commonly copper, and attempts at replacement with aluminum introduce a material more liable to corrosion and of increased fabrication difficulty. Some air collectors are basically a replacement of the metal sheet with a flattened duct. Replacement of the metal by plastic would permit easy fabrication by molding. However, plastic is unacceptable because of degradation from ultraviolet radiation, and its low thermal conductivity.

The packed-bed collector tested in this study involved the typical two glass covers. These glass covers overlie a thin tray with an inlet and outlet which contains the material of the packed bed. In this study the bed was packed with metallurgical coke or scoria, a block volcanic material with a frothy nature. Neither material degrades from ultraviolet radiation, but the packing media does form an ultraviolet radiation shield for any underlying material. Thus, the material for the pan could be plastic and it would

be protected from ultraviolet radiation by the bed of coke or scoria, yet its fabrication could involve simple mass production techniques existing in the plastics industry.

Principal of the Packed Bed Collector

Coke and scoria are vesicular materials which developed when gas evolved from partially fused material. The vesicles are rarely interconnected. Fracturing of this vesicular material results in a surface intersecting many of the vesicles. This leaves semi-spherical cavities on the surface. Interior vesicles are unfractured and generally lack interconnections, but they do reduce of mass of the material and consequently the heat capacity per unit volume.

The surface cavities, or fractured vesicles are important for two reasons. First, they have some honeycomb effect resulting in less reflected radiation loss. This would increase the efficiency of a collector of a given aperture. It is obvious that the high surface area of the vesicular material in no way changes the aperture. A second cause for increased efficiency is obvious from a heat transfer consideration. Heat transfer is a function of many variables, an important variable is the effective bed length. Because a packed bed is porous, the bed length is increased by the highly irregular path of the fluid

through the porous bed. The path is even further increased by the cavernous surface of vesicular pebbles of the bed. It is difficult to estimate the effective bed length, but it is certainly several factors greater than a smooth duct for an air collector.

Model Collectors

The pebel bed collector concept appeared equally suited for using air or water as the heat exchange media. Consequently two collectors were constructed. One was designed to use air as the heat exchanger, the other was for water as the exchange media. Some basic problems developed during test procedure for the water collector, and consequently testing was discontinued. These problems are cited in a later section.

The air collector was rectangular with an aperture of 22 inches by 46 inches, or 1012 square inches. This had a cover of two sheets of double strength window glass separated by 3/8 inch. Inlet and outlet air vents were 3 x 4 inches, both coupled with a twelve element copper constantan thermopile and wet and dry bulb thermometer. Air flow was measured with an anemometer continuously in the inlet duct.

Total depth of the pan for the pebble bed was 1 inch. Scoria or coke then filled the pan, and it was

sealed by the cover glass. Scoria is a black vesicular volcanic rock of basaltic composition. It is domestically available at a cost comparable to other crushed rock, several dollars per ton. The material is stable in regard to weathering and ultraviolet radiation over human time spans. The particular material used has a bulk density of 0.475 gr/cm³. as packed in the bed. The particles used ranged from 1/4 to 3/4 inches (Fig. 1, 2). Thus the material could completely fill the bed and shield the underlying material of the pan.

The coke was of metallurgical grade. It is steel gray to black, and as packed in the bed it has a bulk density of 0.460 gr/cm³. The fragments ranged from 1/2 to 3/4 inches. The vesicles in coke are small, rarely exceeding 1/16 inch; in contrast, vesicles in scoria commonly are 1/8 to 1/4 inches (Fig. 3).

In tests the pressure drop across the collector was small, consequently it was unnecessary to further restrict the pebble size range in order to increase total porosity of the bed.

Tests

Most tests were with the collector horizontal. A recently calibrated pyranometer was mounted adjacent to the collector aperture. Tests were conducted only on days with

low wind, which were continuously measured, and few clouds.

The collector efficiency as a function of temperature differences divided by the solar energy incident on the plane of the collector was determined. The temperature difference is the average temperature of the inlet and exit minus the ambient temperature, or $(\frac{T_i + T_e}{2} - T_a)$. The results are shown in figures 4 to 7 for a coke pebble bed under a low air flow and a high air flow and a scoria pebble bed under a low air flow and a high air flow. A summary of some of the test conditions is given in Table 1.

TABLE 1

Pressure Drop and Mass Transfer for Collectors

	<u>Low Air Flow</u>		<u>High Air Flow</u>	
	<u>Scoria</u>	<u>Coke</u>	<u>Scoria</u>	<u>Coke</u>
Pressure Drop				
in H ₂ O	0.06	0.24	0.42	0.59
Mass Transfer				
(m ³ /s.m ²).10 ⁻²	1.90	2.35	4.20	3.65

The pressure drop across the collector was consistently greater in the coke packed bed than in the scoria.

For both the pressure drop is relatively low, but it could be further decreased by increasing the air space between the cover glass and the pebble bed.

Results

The test results are shown in figures 4 - 7 as plots of collector efficiency vs. the temperature difference of $\left(\frac{T_i + T_e}{2} \right) - T_a$ divided by radiant energy. Using $0.02^\circ\text{C m}^2/\text{watts } (\Delta T/I)$ as a reference, the coke pebble bed collector yielded about five percent greater efficiency than the scoria for both high and low air flow. However, this increased efficiency is accompanied by an increased pressure drop. The slight color difference of coke and scoria appears unimportant. The collectors were operating with about 50 - 60% efficiency for the $0.02^\circ\text{C m}^2/\text{watt}$ condition.

Increasing the flow rate by a factor of about two resulted in an increased efficiency of about 5 percent for both the coke and scoria collectors.

Packed Bed Collector Using Water

A packed bed collector using water as the media permeating through the bed was constructed, and testing was discontinued in an early stage because of major problems. A difficulty, but not major problem, is that the mass of the

collector is appreciable when the packed bed is filled with water. The major problems are the following:

1. A head of water of even several inches over the cross sectional area of the cover glass ruptures seals of the cover glass to the pan. This essentially imposes a requirement of operating the collector in a horizontal position.
2. With operation in a horizontal position, any degassing of the water results in air entrapped under the glass. Since the solubility of gases in water decrease with increasing temperature, such degassing will occur and the quantity of gas increase with continuing use of the collector. Such entrapped air as a thin layer under the glass would have an effect on the reflection, refraction, and transmission of light in the system.
3. The bulk density of the packed bed is about 0.46 gr/cm^3 . Although the density of individual pebbles is greater, some have a density less than water. Thus they float, and this causes a shifting and uneven repacking of the bed.

Potential Problem Areas

Scoria has a hardness sufficient for a sharp fragment to scratch glass. Repeated expansion and contraction of components of a collector with the cover glass pressing on the scoria could result in scratching of the glass. This would alter the transmission of radiant energy and weaken the glass. This was not a problem in the present experiments; however the collector was used mostly in a horizontal orientation.

With a high tilt or a vertical collector the pebble bed would exert appreciable force against the cover glass. This could lead to fracturing of the glass or a slumping of the pebbles from the upper part of the collector. Again, a low tilt or horizontal collector minimizes this problem.

Both scoria and coke have rough, highly irregular surfaces. Such surfaces would tend to catch and hold particulate matter from the air. The magnitude of this problem is unknown; however it would be a function of the quality of the air in a region and the effectiveness of the filter system.

Coke as received for these experiments had an odor of hydrogen sulfide and residual organic compounds. It required several hours of degassing in the collector to

eliminate these odors. This means that the initial use of a coke filled pebble bed would need to be vented to the atmosphere and not restricted to a closed space.

Conclusion

Pebble bed collectors using coke or scoria as the bed material yield an efficiency comparable with other air collectors. An advantage of the pebble bed type collector lies in the thermal and radiation stability of the bed filling material. This in turn protects the material from which the containing pan is constructed. Coke and scoria are both domestically available at low cost. A disadvantage of the pebble bed type collector stems from the shifting of the bed with a tilted collector. As a result, the type of collector used in this study is best suited for a horizontal orientation.

Pebble bed collectors using water as a heat exchange fluid appears impractical.

Figures

- Fig. 1 Massive scoria showing typical volcanic rock features.
- Fig. 2 Crushed scoria as used in the collector. Note the highly vesicular nature of the fragments.
- Fig. 3 Metallurgical coke as used in the collector. Note the smaller vesicules than in the scoria.
- Fig. 4 Efficiency curve-scoria pebble bed collector with flow of $0.0190 \text{ (m}^3/\text{s.m}^2\text{)}$. Collector horizontal. Curve is a linear regression. $\Delta T = \left(\frac{T_i + T_e}{2} - T_a\right)$.
- Fig. 5 Efficiency curve - coke pebble bed collector with flow of $0.0235 \text{ (m}^3/\text{s.m}^2\text{)}$. Collector horizontal. Curve is a linear regression. $\left(\Delta T = \left(\frac{T_i + T_e}{2} - T_a\right)\right)$.
- Fig. 6 Efficiency curve - scoria pebble bed collector with flow of $0.0420 \text{ (m}^3/\text{s.m}^2\text{)}$. Collector horizontal. Curve is a linear regression. $\Delta T = \left(\frac{T_i + T_e}{2} - T_a\right)$.
- Fig. 7 Efficiency curve - coke pebble bed collector with flow of $3.65 \text{ (m}^3/\text{s.m}^2\text{)}$. Collector horizontal. Curve is a linear regression. $\Delta T = \left(\frac{T_i + T_e}{2} - T_a\right)$.

Fig. 1

Fig. 3

Fig. 4

EFFICIENCY CURVE - SCORIA LOW FLOW RATE

Fig. 5

DELTA T / - (DEGREES C)(M.M) / WATTS
EFFICIENCY CURVE - COKE LOW FLOW RATE

Fig. 6

EFFICIENCY CURVE - SCORIA HIGH FLOW RATE

Fig. 7

EFFICIENCY CURVE - COKE HIGH FLOW RATE