APPLICATIONS FOR A BOILING GLYCOL / WATER, FLAT PLATE COLLECTOR, SOLAR COOKER

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ABSTRACT

This evaluation presents the operational principles, test results, a critique and various considerations, plus ideas regarding further development, for a prototype cooker. It employs conventional solar heating panel technology with pressurized propylene glycol/water antifreeze as the working fluid. Automotive cooling system technology functions without pumps or control mechanisms. Topics include system changes to make the original design more practical by: (1) providing for easily removing and exchanging cooking vessels, (2) installing the hotplate indoors, (3) placing the hotplate in an insulated oven box to insulate the cooking process and to increase the cooking capacity several fold, (4) using multiple separately-aimed collecting panels for all-day cooking without user intervention to move the unit or adjust reflectors. Potential applications besides conventional cooking include: retained heat cooking (hayboxing), drying, water heating, pasteurization, distilling, snow melting and manufacturing processing. Also described are attempts to attain high enough temperature for pasteurizing, sterilizing, pressure-cooking/preserving and refrigerating.

Keywords: hotplate, oven, pressurized flat-plate collector, indoors cooker

1. INTRODUCTION (See Fig.1.)

This paper introduces a type of cooker largely unknown to the solar cooking community, with the expectation that it’s novel features may be of interest to some workers to adapt to their needs. It is definitely not a low cost appliance for impoverished families, since the cost would be on the order of $1000 if manufactured in quantity in the USA, and probably half that if produced in some other countries. It represents instead a high-end device for implementation of sustainable, low impact practices in more developed regions. It is believed, if used in “thru-wall” applications, that the ease of installation, simplicity of operation, convenience of use, versatility and long term reliability might yield wider acceptance of solar cooking and related practices in the heavily energy consuming nations. Thus it has the potential to reduce the global depletion of, and dependence on, non-renewable energy sources such as oil, gas, coal and uranium. The cooker may also have application in less developed regions in institutions such as clinics or schools to alleviate the problems of unreliable, expensive, unhealthy, dangerous, resource depleting or unobtainable fuels such as propane, kerosene, dung, grass, wood and electricity.

As more results are produced in this ongoing project, they will be posted on our web site [1]. Interested parties are invited to contact the author to comment, make inquires, make suggestions and exchange ideas.

1.1. Operational Summary (See Fig.2)

When initially heating up, liquid thermo-siphons from the flat plate Collector to the Heat Exchanger soldered to the underside of the Hotplate. (See Fig.3). At full temperature the system boils and live steam from the Collector condenses in the Heat Exchanger, surrendering its latent heat of vaporization. The cooled liquid or condensate returns by gravity to the Collector. An ordinary Radiator Cap controls the pressure of the system, with higher pressures yielding higher cooking temperatures. Vented fluid is captured in the Overflow

Reservoir and returns to the Collector automatically when the Collector cools. The system operates entirely without user intervention.

1.1.1. Some Design and Operational Features

The translucent Liquid Reservoir allows discernment of fluid level for maintenance or discovery of excessive liquid loss. It should be installed in an accessible location visible to the cook. It is elevated one meter above the Hotplate to place a small constant positive pressure on the system, about 10 kPa (1.5 PSI). This is sufficient to overcome the 3 kPa (0.5 PSI) spring loaded anti-vacuum valve incorporated in the "non-venting" Radiator Cap, and insure that any slight leak in the Heat Transfer Loop will weep liquid out, rather than bleed air in. Not only does this make a leak visible, but it also insures that no air will enter to disrupt the initial thermo-siphoning effect. If thermo-siphoning is prevented by air in the system, a major component of heat transfer will be blocked and the system will fail to heat the food until the liquid boils. This is undesirable because the Collector operates much more efficiently to capture heat when it is cool than when it is boiling hot. Failure to thermo-siphon will cause significant energy that could have been transferred to the warming food to be wasted by collector-loss effects instead. Testing per ASAE S580 [3] showed that the load is carried nearly to the boiling point before the Collector began to boil.

The Overflow Reservoir is a convenient point to refill the system without having to remove the Radiator Cap, with the attendant introduction of air into the Heat Transfer Loop. It is desirable to make the height adjustable so the Reservoir can be lowered to the level of the Radiator Cap. This allows Cap removal if need be without excessive liquid loss.

As tested, the connection to the Radiator Cap was below the level of the Heat Exchanger, as indicated in Fig.2. It would have been better to have placed this connection at the height of the Exchanger, as it would have lessened the amount of liquid forced out when boiling occurred. It would also have facilitated filling the Loop by largely eliminating trapped air. This air is purged the first time the Collector boils. Thereafter the Loop will be completely filled with liquid when not boiling. When boiling, steam fills the portion above the level of the Cap connection.

The Collector is double-glazed, to minimize Collector losses. The 11 finned tubes in the 130 cm X 68 cm (0.888 Sq. m) Collector have "black chrome" plated selective absorptive surfaces to minimize infrared radiation losses.

For safety, non-toxic propylene glycol was used for freeze protection, rather than the poisonous ethylene glycol. The mix ratio with water and the Cap pressure determine Collector boiling temperature. Higher-pressure operation is desirable to prevent boiling, thereby allowing higher temperature and more efficient heat transfer. However the higher temperature comes at a cost. Below 120 C (250 F), the glycol can be expected to last a decade. Above this threshold it deteriorates much more rapidly by acidification, losing its protective quality and causing corrosion in perhaps one year at 150 C (300 F). Bad glycol turns from brown to black as viewed in the reservoir, and litmus paper will show a decline in pH from the normal 8.5 to around 5.

2. BACKGROUND

Dr. Barry Butler designed this experimental cooker several years ago as an adjunct to his solar water heating manufacturing business, Butler Sun Solutions [2]. He drew on his long experience as an industrial solar engineer, working with no previous experience or knowledge of the state of the art relating to established box, panel or parabolic designs. The result was a unique and intriguing device worthy of further exploration, albeit with some serious drawbacks as originally configured. As an interested second party, the author tested the original Solar Hotplate in the summer of 2003 and returned a critique to Butler Sun Solutions. Recently Dr. Butler donated the cooker to the Kerr-Cole Sustainable Living Center for further experimentation in the preparation of this paper.

2.1 Detailed Operation Description, Original Prototype

Our operating fluid was a mix of equal amounts of glycol and water. The prototype Loop employs short and relatively large cross-section lengths of tubing, resulting in quite efficient initial heat transfer by thermo-siphoning. When the boiling point is reached, steam expands into the upper portion of the Heat Transfer Loop, pressurizing the system. An American "15-pound" radiator cap would regulate the pressure to about one atmosphere gauge (100 kPa) at sea level, or two atmospheres absolute (200 kPa). This determines the boiling temperature, which would be 127.5 C for a 50/50 glycol/water mix, or 120.6 C for pure water. (At the 1750-meter altitude of our Center, the lowered atmospheric pressure reduces these temperatures by 3.1 C to 124.4 C and 117.5 C respectively.) In the USA, radiator caps rated at 20, 24 and 28 PSI (138, 165 and 193 kPa) are available from automotive racing suppliers, allowing the selection of a release pressure to suit temperature and altitude requirements.

Steam collects first in the Heat Exchanger on the bottom of the Hotplate. It condenses on the walls of this tube at the boiling/condensation temperature of water as determined by the pressure, namely 120.6 C at 100 kPa gauge. The condensate flows by gravity back to the bottom of the collector to complete the cycle. When the Hotplate heats a heavy load of cool food, which can absorb all of the heat available from the steam, the steam pocket remains small.

Note that the glycol/water mix boiling point is higher than the water condensation temperature. For the example given above, this would be 127.5 C and 120.6 C respectively. Thus the maximum temperature deliverable to the food decreases when boiling ensues. In climates where freezing at night cannot occur, the glycol should be omitted and a higher pressure employed to achieve a desired temperature, as mixing glycol with water actually detracts somewhat from the efficiency of heat collection by raising Collector temperature. Also the glycol may present a cost and availability problem in some areas. Furthermore it adds a maintenance requirement to periodically check the condition of the antifreeze mix and eventually to replace it. Operation with water alone allows high temperatures without glycol deterioration concerns.

When the load is reduced relative to the Collector capacity, such as when the food has reached full cooking temperature, the steam will not completely condense. The steam pocket will expand to drive out more liquid until finally steam reaches the level of the tube leading to the Radiator Cap, at which point live steam will exit to the Overflow Reservoir. The overflow tube leads to the bottom of the partially filled reservoir, so that steam will meet cooler liquid and condense; therefore preventing water loss to the atmosphere. As steam continues to exit, the liquid level in the Collector decreases, reducing its efficiency, and thus creating a tendency toward less and less excess steam being generated. However note that, almost always, some steam will continually vent in order to maintain pressure and temperature, leading to concerns described below.

2.1.1. Indeterminate State of Operation

If a demand for heat greater than that being generated now occurs, such as will happen if the sun were to diminish or a new load of cold food were put in the Hotplate, the Loop pressure and temperature will drop. The system will now operate with a pocket of steam of unreduced volume, but at a lower temperature and pressure somewhere between the atmospheric (100kPa absolute) and full pressure (200 kPa absolute), yielding a Hotplate temperature somewhere between 100 C and 120.6 C. Overall this is undesirable, since less liquid in the tubes translates into lower heat collection efficiency, with attendant lower heat transfer rate. This will particularly be a problem when attempting higher temperature processes such as pressure-cooking. Eventually, one of two things has been observed to happen: (1) An increasing heat balance will re-pressurize the system fully (steam exiting) to produce 120.6 C at the Hotplate. (This will happen when the food heats up or the sun returns to a higher intensity). Or (2) the decreasing temperature will cause the steam pocket to start shrinking and begin to draw liquid back from the Overflow Reservoir. When this happens, the entire loop will completely refill rather quickly as entering cool liquid meets and absorbs all of the steam.

One way to minimize the liquid venting problem would be to relocate the tube leading to the Radiator Cap to the level of the Hotplate so that minimal fluid is expelled in liquid form. This, in conjunction with a larger diameter Heat Exchanger tube, would allow passage of steam over the water in the bottom of the tube, enabling continuation of thermo-siphoning (assisted considerably) by rising steam bubbles. Liquid circulation would continue until boil-off reduced the level enough to break the path.

3. TEST, EVALUATION AND COMMENTARY

3.1. Some Initial Observations of Prototype, 2003

The off-axis capability of this large and heavy unit was rather poor, as its operation depended on strong and rather direct sun. It was quite cumbersome to turn toward the sun. If faced due south all day without aiming, boiling ceased about 3:PM at the equinox. To facilitate moving and turning a freestanding unit, one should consider putting it on a cart, wagon, or under-car crawler. The cooker did not seem to perform nearly as well as a box cooker in weak sunlight.

3.1.1. The Water Puddle Technique for Accommodating Removable Pots

The Hotplate of the original design was a disconnectable pot or skillet in which the food cooked directly. Despite a heating efficiency which made it possible to fry bacon, it was undesirable for several reasons – system leaks, burn hazard when disconnecting the hot vessel, working fluid spillage when disconnecting, vessel clumsy to handle due to attached tubes, excessive working fluid boil-off with the shut-off valves closed, and the need to deal with insulation to surround the vessel.

Placing a second pot on the skillet and using the skillet as a Hotplate did not work to solve these problems, even with heavy insulation surrounding the Hotplate and cooking pot. The heat transfer was so poor that one could barely boil water. However, placing a puddle of cooking oil in the Hotplate (skillet) as a heat transfer medium did work to boil water quickly, but was too messy to be practical. Then it was found that using a puddle of water instead of oil also worked well. The thin water layer trapped between pot and skillet remained until the pot had nearly reached the boiling point. By the time the water had boiled off, the pot was hot enough to cook like a crock pot even though the heat transfer efficiency had greatly diminished. The writer cooked chili, a whole chicken, a casserole, polenta and soup this way.

This is practical way of slow cooking. It allows for a choice of different types of readily removable cookware. - for serving food, for moving to a conventional fuel stove (as required to preheat, re-warm or continue cooking when sunlight fails), for moving to shelf in a Sustained Heat Chamber to make way for another dish, for cleaning, and for refrigeration. There is no requirement for specially blackened vessels. The gentle heat does a good job of defrosting food, re-warming food without burning, keeping food hot, slow roasting, vegetable cooking and casserole baking.

3.2. <u>Heating Performance Testing, 2006</u> (per Fig. 2)

<u>Result</u> (1). The pressure gauge on the Loop indicates temperature accurately only when the system is boiling with all air expelled. Initial readings during warm-up are the result of liquid thermal expansion, or may be affected by air in the system. The gauge is recommended only for experimental testing, and not for use by the cook, as the readings may be mis-interpreted. <u>Result</u> (2). The clear plastic tube leading to the Reservoir affords an important means for judging the venting process. When steam is seen exiting the Radiator Cap, the cook knows the system is up to design pressure and temperature. Air bubbles, if present, can be easily distinguished from live steam. <u>Result</u> (3). The translucent or clear Overflow Reservoir also acts as a useful indicator of system state. When the level is lowest, the operator knows the Loop is full of liquid and thermo-siphoning. When it is higher, the operator knows steam is being generated, with the height proportional to the size of the steam pocket. <u>Result</u> (4). With air in the upper portion of the Loop, very little heat reaches the Hotplate until boiling commences. <u>Result</u> (5). Fluid loss from the Loop due to venting of steam was not found to be a major problem, at least for lower temperature slow cooking, where a modest loss of efficiency was not critical. The major cause for expulsion of liquid is occupation of the upper Loop with steam, rather than steam escaping past the Radiator Cap. <u>Result</u> (6). Fluctuating heat transfer as discussed in 2.1.1, did occur as predicted. It was judged not to be a problem for slow cooking around 100 C. <u>Result</u> (7). On some occasions the Collector would remain quiescent for a while, then boil suddenly to cause sharp pressure surges and bursts of steam venting. This “bump boiling” would pump out steam and resulted in a gauge pressure about half of the release pressure of the Radiator Cap.

3.3. <u>Higher Pressure/Temperature Operation</u>

For pressure-cooking, canning, medical sterilization and ammonia/hydrogen absorption refrigeration, load temperatures of 120 C or more are required. As presently configured the tested unit was marginal in achieving this. 100 kPa in the collector yielded only 40 kPa in a pressure cooker placed on the Hotplate, with an oil puddle to promote efficient heat transfer. Certainly the effect described in 2.1.1. contributed to the problem. Ongoing experiments may prove that operating the Collector at a higher pressure/temperature will be successful. Using a pump to circulate liquid may also be needed. If 120 C can be readily achieved, then the unit becomes a very useful “off-grid” appliance, as the collector could power processes to rapidly pressure-cook food, then preserve it for later consumption either by canning or refrigeration. The ability to store cooked food greatly increases the percentage of total food cooking that can be done by solar, up to 100 %, thus alleviating fuel shortages, etc.

3.4. <u>Sustained Heat Chamber</u> (See Fig.4.)

Testing is underway to see if placing the Hotplate inside an insulated box will produce enough heat to maintain cooking in vessels previously brought to temperature on the Hotplate. This low temperature oven technique has several advantages: (1) It eliminates placing insulation directly on the cooking vessel since the chamber now serves to retard heat loss. (2) No shut off valve is required (one simply keeps the door closed to prevent unwanted heat in an indoor installation). (3) The cooking capacity is increased several times by accommodating multiple dishes simultaneously. The Sustained Heat Chamber acts similarly to a retained heat cooker, except that the “waste” heat from the Hotplate maintains cooking temperature for as long as the sun shines.

Initial testing shows the food on the Hotplate can be cooked in an un-insulated vessel, but not enough heat develops in the Chamber to keep the other pots up to cooking temperature. The cook must periodically rotate each of the vessels to the Hotplate to keep them sufficiently hot. Potential solutions to this problem are: (1) Thicker Chamber insulation and/or smaller Chamber size. (2) Circulate spent fluid through auxiliary finned tube radiators in the Chamber. (3) Pump the working fluid. (4) Circulate spent fluid through series-connected auxiliary Heat Exchanger/Hotplates in the chamber.

3.5. Experiment to Operate Thermo-Siphoning Only

An initial test was made to operate the system so that liquid would always be available to thermo-siphon to the Heat Exchanger. A Liquid Recovery Unit, Butler Sun Solutions Model OTP-1 [2], was connected to the tube leading to the optional Pressure Gauge. The Radiator Cap depicted in Figs. 1 and 2 was defeated. The OTP-1 device incorporates a Radiator Cap and Overflow Reservoir. It condenses steam and returns water to the Loop to prevent liquid boil-off, thus maintaining liquid level in the Loop. The Cap vents to the Reservoir only in the unlikely event the OTP-1 is unable to condense all the steam being generated. This idea did not work because the device placed an unacceptable load on the system. Fluid circulating in the tubing leading to the OTP-1 robbed excessive heat from the system.

Perhaps a re-configuration of the tubing to the OTP-1 would solve this problem. If so, a 24 lb or 28 lb (165 or 193 kPa) high pressure racing Radiator Cap would allow circulation of liquid hot enough for high temperature processes.

3.6. Thru-Wall Installation

A major advantage of the Solar Hotplate is that the Collector can be placed outdoors (must be below hotplate level) in the best sun exposure, with the cooking unit placed indoors at a convenient location. Calculations per reference (4) pages 348–349 and 364–365 indicate that thermo-siphoning is practical for a Hotplate several meters removed from the Collector, using one cm. inside diameter tubing. The writer suspects that the actual liquid circulation rate will be much higher than calculated when steam bubbles begin rising in the tubing leading to the Hotplate. For longer runs, a pumped system with smaller diameter tubing would be needed. All exposed metal along the Loop must be well insulated. Non-pumped installations require attention to the slope of the tubing to be ever upward from Collector to Heat Exchanger and ever downward on the return leg to prevent vapor traps.

3.7. Dual Collector Installation

Especially in a thru-wall installation, it would be advantageous to design for extended cooking hours without having to periodically re-aim the collector or manipulate reflectors. It appears that installing two collectors, one angled to the east and one angled to the west, will suffice to yield eight hours of cooking summer and winter in temperate latitudes. A three-collector system would extend cooking time twelve hours or more in summer. Multi-collector configurations lend themselves to supplementation by horizontal reflectors similar to that shown in Fig.1. Such systems would require separate Heat Transfer Loops to avoid robbing from one Collector to the next. The Hotplate would have to incorporate two or three independent Heat Exchanger tubes.

4. CONCLUSIONS

Overall the apparatus holds the as-yet-unproven promise of an all-in-one, large capacity, indoor appliance with combined cooking, canning, sterilizing, incubating, drying and refrigeration capability. Without reflector, the unit has the capacity to deliver 200 Watts to a 50 C standard load per ASAE S580 [3] (20% efficiency referred to the Collector). This is sufficient to pasteurize two kilograms of water to 70 C in one hour. The power delivered to the load drops to 70 watts at a cooking temperature of 95 C.

4.1. Future Investigation Issues

Improved Collector efficiency by insulating to eliminate glazing edge loss effects. Reflectors. Refrigeration. Baking bread. Electrical backup (100 watts required for Sustained Heat Chamber). Fuel backup. Auxiliary Warm Chamber heated with returning liquid for drying, raising bread, making yogurt, etc. Development of "waterless" removable cooking vessels by Butler [2]. Evaluate parallel tube *versus* series tube Collectors. Field test thru-wall unit installed in a home. Address issues indicated in this paper: (1) sufficient heat for high temperature processes, (2) greater temperature stability per 2.1.1, (3) raise the temperature achievable in the Sustained Heat Chamber, (4) experiment with pumping liquid working fluid, (5) investigate long distance thermo-siphoning, (6) design and evaluate multi-collector system, (7) OPT-1 to stop loss of steam per 3.6.

5. REFERENCES

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Double Glazed 0.888 M^2 Solar Heat Collecting Panel With Attached 24 Cm Diameter Hotplate (Skillet)

Automotive Radiator Cap Regulates Pressure

Insulated Fluid Return Tube Along Side of Collector

Insulation Removed From Upper Loop Components for Clarity of Illustration

Original Overflow Reservoir on Leg

Insulation Covers Side and Bottom of Hotplate (Skillet)

Not Shown: Lid and Insulation Above Lid for Skillet

Fig. 1. Original Butler Sun Solutions Solar Hotplate. Shown with experimental front reflector for low sun angle. The valve and disconnect fittings caused leaks and user inconvenience, and were replaced with direct connections after initial testing.

For Loop Circulation, The Hotplate Must Be Higher Than the Top of the Collector

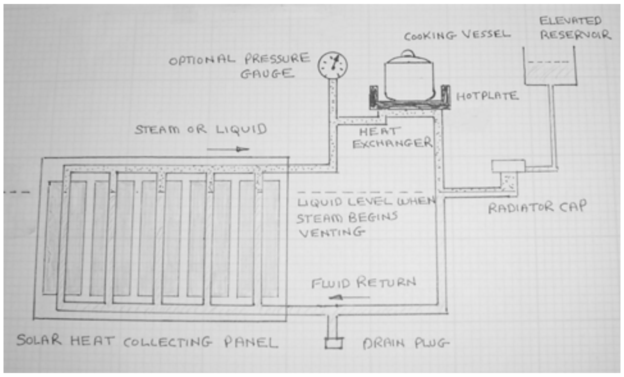

Fig. 2. Test Unit Heat Transfer Loop. The original configuration cooked food directly in a skillet or a pot. The removable cooking vessel shown on Hotplate (skillet) improves practicality, at the expense of slower, lower-temperature cooking.

Copper Bottom Stainless Steel Pot With soldered-on 7 Mm Inside Diameter Copper Tubing

Fig.3. Heat Exchanger Detail. Disconnect fittings were eliminated after initial testing in favor of non-removable Hotplate installation.

Inside Dimensions: 43 Cm High X 38 Cm Deep X 71Cm Wide

Insulation: Foam Board: 5 Cm Thick

Fig.4. Sustained Heat Chamber. Three pots inside to be kept at cooking temperature. The lower left pot is in position on Hotplate to be brought up to cooking temperature.