Considerations, design calculations, construction, test and evaluation of a cavity walled solar oven.

Part 2.

Evaluation of insulation materials suitable for a cavity walled solar oven.

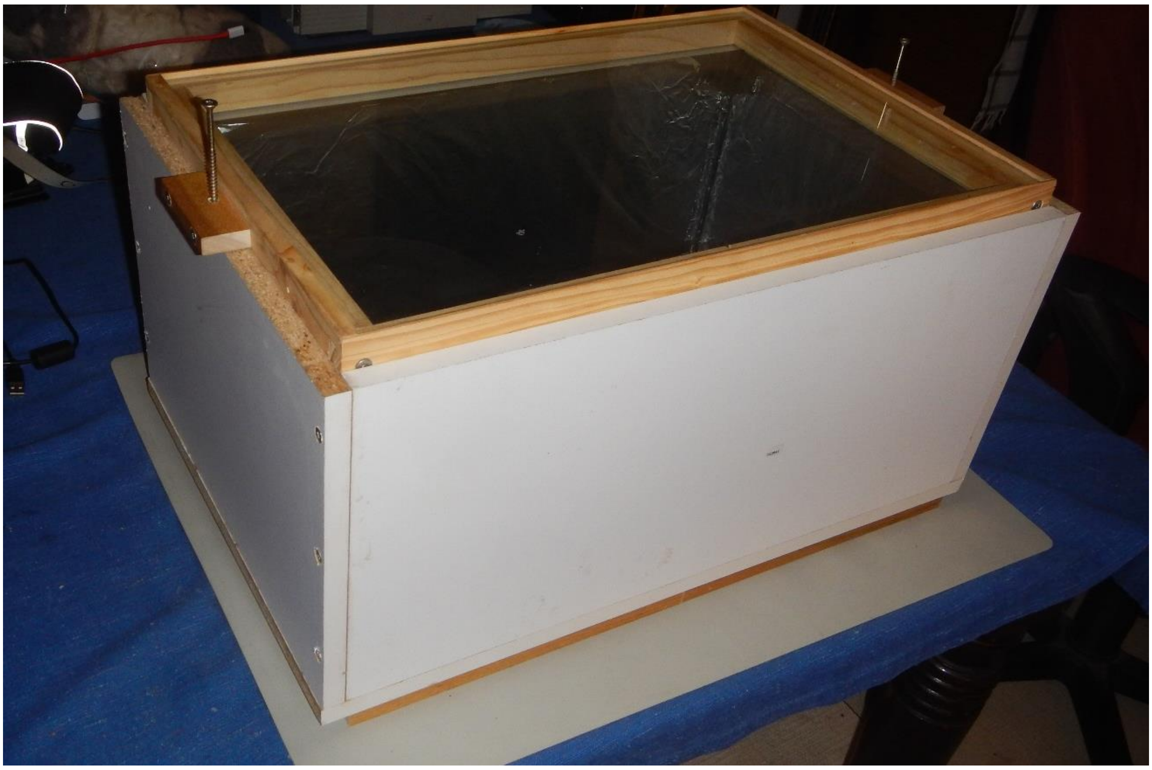

Fig. 1. The solar oven.

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Contents.

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1. Abstract. This present report is “published” in Martz 2024. It is Part 2 of- (and an addendum to-) the Part 1 of: “Considerations, design calculations, construction, test and evaluation of a cavity walled solar oven”, which was “published” in December 2022. Both Part 1 and Part 2 of the report are based on a cavity walled solar oven consisting of two boxes – one within the other – with a double paned lit.

The prototype, which was build and described in Part 1 was largely made of chipboard. Plywood or solid wood were suggested as alternative materials to chipboard. Not until this moment, did I learn that both chipboard and plywood can contain a chemical - formaldehyde – which can cause cancer; and particular leukaemia. Hence, I must strongly advise *not* to use neither chipboard – nor plywood – but only plain solid wood.

In Part 1, the 10 mm space between the sides and the bottom of the two boxes contained only plain air – no solid insulation material was used. The aim was the highest possible operation temperature. The oven reached a temperature of 83 ºC by an ambient temperature of 29 ºC. In 2022 the time schedule did not permit to extend the tests to other insulation materials than plain air.

Part 2 is a follow up to Part 1. The main outcome of Part 2 are the measurements and calculations, which proved that it is the heat leakage through the pane, which is the main limitation to the temperature of the oven. Part 2 also presents the results of thermal tests of other insulating materials than plain air. The thermal tests further comprise the measurements for a duvet used as an external insulation of the oven.

Part 2 also addresses the impact of the oven’s thermal time constant on the cooking time of the oven and recommendations for the design of the oven. This leads to an explanation of how a change of material from to solid wood, will yield both a lighter construction and a shorter cooking time.

In Part 1 - the measurements of the final temperatures of the oven were based on subjective “by eye” estimations of the heating graphs (i.e. temperature versus time). In Part 2 the final temperatures of the oven have been obtained using the solution to the mathematical equations, which were derived in Part 1. Both methods have yielded similar results for air. The most promising of the tested insulating materials was popcorn.

2. Retrieval of the test results found for plain air in Part 1 of the report.

I believe it is fair to claim, that the most important quality of a solar oven is how much it can raise its internal temperature above its ambient temperature. If the thermal resistance (R_{Th}) from the interior of the oven to the ambient can be increased, that will correspond to a proportional increase in the temperature of the oven.

In Part 1 (section 8.5.) two different calculations of the thermal resistance R_{Th} of the solar oven were made:

A: $R_{Th\ AD} = \Delta T / P = (90.1^oC - 25^oC) / 125.1\ W \qquad = 0.52\ K/W.$

B: $R_{Th\ AD} = ((R_{Th\ AB} + R_{Th\ BD})^{-1} + (R_{Th\ AC} + R_{Th\ CD})^{-1})^{-1}$

$= ((12.63\ K/W + 1.05\ K/W)^{-1} + (0.490\ K/W + 0.182\ K/W)^{-1})^{-1} \qquad = 0.64\ K/W.$

In section 2.1. I will compare these “by eye” obtained results from Part 1 - to the corresponding results from Part 2, which were obtained by using the “mathematical solution”.

2.1 Errata. In the appendix of the Part 1 (page 46 - 47) the readings/measurements were used to calculate the thermal resistance (R_{Th}). Unfortunately, I made a mistake, as the figures, which were listed, were the thermal conductivities. Hence, they must be inverted to present the thermal resistance. In the table below, matters should have been rectified. Please note, these figures were "by eye" estimates, thus, linked with some uncertainty.

The figures presented in the appendix of the Part 1 should have been:

Date	Hour	Power [W]	Conductivity [W/K]	Resistance [K/W]
11/8	09.00	151	2.15	0,47
11/8	11.54	121	1.88	0.53
11/8	14.09	83	1.72	0.58
11/8	17.00	46	1.48	0.68
11/8	17.48	42	1.39	0.72
12/8	14.04	117	1.82	0.55
12/8	15.43	160	2.32	0,43
12/8	17.38	102	1.73	0.58

Table 1. The measurements of the conductivities made in 2022 – and their associated thermal resistances.

A. Comparing the two columns Power and Conductivity, there is an evident correlation between them – higher power leads to higher conductivity, leading to a lower thermal resistivity. This correspond well to the fact, that the power radiated from the oven increases by the absolute temperature to the power of four.

B. The resistance found by a power of 117 W was 0.55 K/W - and by 121 W it was 0.53 K/W – both of which are well in line with the value of $R_{Th\ AD}$ = 0.52 K/W, as found in section 8.5. in Part 1.

3. How to find the equation for an entire exponential graph based on just three points / measurements.
As discussed in Part 1, the curve of the temperature as function of time - a "heating graph" is a suitable name for it - for an **ideal** linear thermal system would be an exact exponential graph.

Such a heating graph (Fig. 2A) can mathematically be expressed on the form: $T(t) = A\,(1 - e^{-t/\tau})$ – where

T(t) is the temperature as function of time

A is the product of power P x thermal resistance R_{Th} – and

τ is the time constant.

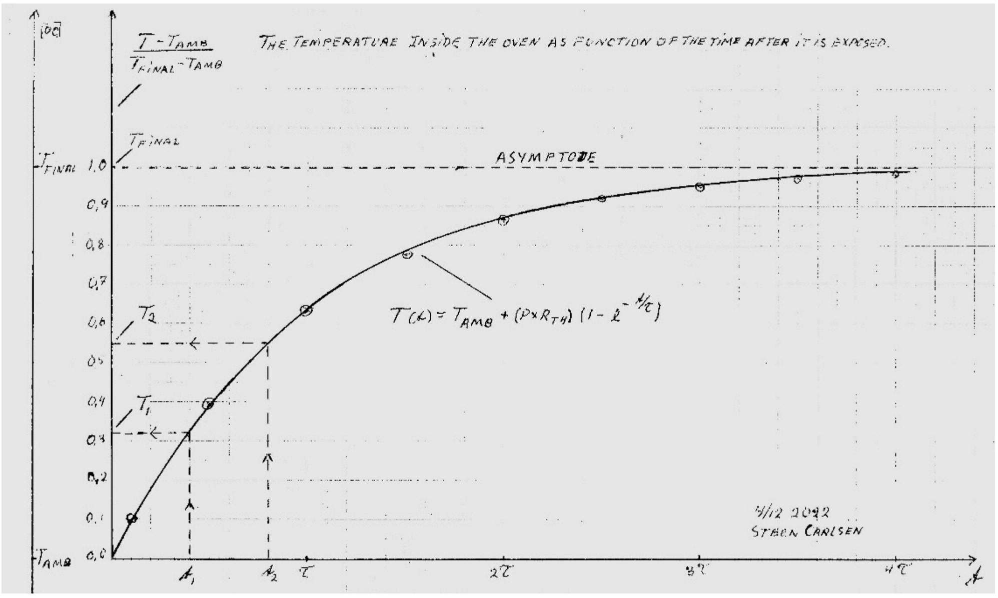

*Fig. 2A. The heating graph for an **ideal** linear thermal system would be an exact exponential graph.*

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In section 9.2. in Part 1, it is shown, that if you know just three points out of a heating graph (showing an exponential rise of a temperature as a function of time), you will – based on these three points - be able to calculate all points on the entire heating graph.

However, this only applies under the following conditions (see fig. 2A):
1. The first point in time T_0,(t_0) must be origo = 0, and that is the starting point (0,0) of the graph.
2. Starting at (t_0), the time to the third measurement (t_2) must be twice the time to the second measurement (t_1); (t_2 - t_0) = 2 x (t_1 - t_0).

Provided that the prerequisite are fulfilled as stated above, the outcome of section 9.2. in Part 1 states that:

I. The final temperature will rise by: $A = T_{End} = T_1^2 / (2T_1 – T_2) = P \times R_{Th}$ - and
II. The time constant $\tau = t_1 / (\ln (T_1 / (T_2 – T_1)))$ - where

t_1 is the elapsed time from start-up (t_0) to the time of the first temperature reading.
t_2 is the elapsed time from start-up (t_0) to the time of the second temperature reading.
T_1 is the temperature of the solar oven at the first temperature reading after starting – and
T_2 is the temperature of the solar oven at the second temperature reading after starting.

When we have found A, we obtain the thermal resistance R_{Th} by dividing A by the power P.
A more detailed description of the solution to the equations and the theory behind the mathematical processing of the measurements is presented in section 14 of the appendix. The following section four and five contains a description of how the temperature readings are organized and processed.

Each measurement is based on three readings of the temperature $T(t_N)$ as a function of the time (t_N). The readings take place at the sampling times $t_{N.}$ - where $t_N = N \times t_s$, and N is an integer. Each temperature reading is indexed, so that the temperature T, at the time $t_s = 0$, (when power is just applied to the oven), is named T_0.

To sum up:
T_0 is the temperature at the beginning of the test = the time t = 0.
T_1 is the temperature at the time $t_1 = 1 \times t_s$ after the beginning of the test.
T_2 is the temperature at the time $t_2 = 2 \times t_s$ after the beginning of the test.
T_3 is the temperature at the time $t_3 = 3 \times t_s$ after the beginning of the test.
T_N is the temperature at the time $t_N = N \times t_s$ after the beginning of the test (where N is an integer).
t_s is the sampling rate - i.e. the time span between each measurement of the temperature.

Because t_s has been used as the common "yard stick", we also know that: $t_2 = 2\ t_1$; $t_4 = 2\ t_2$ - and $t_6 = 2\ t_3$ – which was a prerequisite for the solution. (Note: We have no need for the readings of T_5 (t_5) and T_7 (t_7).)

4. Estimating the ratio between radiation, convection and conduction, using the heating graph.
In Part 1 it was described how the thermal resistance between any two points is determined by the temperature difference between the two points divided by the total heat / power flowing between these two points.

It was also descripted how the total power is comprised of:
A. The radiation (which rises by the absolute temperature to the power of 4.0).
B. The convection (which rises by the temperature to the power of 1.25). - and
C. The conduction (which rises almost linearly by the temperature).

In the thermal designs of many instruments, which have operating temperatures comparable to that of the temperature range of a solar oven - it is said that - as a rule of thumb – the power dissipation from an enclosure is more or less evenly divided between convection and radiation. Hence, the radiation will generally become the most significant contribution to the unlinearity of a heating graph – and thereby the deviation from an exponentially shaped curve (for the heating graph).

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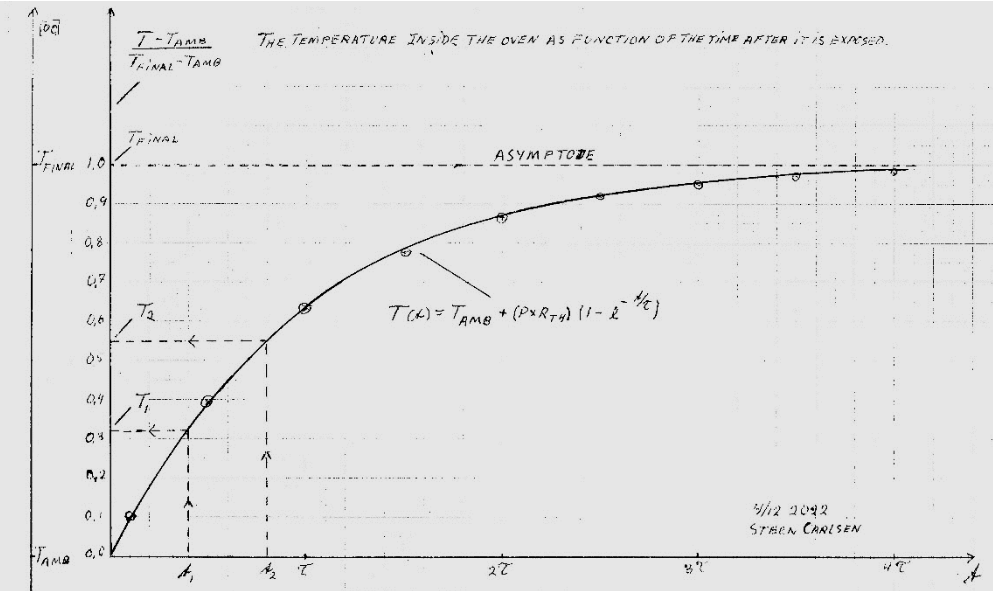
Thus, both the power radiated from an item and the convection from that item depends on the temperature of that item raised to a power of 4.0 and 1.25 respectively. These are the reasons, why a thermal resistance is unlinear and change by the temperature of the body. If the thermal resistance had been independent of the temperature, our results would had been the same, for the entire heating graph.

Hence, in the real world of unlinearity, particularly the radiation – and to a lesser extent the convection – are reflected in the unlinearity of R_{Th}, which causes the graph to deviate from an exact exponential curve. This deviation can be used as a tool to estimate by which ratio the radiation, the convection and the conduction contribute to an actual thermal resistance. This is why I wish to find the thermal resistance for a number (I have chosen three) different temperature ranges for each of the tests of the insulation materials. I have chosen each test to comprises three pairs of temperature readings; one from the first, one from the middle and one from the last part of the heating graphs to see how the thermal resistance variates as a function of the temperature of the oven.

5. How to time the measurements to extract three (or more) tests from each heating graph.



1 x t_S -> | t_0 |<- t_1 | t_2 | | | => A_{12} and τ_{12}

2 x t_S -> | t_0 |<- t_2 | | t_4 | => A_{24} and τ_{24}

3 x t_S -> | t_0 |<- t_3 | t_6 => A_{36} and τ_{36}

Fig. 2B. The heating graph for an ***ideal*** *linear thermal system would be an exact exponential graph*.

For each of the insulation materials, I wish to find both the thermal resistance R_{Th} and the time constant τ - at the beginning-, at the middle- and at the last part of the heating graph. As explained in section 3, the thermal resistance R_{Th} can be found by dividing A by the power P. Hence we only need to find A and τ - at the beginning-, at the middle- and at the last part of the heating graph. Looking at the heating graph on fig. 2B, t_1, t_2 and t_3 appear to be suitable times at the heating graph to do the measurements of the temperatures.

As discussed in section 3 and 4, to measure A and τ, we need to measure the temperature T at three points in time (t) with the same distance in time between the first and the second measurement as between the second and the third measurement. Returning to fig. 2B, it can be seen, that if we measure the temperature at t_0, t_1 and t_2 and use the measured temperatures T_1 and T_2 to solve the equations for A_{12} and τ_{12}, we will obtain the values for A and τ, which corresponds to exact that exponential graph, which will fit through the three points:
$t_0,(T_0)$; $t_1,(T_1)$ and $t_2,(T_2)$ at the beginning of the graph.

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Likewise, when A_{24} and τ_{24} must be found for the middle of the heating graph. As can be seen at fig. 2B, both A_{12} and τ_{12}; A_{24} and τ_{24}; A_{36} and τ_{36} - and onwards – all uses the same starting temperature t_0,(T_0).

And because we have chosen to use the same sampling time t_S as yard stick / unit for the measurements of A and τ (for both the first, the middle and the last part of the heating graph) we can now reuse the measurement of T_2, so that T_0, T_2 and T_4 now can be used to calculate A_{24} and τ_{24}. The same pattern applies to A_{36} and τ_{36}, A_{48} and τ_{48} - and onwards. If the heating graph would be an exact exponential graph then the solution for A_{12}, A_{24}, A_{36} - and onwards would be exactly the same - and likewise for τ_{12}, τ_{24} and τ_{36}. I chose the sampling time t_S to be 30 minutes, because it is approx. the half of the time constant of the oven.

6. The test setup.

In the setup of the test, I have exploited that the thermal resistance between the ambient and the interior of the oven, is independent of the direction of the heat flow. When I took the thermal measurements for Part 1, I had noticed how changing mains voltages influenced the readings. Having also learned the lesson with the pane, which cracked due to uneven heating (see the Part 1), I found a large heatsink (45 x 15 x 7 cm) and 6 W fan. I mounted three 75 Ω / 50 W power resistors in parallel – distributed along the bottom of the heatsink, and used them to heat the oven. The heat sink profile was placed at the bottom of the solar oven. It was equipped with 4 legs / studs yielding 3 cm space between the bottom of the oven and the heatsink. This space was in order to allow for the air to circulate freely, and to obtain an even temperature in the oven.

In Part 1, I used a vario transformer supplied directly from the mains. In Part 2, I used a stabilized dual power supply of 2 x 60 V / 20 A - supplied from the mains – to supply the power resistors. To ensure an efficient air circulation a 24 V / 0.25 A / 6.0 W fan was suppling an airflow along the cooling fins. See fig 3, 4 and 5.

Fig. 3. The heatsink resting on 30 mm 4M screws at the bottom of the oven. Power supplied by red, blue and grey wires. The two aligned 5.0 mm holes in the end of the inner box and the end of the outer box accommodated:
A. The two 1.65 mm Ø wires to the three 75 Ω / 50 W power resistors - and
B. The two 0.9 mm Ø wires to the fan.
C. Finally, the 2.0 mm Ø wire for the thermometer was also fitted in.

The grey wires in the bottom right corner of the fig. 3 supply power for the three 50 W resistors at the bottom of the heat sink. The fan is suspended in 1.5 mm^2 copper wires and adjusted for an evenly distributed flow along the heat sink. The thermos-sensor wire enters the oven through the 5 mm hole at the end of the oven and is placed at a distance of a few centimetres below the lower pane and equally from the vertical side of the inner box.

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Any change in the ambient temperature during the measurements will influence the readings of the temperature of the oven. Likewise, any change in the irradiation into the oven will change the temperature of the oven. To minimize such errors, I made the measurements in my apartment, which has central heating - controlled by thermostats. The measurements were made in November 2023, where the outdoor temperatures were around -5 to +10 oC. By such outdoor temperatures the thermostats of the central heating will be active, and hence, maintain a stable indoor temperature – independent of variations in the power dissipated in the oven.

7. Measuring the thermal resistance of the insulation materials.
The use of cheap and accessible materials, simple technology and low cost have had priority. Nine materials - which have been assessed to be: A. suitable and B. more (- and for some of them slightly less -) likely to find in refugee camps – have been tested for their impact on the thermal resistance between the oven and ambient.

The insulation materials, which were tested, were inserted in the 10 mm space between the outer and the inner box of the solar oven. To get a fair resolution, a sample time of 30 minutes was chosen, and the temperature was recorded over at least three hours. The readings of the temperature were made with a Fluke 189 multimeter with an accuracy of 0.1 K. During the measurements the ambient temperature was monitored by a mercury thermometer with an accuracy of 1 K.

Between measurements of each new insulation material, the oven was cooled down - first by forced cooling from the fan - and subsequent by a prolonged pause of several hours over night, to establish thermal equilibrium with the surroundings.

Of the tested materials, polystyrene came out as the best (yet, only 20% better than for plain air). Popcorn came out second best, (3.5% better than plain air). Over all, the results of table 2 were disappointing.

Insulation	Power	A1	A2	A3	A_{Mean}	τ_{12}	τ_{24}	τ_{36}	τ_{Mean}	R_{TH12}	R_{TH24}	R_{TH36}
Units	[W]	[K]	[K]	[K]	[K]	[Min.]	[Min.]	[Min.]	[Min.]	[K/W]	[K/W]	[K/W]
Air	104.5	59.7	64.5	64.4	62.9	116	128	131	125	0.571	0.617	0.616
Air	145.4	76.4	78.8	74.1	76.4	96.0	100.2	97.2	97.8	0.525	0.542	0.510
Towel	145.4	58.8	65.1	67.5	63.8	68	78	81	75.7	0.411	0.448	0.462
Cardboard	143.6	56.8	53.5	64.8	58.4	70.0	78.3	85.3	77.9	0.396	0.392	0.451
Cardboard	143.0	62.1	74.0	77.9	71.3	68.5	89.4	85.3	81.3	0.434	0.517	0.545
Paper	143.6	59.1	69.6	73.4	67.6	60.2	78.1	86.9	75.1	0.412	0.484	0.511
Hey	143.6	64.5	75.5	82.0	74.0	58.4	75.5	88.3	74.9	0.449	0.526	0.571
Wool	143.6	66.9	77.7	80.8	75.1	66.1	83.2	90.0	79.8	0.466	0.541	0.562
Fabrics	143.6	52.0	73.8	80.8	68.9	43.0	79.6	93.9	72.2	0.363	0.514	0.563
Polystyrene	145.2	75.6	82.8	88.7	82.4	76.3	87.2	131.4	98.3	0.521	0.570	0.611
Popcorn	145.2	68.8	81.2	82.8	79.0	67	93.7	89.5	83.4	0.474	0.559	0.570
Ext. duvet	98.0	52.9	57.8	62.3	57.7	82.7	93.8	107.3	94.6	0.540	0.590	0.636
Ext. duvet	145.2	69.0	80.9	85.9	71.9	64.7	82.8	92.6	80.0	0.475	0.557	0.592

Table 2. The readings of rows starting in italic are doubtful, as the thermosensor might have touched the side of the box. Ext. duvet means that a dual layer of a fibre duvet is wrapped around the outside of the oven.

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7.0 Plain air.

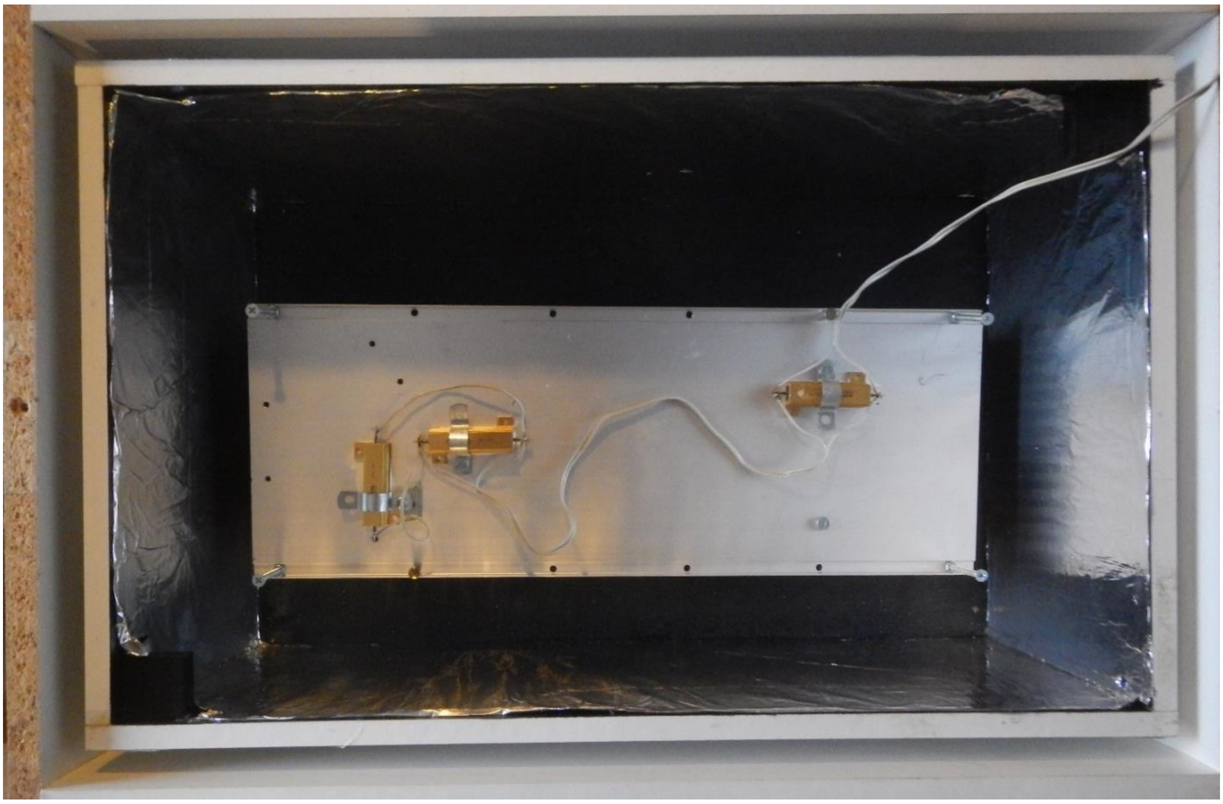

Fig. 4. The heat sink turned upside down to show the resistors. Insulation material: Plain air.

Plain air is a great insulating material for cavity walled solar ovens; it is very cheap and it is readily available – qualities, which are in short supply in refugee camps. Air has an excellent insulation property as long as the air does not move too much (i.e. limited convection). This suggest that further development of the solar oven could benefit from am optimisation of the spacing between the inner and the outer box with respect to the thermal resistance between the boxes.

In order to compare the – “by eye” measurement used in the Part 1 - to the “mathematical” method used in this Part 2, the first two tests made with the “mathematical” method – were measurement with plain air as the only insulation material. These first two tests were made for A. a power of 104.5 W and B. a power of 145.4 W.

Two series of tests of plain air as insulation material have been made using the “mathematical” method.
The one with a power dissipation of 104.5 W - yielded three thermal resistances:
A: R_{TH12} = 0.571 K/W, R_{TH24} = 0.617 K/W and R_{TH36} = 0.616 K/W.
The test series for 145.4 W yielded: B: R_{TH12} = 0.525 K/W, R_{TH24} = 0.542 K/W and R_{TH36} = 0.510 K/W.
When hereinafter the solid insulation materials have been compared to plain air, it has been the B. test series (145.4 W), which has been chosen as reference.

For both plain air tests series (A and B) the maximum thermal resistance, occurs midway on the graph.
The explanation as to why the measured thermal resistance for the 104.5 W test series comes out approx. 10% higher than for the 145.4 W series lies in the increased heat radiation by the higher temperature.

The test series A and B were compared to the calculation of the thermal resistance from the oven to the ambient – based on two different partial resistances, which were made in Part 1, section 8.5.1. One of the calculations yielded an R_{TH} = 0.52 K/W – the other 0.64 K/W – depending on which of the two partial resistances were used. These results were based upon an irradiated power of 125.1 W and an oven temperature of 90.1 ^{o}C. Both the results from the Part 1 compare well to the in Part 2 measured and calculated results for R_{TH12}, R_{TH24} and R_{TH36} from above – spanning from 0.510 to 0.617 K/W.

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Dubious test results. Insulation material: Plain air = no isolation of oven (A). Date: 2023.11.16.
NB. Please, be cautious with this set of readings. I suspect, that the thermosensor might have touched the aluminium foil of the oven during the measurements, which might have offset the temperature readings.

Heatsink dissipation 50 V / 1,97A; P = 98.5W; Fan power = 6,0 W.
Total power dissipation in the oven: 98.5 W + 6.0 W = **104.5 W**. Initial temperature T_0 = 21,2 ^oC;

No Insulation. Time:	17.30	18.00	18.30	19.00	19.30	20.00	20.30
Temperature in Oven T [^oC]	21.2	34.8	45.3	53.2	60.4	65.1	69.3
Ambient Temperature T_{Amb} [^oC]	22	22	22	22	22	22	22
Power dissipated in oven [W]	104.5	104.5	104.5	104.5	104.5	104.5	104.5
T - T_{Amb} [^oC]	0	13.6	24.1	32.0	39.2	43,9	48.1
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

Table 3. Plain air - 104.5 W.

The reading of T6 was missed by 16 minutes. T(20.46) = 72.1 oC. Applying linear extrapolation between T(20.00) and T(20.46) yields:

T20.30 = 65.1 ^oC. + (72.1 ^oC. - 65.1 ^oC.) (20.30-20.00) / (20.46 – 20.00) = 69.7 ^oC.

$A_{12} = T_1^2 / (2T_1 – T_2)$ = (13.6 K)^2 / (2 x 13.6 K - 24.1 K) = 59.7 K.
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1)))$ = (30.0 Min.) / (ln (13.6 K/ (24.1 K - 13.6 K))) = 116 min.
$T_{End} = T_{Amb} + A$ = 21.2 ^oC + 59.7 K = 80.9 ^oC. $R_{Th} = \Delta T/P$ = 59.7 K / 104.5 W = 0.571 K/W.

$A_{24} = T_2^2 / (2T_2 – T_4)$ = (24.1 K)^2 / (2 x 24.1 K - 39.2 K) = 64.5 K.
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2)))$ = (60.0 Min.) / (ln (24.1 K/ (39.2 - 24.1 K))) = 128 min.
$T_{End} = T_{Amb} + A$ = 21.2 ^oC + 64.5 K = 85.7 ^oC. $R_{Th} = \Delta T/P$ = 64.5 K / 104.5 W = 0.617 K/W.

$A_{36} = T_3^2 / (2T_3 – T_6)$ = (32.0 K)^2 / (2 x 32.0 K - 48.1 K) = 64.4 K.
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3)))$ = (90.0 Min.) / (ln (32.0 K/ (48.1 K - 32.0 K))) = 131 min.
$T_{End} = T_{Amb} + A$ = 21.2 ^oC + 64.4 K = 85.6 ^oC. $R_{Th} = \Delta T/P$ = 64.4 K / 104.5 W = 0.616 K/W.

Valid test results. Insulation material: Plain air = no isolation of oven (B). Date: 2023.11.17.
Fan power = 6,0 W; Heatsink dissipation 59.58 V / 2.34 A = 139.42 W.
Fan power + Heatsink dissipation = 6,0 W + 139.42 W = **145.4 W.**

No Insulation. Time:	8.15	8.45	9.15	9.45	10.15	10.45	11.15	11.45	12.15
Temperature in Oven T [ºC]	21.1	41.6	56.6	67.8	76.1	81,8	86.7	90.1	93.0
Ambient Temperature T_{Amb} [ºC]	22	22	22	22	22	2 2	22	22	22
Power dissipated in oven [W]	145.4	145.4	145.4	145.4	145.4	145.4	145.4	145.4	145.4
T - T_{Amb} [ºC]	0	20.5	35.5	46.7	55.0	63,7	65.2	70.0	71.9
Elapsed time [min.]	0	30	60	90	120	150	180	210	240
Column / Reading no.	0	1	2	3	4	5	6	7	8

Table 4. Plain air – 145.4 W.

$A_{12} = T_1^2 / (2T_1 – T_2) = (20.5\ K)^2 / (2 \times 20.5\ K - 35.5\ K) = 76.4\ K$.
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1))) = (30.0\ Min.) / (\ln (20.5\ K/ (35.5\ K – 20.5\ K))) = 96\ min$.
$T_{End} = T_{Amb} + A = 21.2\ ^oC + 76.4\ K = 97.6\ ^oC$. $R_{Th} = \Delta T/P = 76.4\ K / 145.4\ W = 0.525\ K/W$.

$A_{24} == T_2^2 / (2T_2 – T_4) = (35.5\ K)^2 / (2 \times 35.5\ K - 55.0\ K) = 78.8\ K$.
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2))) = (60.0\ Min.) / (\ln (35.5\ K/ (55.0 - 35.5\ K))) = 100.2\ min$.
$T_{End} = T_{Amb} + A = T_{End} = 21.2\ ^oC + 78.8\ K = 100.0\ ^oC$. $R_{Th} = \Delta T/P = 78.8\ K / 145.4\ W = 0.542\ K/W$.

$A_{36} = T_3^2 / (2T_3 – T_6) = (46.7\ K)^2 / (2 \times 46.7\ K - 65.2\ K) = 74.1\ K$.
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3))) = (90.0\ Min.) / (\ln (46.7\ K/ (65.2\ K - 46.7\ K))) = 97.2\ min$.
$T_{End} = T_{Amb} + A = 21.2\ ^oC + 74.1\ K = 95.3\ ^oC$. $R_{Th} = \Delta T/P = 74.1\ K / 145.4\ W = 0.510\ K/W$.

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7.1. Thick fabrics in form of two towels.

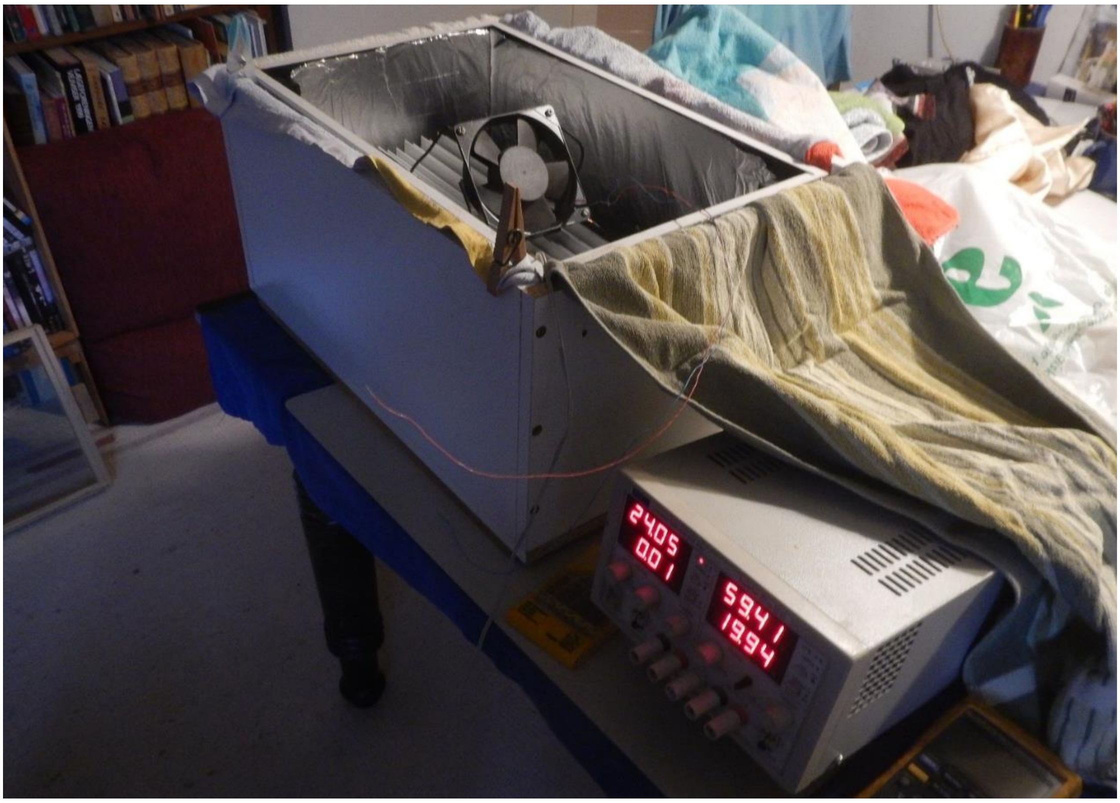

Fig. 5. Insulation material: Two towels. Left: solar oven, middle: Power supply (24 V and 59.4 V) right: multimeter.

Two towels with a thickness of approximate 4 mm were suspended in the space between the two boxes. I had problems to keep the towels in the place, particularly where the edges of the towels merged - and along the top rims of the boxes. Hence, the lid of the solar oven did not fit well into the trench along the top of the oven. More over, the towels waved forth and back in the space between the walls causing a lot of physical contact between the inner and the outer box, which in turn can have led to a rise in the thermal conduction between the boxes.

Test results for one layer of towel. Date: 2023.11.17.

The two towels were inserted as a single layer in the space between the two boxes of the oven. The suspension of the towels was, however, doubtful and it did not fit tight to the lit. Hence, the results are doubtful.

Fan power = 6,0 W; Heatsink dissipation 59.58 V / 2.34 A = 139.4 W.
Fan power + Heatsink dissipation = 6,0 W + 139.4 W = 145.4 W.

Insulation: Towel. Time:	15.30	16.00	16.30	17.00	17.30	18.00	18.30
Temperature in Oven T [ºC]	22.1	44.2	58,0	67.4	74.1	79.1	82.3
Ambient Temperature T_{Amb} [ºC]	22	22	22	22	22	22	22
Power dissipated in oven [W]	145.4	145.4	145.4	145.4	145.4	145.4	145.4
T - T_{Amb} [ºC]	0	22.1	35.9	45.3	52.0	57.0	60.2
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

Table 5. Towels.

$A_{12} = T_1^2 / (2T_1 – T_2) = (22.1 K)^2 / (2 x 22.1 K - 35.9 K) = 58.8 K.$
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1))) = (30.0 Min.) / (\ln (20.5 K/ (35.9 K – 22.1 K))) = 68 min.$
$T_{Amb} + A = T_{End} = 21.2 ºC + 58.8 K = 80.0 ºC.$ $R_{Th} = \Delta T/P = 58.8 K / 145.4 W = 0.405 K/W.$

$A_{24} = T_2^2 / (2T_2 – T_4) = (35.9 K)^2 / (2 x 35.9 K - 52.0 K) = 65.1 K.$
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2))) = (60.0 Min.) / (\ln (35.5 K/ (52.0 - 35.9 K))) = 78.3 min.$
$T_{End} = T_{Amb} + A =21.2 ºC + 78.8 K = 100.0 ºC.$ $R_{Th} = \Delta T/P = 65.1 K / 145.4 W = 0.448 K/W.$

$A_{36} = T_3^2 / (2T_3 – T_6) = (45.3 K)^2 / (2 x 45.3 K – 60.2 K) = 67.5 K.$
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3))) = (90.0 Min.) / (\ln (45.3 K/ (60.2 K – 45.3 K))) = 80.9 min.$
$T_{End} = T_{Amb} + A = 21.2 ºC + 67.5 K = 88.7 ºC.$ $R_{Th} = \Delta T/P = 67.2 K / 145.4 W = 0.462 K/W.$

The results were disappointing - R_{TH12} = 0.411 K/W, R_{TH24} = 0.448 K/W and R_{TH36} = 0.462 K/W.
And comparing with plain air, which had: R_{TH12} = 0.525 K/W, R_{TH24} = 0.542 K/W and R_{TH36} = 0.510 K/W,

Compared to plain air the insulation of the oven *increased / worsened* by: -20%, -18% and –9 %.

7.2. Cardboard 2.5 mm.
Stiff cardboard pieces were cut to sizes, which fitted tight and well into the oven. The type of cardboard was two layers with air canals.

When the results were calculated to R_{TH12} = 0.396 K/W, R_{TH24} = 0.392 K/W and R_{TH36} = 0.451 K/W, it was evident, that something had gone wrong. It was discovered that during the heating of the oven, the thermosensor had been touching the aluminium foil glued on to the inner side of the inner box, thereby cooling the sensor.

The following test results are erroneous! Insulated with 2.5 mm cardboard. Date: 2023.11.19
NB. Please, be cautious with this set of readings, as I later found that the thermosensor might have touched the internal aluminium foil of the inner box during the measurements. For the correct readings, see next pages.

Fan power = 6,0 W; Heatsink dissipation 59.58 V / 2.31 A = 137.6 W.
Fan power + Heatsink dissipation = 6,0 W + 137.6 W = 143.6 W.

Insulation: Cardboard. Time:	8.05	8.35	9.05	9.35	10.05	10.35	11.05	11.35	12.05
Temperature in Oven T [ºC]	20.9	40.7	53.6	63.1	67.3	73,5	77.8	80.9	83.3
Ambient Temperature T_{Amb} [ºC]	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5
Power dissipated in oven [W]	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6
T - T_{Amb} [ºC]	0	19.8	32.7	42.2	46.4	52,6	56.9	60.0	62.4
Elapsed time [min.]	0	30	60	90	120	150	180	210	240
Column / Reading no.	0	1	2	3	4	5	6	7	8

Table 6. Cardboard.

$A_{12} = T_1^2 / (2T_1 – T_2) = (19.8\ K)^2 / (2 \times 19.8\ K - 32.7\ K) = 56.8\ K.$
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1))) = (30.0\ Min.) / (\ln (19.8\ K/ (32.7\ K – 19.8\ K))) = 70\ min.$
$T_{End} = T_{Amb} + A = 21.2\ ^oC + 56.8\ K = 78.0\ ^oC.$ $R_{Th} = \Delta T/P = 56.8\ K / 143.6\ W = 0.396\ K/W.$

$A_{24} = T_2^2 / (2T_2 – T_4) = (32.7\ K)^2 / (2 \times 32.7\ K - 46.4\ K) = 56.3\ K.$
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2))) = (60.0\ Min.) / (\ln (35.5\ K/ (46.4 - 32.7\ K))) = 78.3\ min.$
$T_{End} = T_{Amb} + A = 21.2\ ^oC + 56.3\ K = 77.5\ ^oC.$ $R_{Th} = \Delta T/P = 56.3\ K / 143.6\ W = 0.392\ K/W.$

$A_{36} = T_3^2 / (2T_3 – T_6) = (42.2\ K)^2 / (2 \times 42.2\ K – 56.9\ K) = 64.8\ K.$
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3))) = (90.0\ Min.) / (\ln (42.2\ K/ (56.9\ K – 42.2\ K))) = 85.3\ min.$
$T_{End} = T_{Amb} + A = 21.2\ ^oC + 64.8\ K = 86.0\ ^oC.$ $R_{Th} = \Delta T/P = 64.8\ K / 143.6\ W = 0.451\ K/W.$

The oven was left to cool down and the next day (see next page) a new test was made, yielding valid results:
R_{TH12} = 0.434 K/W, R_{TH24} = 0.517 K/W and R_{TH36} = 0.545 K/W.
When comparing with plain air, which had: R_{TH12} = 0.525 K/W, R_{TH24} = 0.542 K/W and R_{TH36} = 0.510 K/W
Relative to plain air the insulation of the oven *increased / worsened* by: -17%, -5% and +7 %.

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Rectified test results for the 2.5 mm cardboard insulation (replacing the results of last page).
Date: 2023.11.20 **-** and now with the thermo-sensor retracted 2 cm from the internal side of the inner box!

Fig. 6. Insulation: 2.5 mm cardboard.

Fan power = 6,0 W; Heatsink dissipation 59.58 V / 2.30 A = 137.0 W.
Fan power + Heatsink dissipation = 6,0 W + 137.0 W = 143.0 W.

Insulation: Cardboard. Time:	9.00	9.30	10.00	10.30	11.00	11.30	12.00	12.30	13.00
Temperature in Oven T [ºC]	21.6	43.6	57.8	68.2	76.3	82.0	?	?	92.6
Ambient Temperature T_{Amb} [ºC]	22	22	22	22	22	22	22	22	22
Power dissipated in oven [W]	143.0	143.0	143.0	143.0	143.0	143.0	143.0	143.0	143.0
T - T_{Amb} [ºC]	0	22.0	36.2	46.6	54.7	60.4	?	?	71.0
Elapsed time [min.]	0	30	60	90	120	150	180	210	240
Column / Reading no.	0	1	2	3	4	5	6	7	8

Table 7. Cardboard.

$A_{12} = T_1^2 / (2T_1 – T_2) = (22.0\ K)^2 / (2 \times 22.0\ K - 36.2\ K) = 62.1\ K.$
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1))) = (30.0\ Min.) / (\ln (22.0\ K/ (36.2\ K – 22.0\ K))) = 68.5\ min.$
$T_{End} = T_{Amb} + A = 21.2\ ºC + 62.1\ K = 83.3\ ºC.$ $R_{Th} = \Delta T/P = 62.1\ K / 143.0\ W = 0.434\ K/W.$

$A_{24} = T_2^2 / (2T_2 – T_4) = (36.2\ K)^2 / (2 \times 36.2\ K - 54.7\ K) = 74.0\ K.$
$\tau_{24} = t_1 / (\ln (T_2 / (T_4 – T_2))) = (60.0\ Min.) / (\ln (35.5\ K/ (54.7 - 36.2\ K))) = 89.4\ min.$
$T_{End} = T_{Amb} + A = 21.2\ ºC + 74.0\ K = 95.2\ ºC.$ $R_{Th} = \Delta T/P = 74.0\ K / 143.0\ W = 0.517\ K/W.$

NB. I missed the readings at t_6 and t_7. Hence, A_{36} and τ_{36} have been replaced with A_{48} and τ_{48}.
$A_{48} = T_4^2 / (2T_4 – T_8) = (54.7\ K)^2 / (2 \times 54.7\ K – 71.0\ K) = 77.9\ K.$
$\tau_{48} = t_1 / (\ln (T_4 / (T_8 – T_4))) = (120.0\ Min.) / (\ln (54.7\ K/ (71.0\ K – 54.7\ K))) = 85.3\ min.$
$T_{End} = T_{Amb} + A = 21.2\ ºC + 77.9\ K = 99.1\ ºC.$ $R_{Th} = \Delta T/P = 77.9\ K / 143.0\ W = 0.545\ K/W.$

7.3. Paper balls.

Fig. 7. Insulation: Hand curled paper balls.

The thickness of the paper used for the paper balls was approximate 100 µm. It had been cut to sheets in a size of approximate 50 x 100 mm that were curled by hand to form paper balls with a diameter of 10 – 15 mm. The intension was to form paper balls with a diameter slightly bigger than the space between the boxes so that they could be kept in position / suspended between the vertical sides of boxes. The aim was – that only a minimum of the paper surface should touch the sides of the boxes (in order to minimize the heat conduction through the paper) - while still obstructing airflow / i.e. convection in the space between the boxes.

It turned out to be a challenge to achieve both objectives. Without experience you will easily either pack the paper balls too dense – causing excessive heat conduction from the inner- to the outer box – or you might pack the paper balls too sparsely – causing insufficient obstruction to the air flow in the gap between the inner- and the outer box. I have properly packed the oven too densely and thereby caused an excessive heat conduction from the inner- to the outer box.

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Test results. Insulation: Paper balls with a diameter = ca. 10 mm. The oven was stuffed! Date: 2023.11.21.
Fan power = 6,0 W; Heatsink dissipation 59.58 V / 2.31 A = 137.6 W.
Fan power + Heatsink dissipation = 6,0 W + 137.6 W = 143.6 W.

Insulation: Paper balls. Time:	17.30	18.00	18.30	19.00	19.30	20.00	20.30	21.00	21.30
Temperature in Oven T [ºC]	21.7	44.9	59.0	69.0	76.3	81.7	85.8	88.9	91.2
Ambient Temperature T_{Amb} [ºC]	22	22	22	22	22	22	22	22	23
Power dissipated in oven [W]	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6
T - T_{Amb} [ºC]	0	23.2	37.3	47.3	54.6	60.0	64.1	67.2	69.5
Elapsed time [min.]	0	30	60	90	120	150	180	210	240
Column / Reading no.	0	1	2	3	4	5	6	7	8

Table 8. Hand curled paper balls.

$A_{12} = T_1^2 / (2T_1 – T_2) = (23.2\ K)^2 / (2 x 23.2\ K - 37.3\ K) = 59.1\ K$.
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1))) = (30.0\ Min.) / (\ln (23.2\ K/ (37.3\ K – 23.2\ K))) = 60.2\ min$.
$T_{End} = T_{Amb} + A = 21.7\ ºC + 59.1\ K = 80.8\ ºC$. $R_{Th} = \Delta T/P = 59.1\ K / 143.6\ W = 0.412\ K/W$.

$A_{24} = T_2^2 / (2T_2 – T_4) = (37.3\ K)^2 / (2 x 37.3\ K - 54.6\ K) = 69.6\ K$.
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2))) = (60.0\ Min.) / (\ln (37.3\ K/ (54.6 - 37.3\ K))) = 78.1\ min$.
$T_{End} = T_{Amb} + A = 21.2\ ºC + 69.6\ K = 90.8\ ºC$. $R_{Th} = \Delta T/P = 69.6\ K / 143.6\ W = 0.484\ K/W$.

$A_{36} = T_3^2 / (2T_3 – T_6) = (47.3\ K)^2 / (2 x 47.3\ K – 64.1\ K) = 73.4\ K$.
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3))) = (90.0\ Min.) / (\ln (47.3\ K/ (64.1\ K – 47.3\ K))) = 86.9\ min$.
$T_{End} = T_{Amb} + A = 21.2\ ºC + 73.4\ K = 94.6\ ºC$. $R_{Th} = \Delta T/P = 73.4\ K / 143.6\ W = 0.511\ K/W$.

$A_{48} = T_4^2 / (2T_4 – T_8) = (54.6\ K)^2 / (2 x 54.6\ K – 69.5\ K) = 75.1\ K$.
$\tau_{48} = t_4 / (\ln (T_4 / (T_8 – T_4))) = (120.0\ Min.) / (\ln (54.6\ K/ (69.5\ K – 54.6\ K))) = 92.4\ min$.
$T_{End} = T_{Amb} + A = 21.2\ ºC + 75.1\ K = 96.3\ ºC$. $R_{Th} = \Delta T/P = 75.1\ K / 143.6\ W = 0.523\ K/W$.

The results of the paper ball test were: $R_{TH12} = 0.412$ K/W, $R_{TH24} = 0.484$ K/W and $R_{TH36} = 0.511$ K/W.
And comparing with plain air, which had: $R_{TH12} = 0.525$ K/W, $R_{TH24} = 0.542$ K/W and $R_{TH36} = 0.510$ K/W
Relative to plain air the insulation of the oven *increased+ / worsened-* by: -22 %, -11 % and +0 %.

7.4. Hey.

Fig. 8. *The grass, which I cut from my allotment -*

Fig. 9. The hey which it had turned into three months later.

In the summer 2023 grass and weed had taken over a patch of my allotment. I cut the grass, collected it in a 35 litre black plastic bowl and stored it in darkness to dry by eight degrees in my basement. The length of the grass strays ranged from ten to twenty centimetres. With the hey straws aligned, the hey straws pack tight and nicely with each other and they appear to form a good obstruction to convection. Both the bottom and the vertical trenches were lightly packed.

Test results. Insulation: Lightly stuffed hey. Date: 2023.11.23.
Fan power = 6,0 W; Heatsink dissipation 59.58 V / 2.31 A = 137.6 W.
Fan power + Heatsink dissipation = 6,0 W + 137.6 W = 143.6 W.

Insulation: Hey. Time:	19.30	20.00	20.30	21.00	21.30	22.00	22.30	23.00	23.36
Temperature in Oven T [ºC]	21.4	47.3	62.8	73.8	81.5	88.1	92.7	96.1	98,8.
Ambient Temperature T_{Amb} [ºC]	21.5	21.5	22	22	22	22	22	22	23
Power dissipated in oven [W]	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6
T - T_{Amb} [ºC]	0	25.9	41.4	52.4	60.1	66.7	71.3	74.7.	77.4
Elapsed time [min.]	0	30	60	90	120	150	180	210	240
Column / Reading no.	0	1	2	3	4	5	6	7	8

Table 9. Hey.

$A_{12} = T_1^2 / (2T_1 – T_2) = (25.9\ K)^2 / (2 \times 25.9\ K - 41.4\ K) = 64.5\ K$.
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1))) = (30.0\ Min.) / (\ln (25.9\ K/ (41.4\ K – 25.9\ K))) = 58.4\ min$.
$T_{End} = T_{Amb} + A = 21.4\ ºC + 64.5\ K = 85.6\ ºC$. $R_{Th} = \Delta T/P = 64.5\ K / 143.6\ W = 0.449\ K/W$.

$A_{24} = T_2^2 / (2T_2 – T_4) = (41.4\ K)^2 / (2 \times 41.4\ K - 60.1\ K) = 75.5\ K$.
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2))) = (60.0\ Min.) / (\ln (41.4\ K/ (60.1 - 41.4\ K))) = 75.5\ min$.
$= T_{End} = T_{Amb} + A = 21.2\ ºC + 75.5\ K = 96.7\ ºC$. $R_{Th} = \Delta T/P = 75.5\ K / 143.6\ W = 0.526\ K/W$.

$A_{36} = T_3^2 / (2T_3 – T_6) = (52.4\ K)^2 / (2 \times 52.4\ K – 71.3\ K) = 82.0\ K$.
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3))) = (90.0\ Min.) / (\ln (52.4\ K/ (71.3\ K – 52.4\ K))) = 88.3\ min$.
$T_{End} = T_{Amb} + A = 21.2\ ºC + 82.0\ K = 103.2\ ºC$. $R_{Th} = \Delta T/P = 82.0\ K / 143.6\ W = 0.571\ K/W$.

$A_{48} = T_1^2 / (2T_1 – T_2) = (60.1\ K)^2 / (2 \times 60.1\ K – 77.4\ K) = 84.4\ K$.
$\tau_{48} = t_4 / (\ln (T_4 / (T_8 – T_4))) = (120.0\ Min.) / (\ln (60.1\ K/ (77.4\ K – 60.1\ K))) = 96.4\ min$.
$T_{End} = T_{Amb} + A = 21.2\ ºC + 84.4\ K = 105.6\ ºC$. $R_{Th} = \Delta T/P = 84.4\ K / 143.6\ W = 0.588\ K/W$.

The results of the hey test were: $R_{TH12} = 0.449$ K/W, $R_{TH24} = 0.526$ K/W and $R_{TH36} = 0.571$ K/W.
And comparing with plain air, which had: $R_{TH12} = 0.525$ K/W, $R_{TH24} = 0.542$ K/W and $R_{TH36} = 0.510$ K/W
Relative to plain air the insulation of the oven *increased / worsened* by: -14%, -3% and +12 %.

The results are disappointing and I cannot provide any good explanation for them.

7.5. Wool – untreated - straight from the sheep.

Fig. 10. *A kind lady, who raises her own sheep and trades in raw wool, has sponsored this project with a plastic bag of her wool. I distributed the wool lightly and evenly. I stuffed the space between the boxes lightly.*

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Test results. Insulated with lightly stuffed untreated / raw wool. Date: 2023.11.23
Fan power + Heatsink dissipation = 6,0 W + 137.6 W = 143.6 W.

Insulation: Wool. Time:	10.30	11.00	11.30	12.00	12.30	13.00	13.30	14.00	14.30
Temperature in Oven T [ºC]	21.9	46.3	61.8	73.0	81.2	87.1	91.8	95.4	98.1
Ambient Temperature T_{Amb} [ºC]	21.5	21.5	22	22	22	22	22	22	23
Power dissipated in oven [W]	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6
$T - T_{Amb}$ [ºC]	0	24.4	39.9	51.1	59.3	65.2	69.9	73.5	76.2
Elapsed time [min.]	0	30	60	90	120	150	180	210	240
Column / Reading no.	0	1	2	3	4	5	6	7	8

Table 10. Wool.

$A_{12} = T_1^2 / (2T_1 – T_2) = (24.4 K)^2 / (2 x 24.4 K - 39.9 K) = 66.9 K.$
$τ_{12} = t_1 / (ln (T_1 / (T_2 – T_1))) = (30.0 Min.) / (ln (24.4 K/ (39.9 K – 24.4 K))) = 66.1 min.$
$T_{End} = T_{Amb} + A = 21.4\,^oC + 66.9 K = 88.3\,^oC.$ $R_{Th} = ΔT/P = 64.5 K / 143.6 W = 0.466 K/W.$

$A_{24} = T_2^2 / (2T_2 – T_4) = (39.9 K)^2 / (2 x 39.9 K - 59.3 K) = 77.7 K.$
$τ_{24} = t_2 / (ln (T_2 / (T_4 – T_2))) = (60.0 Min.) / (ln (39.9 K/ (59.3 K - 39.9 K))) = 83.2 min.$
$T_{End} = T_{Amb} + A = 21.2\,^oC + 77.7 K = 98.9\,^oC.$ $R_{Th} = ΔT/P = 77.7 K / 143.6 W = 0.541 K/W.$

$A_{36} = T_3^2 / (2T_3 – T_6) = (51.1 K)^2 / (2 x 51.1 K – 69.9 K) = 80.8 K.$
$τ_{36} = t_3 / (ln (T_3 / (T_6 – T_3))) = (90.0 Min.) / (ln (51.1 K/ (69.9 K – 51.1 K))) = 90.0 min.$
$T_{End} = T_{Amb} + A = 21.2\,^oC + 80.8 K = 102.0\,^oC.$ $R_{Th} = ΔT/P = 80.8 K / 143.6 W = 0.562 K/W.$

$A_{48} = T_4^2 / (2T_4 – T_8) = (59.3 K)^2 / (2 x 59.3 K – 76.2 K) = 82.9 K.$
$τ_{48} = t_4 / (ln (T_4 / (T_8 – T_4))) = (120.0 Min.) / (ln (59.3 K/ (76.2 K – 59.3 K))) = 92.4 min.$
$T_{End} = T_{Amb} + A = 21.2\,^oC + 82.9 K = 104.1\,^oC.$ $R_{Th} = ΔT/P = 82.9 K / 143.6 W = 0.577 K/W.$

By an internal temperature of 81.2 ºC the external temperature of the vertical outside was 23 ºC and the temperature of the horizontal external glass pane was 30 ºC (measured with a mercury thermometer).

By an internal temperature of 98.8 ºC the external temperature of the horizontal external glass pane was still 30 ºC! This must certainly be a fault – please refer to section 7.10.

The following test results were obtained: $R_{TH12} = 0.466$ K/W, $R_{TH24} = 0.541$ K/W and $R_{TH36} = 0.562$ K/W.
And comparing with plain air, which had: $R_{TH12} = 0.525$ K/W, $R_{TH24} = 0.542$ K/W and $R_{TH36} = 0.510$ K/W
Relative to plain air the insulation of the oven *increased / worsened* by: -11%, -0% and +10%.

Again, I must confess that the results are disappointing and that I cannot provide any good explanation.

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7.6. Thin fabrics – in form of a shirt and a skirt – suspended on cardboard.

Fig. 11. Insulation material: Thin fabrics - in form of a shirt and a skirt suspended on cardboard.

Thin fabrics were tested. To keep it in place in the vertical trenches I used 2.5 mm cardboard as hangers and the fabrics was placed at the inner side of the cardboard. The fabrics consisted of a white shirt (weight = 174 gram) covering the bottom and three of the four vertical sides. A white, blue yellow skirt (weight = 112 gram) covered the fourth side.

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Test results. Isolation: Cardboard and thin fabrics. Date: 2023.11.24.
Fan power = 6,0 W; Heatsink dissipation 59.58 V / 2.31 A = 137.6 W.
Fan power + Heatsink dissipation = 6,0 W + 137.6 W = 143.6 W.

Insulation: Cardboard & Fabrics. Time:	7.00	7.30	8.00	8.30	9.00	9.30	10.00	10.30	11.00
Temperature in Oven T [ºC]	21.5	47.6	60.6	71.3	79.0	85.0	89.4	92.7	95.3
Ambient Temperature T_{Amb} [ºC]	22	22	22	22	22	22	22	22	22
Power dissipated in oven [W]	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6	143.6
T - T_{Amb} [ºC]	0	26.1	39.1	49.8	57.5	63.5	68.9	71.2	73.8
Elapsed time [min.]	0	30	60	90	120	150	180	210	240
Column / Reading no.	0	1	2	3	4	5	6	7	8

Table 11. Thin fabrics.

$A_{12} = T_1^2 / (2T_1 – T_2) = (26.1\text{ K})^2 / (2 \times 26.1\text{ K} - 39.1\text{ K}) = 52.0\text{ K}$.
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1))) = (30.0\text{ Min.}) / (\ln (26.1\text{ K}/ (39.1\text{ K} – 26.1\text{ K}))) = 43.0\text{ min}$.
$T_{End} = T_{Amb} + A = 21.5\text{ ºC} + 52.0\text{ K} = 74.5\text{ ºC}$. $R_{Th} = \Delta T/P = 52.0\text{ K} / 143.6\text{ W} = 0.363\text{ K/W}$.

$A_{24} = T_2^2 / (2T_2 – T_4) = (39.1\text{ K})^2 / (2 \times 39.1\text{ K} - 57.5\text{ K}) = 73.8\text{ K}$.
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2))) = (60.0\text{ Min.}) / (\ln (39.1\text{ K}/ (57.5\text{ K} - 39.1\text{ K}))) = 79.6\text{ min}$.
$T_{End} = T_{Amb} + A = 21.5\text{ ºC} + 73.8\text{ K} = 95.4\text{ ºC}$. $R_{Th} = \Delta T/P = 73.8\text{ K} / 143.6\text{ W} = 0.514\text{ K/W}$.

$A_{36} = T_3^2 / (2T_3 – T_6) = (49.8\text{ K})^2 / (2 \times 49.8\text{ K} – 68.9\text{ K}) = 80.8\text{ K}$.
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3))) = (90.0\text{ Min.}) / (\ln (49.8\text{ K} / (68.9\text{ K} – 49.8\text{ K}))) = 93.9\text{ min}$.
$T_{End} = T_{Amb} + A = 21.5\text{ ºC} + 80.8\text{ K} = 102.3\text{ ºC}$. $R_{Th} = \Delta T/P = 80.8\text{ K} / 143.6\text{ W} = 0.563\text{ K/W}$.

$A_{48} = T_4^2 / (2T_4 – T_8) = (57.5\text{ K})^2 / (2 \times 57.5\text{ K} – 73.8\text{ K}) = 80.2\text{ K}$.
$\tau_{48} = t_4 / (\ln (T_4 / (T_8 – T_4))) = (120.0\text{ Min.}) / (\ln (57.5\text{ K}/ (73.8\text{ K} – 57.5\text{ K}))) = 95.2\text{ min}$.
$T_{End} = T_{Amb} + A = 21.2\text{ ºC} + 80.2\text{ K} = 101.4\text{ ºC}$. $R_{Th} = \Delta T/P = 80.2\text{ K} / 143.6\text{ W} = 0.559\text{ K/W}$.

The test results were: R_{TH12} = 0.363 K/W, R_{TH24} = 0.514 K/W and R_{TH36} = 0.563 K/W.
And comparing with plain air, which had: R_{TH12} = 0.525 K/W, R_{TH24} = 0.542 K/W and R_{TH36} = 0.510 K/W
Relative to plain air the insulation of the oven *increased / worsened* by: -31%, -5% and +10%.

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7.7. Polystyrene.

Fig. 12. Insulation material: Polystyrene Thickness 10 mm. A scalpel and a breadboard were used for the sizing.

A friend of mine, who was formerly employed with the Danish Technological Institute, suggested to try to test polystyrene. I cannot recall ever to have seen polystyrene in Africa, but he claimed that polystyrene can be found everywhere.

Polystyrene have excellent thermal insulation properties, it is light and can easily be shaped with a common knife. Polystyrene is the most common kind of plastic and it is 100% recyclable. The disadvantage of polystyrene is its high flammability. Extruded Polystyrene (EPS) will soften and start to melt if exposed to temperatures higher than 100°C. Usually at temperatures of 200°C and above, the material will give off flammable gases, which can combust into flames. Polystyrene is cheap. (I paid approximate 1.50 US$ retail price for piece sized 10 x 600 x 1200 mm, which was enough to line the solar oven).

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Test results. Insulated with polystyrene, thickness 10 mm. Date: 2023.12.02.
Fan power = 6,0 W; Heatsink dissipation by start-up 60.00 V / 2.33 A = 139.8 W.
Fan power + Heatsink dissipation = 6,0 W + 139.8 W = 145.8 W.

Insulation: Polystyrene. Time:	9.00	9.30	10.00	10.30	11.00	11.30	12.00	12.30	13.00
Temperature in Oven T [ºC]	21.0	45,6	62.2	74.1	82.9	89.3	94.4	98.3	101.4
Ambient Temperature T_{Amb} [ºC]	21	21	21	21	21	21	21	21	21
Power dissipated in oven [W]	145.8	145.2	145.2	145.2	145.2	145.2	145.2	145.2	145.2
$T - T_{Amb}$ [ºC]	0	24.6	41.2	53.1	61.9	69.3	74.4	78.3	81.4
Elapsed time [min.]	0	30	60	90	120	150	180	210	240
Column / Reading no.	0	1	2	3	4	5	6	7	8

Table 12. Polystyrene Thickness 10 mm.

$A_{12} = T_1^2 / (2T_1 – T_2) = (24.6\ K)^2 / (2 \times 24.6\ K - 41.2\ K) = 75.6\ K.$
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1))) = (30.0\ Min.) / (\ln (24.6\ K/ (41.2\ K – 24.6\ K))) = 76.3\ min.$
$T_{End} = T_{Amb} + A = 21.0\ ^oC + 75.6\ K = 96.6\ ^oC.$ $R_{Th} = \Delta T/P = 75.6\ K / 145.2\ W = 0.521\ K/W.$

$A_{24} = T_2^2 / (2T_2 – T_4) = (41.2\ K)^2 / (2 \times 41.2\ K - 61.9\ K) = 82.8\ K.$
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2))) = (60.0\ Min.) / (\ln (41.2\ K / (61.9 - 41.2\ K))) = 87.2\ min.$
$T_{End} = T_{Amb} + A = 21.0\ ^oC + 82.8\ K = 103.8\ ^oC.$ $R_{Th} = \Delta T/P = 82.8\ K / 145.2\ W = 0.570\ K/W.$

$A_{36} = T_3^2 / (2T_3 – T_6) = (53.1\ K)^2 / (2 \times 53.1\ K – 74.4\ K) = 88.7\ K.$
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3))) = (120.0\ Min.) / (\ln (53.1\ K/ (74.4\ K – 53.1\ K))) = 131.4\ min.$
$T_{End} = T_{Amb} + A = 21.2\ ^oC + 88.7\ K = 109.9\ ^oC.$ $R_{Th} = \Delta T/P = 88.7\ K / 145.2\ W = 0.611\ K/W.$

$A_{48} = T_4^2 / (2T_4 – T_8) = (61.9\ K)^2 / (2 \times 61.9\ K – 81.8\ K) = 91.2\ K.$
$\tau_{48} = t_4 / (\ln (T_4 / (T_8 – T_4))) = (150.0\ Min.) / (\ln (61.9\ K/ (81.8\ K – 61.9\ K))) = 132.2\ min.$
$T_{End} = T_{Amb} + A = 21.2\ ^oC + 91.2\ K = 112.4\ ^oC.$ $R_{Th} = \Delta T/P = 91.2\ K / 145.2\ W = 0.628\ K/W.$

The test results were: $R_{TH12} = 0.531$ K/W, $R_{TH24} = 0.570$ K/W and $R_{TH36} = 0.611$ K/W.
And comparing with plain air, which had: $R_{TH12} = 0.525$ K/W, $R_{TH24} = 0.542$ K/W and $R_{TH36} = 0.510$ K/W
Compared to plain air the insulation of the oven *increased* by: +1 %, +5 % and +20 %.

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7.8. Popcorn.

Fig. 13. Insulation material: Popcorn.

I discussed the results of the first seven tests of insulation materials with my friend Jesper Berggreen, who grew up in Zambia, where both he and I have been treated to the national meal - ugali (i.e. corn porridge). Jesper came up with the bright idea to use popcorn as insulation material. Corn is ubiquitous in Africa and can easily be popped in a pot. Remember to use a lit – if not - it will jump all over! Thus, I bought a bag of unpopped corn, popped them and covered ca. 80% of the bottom of the oven with popcorn.

When corn pops, it swells up to an irregular ball with a diameter of 10-20 mm. As I tried to fill up the vertical space between the two boxes of the oven, I had expected to have to crush the popcorn balls to get them fit into the vertical space along the sides of solar oven. But when popcorn crush, a lot of corn dust is generated - dust which fills up - and bridge the gap between the boxes, thus causing an increased heat loss. Hence, I decided to test the oven with popcorn covering only the bottom of the outer box, and a minor fraction of one of the sides of the oven. The test of a completely filled space between the vertical sides is postponed until a solar oven will be available with a 15 or 20 mm space between the boxes.

Test results. Insulation material: Popcorn. Date: 2023.12.04.
The bottom was covered to a degree where it could only just be seen. The vertical trenches between the boxes were empty – except for one (long) side, which was filled up to a height of approx. 50 mm.
Heatsink dissipation 60 V / 2.32A; P = 139.2W; Fan power = 6,0 W.
Total power dissipation in the oven: 139.2 W + 6.0 W = 145.2 W.

Insulation: Popcorn. Time:	8.00	8.30	9.00	9.30	10.00	10.30	11.00
Temperature in Oven T [ºC]	21.5	46.1	61.9	73.6	82.2	88.6	93.2
Ambient Temperature T_{Amb} [ºC]	22	22	22	22	22	22	22
Power dissipated in oven [W]	145.2	145.2	145.2	145.2	145.2	145.2	145.2
T - T_{Amb} [ºC]	0	24.6	40.4	51.1	60.7	67.1	71.7
Elapsed time [min.]	0	30	60	90	120	150	180
Column / Reading no.	0	1	2	3	4	5	6

Table 13. Popcorn.

$A_{12} = T_1^2 / (2T_1 – T_2) = (24.6\ K)^2 / (2 \times 24.6\ K - 40.4\ K) = 68.8\ K.$
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1))) = (30.0\ Min.) / (\ln (24.6\ K/ (40.4\ K - 24.6\ K))) = 67\ min.$
$T_{End} = T_{Amb} + A = 21.5\ ºC + 68.8\ K = 90.3\ ºC.$ $R_{Th} = \Delta T/P = 68.8\ K / 145.2\ W = 0.474\ K/W.$

$A_{24} = T_2^2 / (2T_2 – T_4) = (40.4\ K)^2 / (2 \times 40.4\ K - 60.7\ K) = 81.2\ K.$
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2))) = (60.0\ Min.) / (\ln (40.4\ K/ (61.7 - 40.4\ K))) = 93.7\ min.$
$T_{End} = T_{Amb} + A = 21.2\ ºC + 81.2\ K = 102.4\ ºC.$ $R_{Th} = \Delta T/P = 81.2\ K / 145.2\ W = 0.559\ K/W.$

$A_{36} = T_3^2 / (2T_3 – T_6) = (52.5\ K)^2 / (2 \times 52.5\ K – 71.7\ K) = 82.8\ K.$
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3))) = (90.0\ Min.) / (\ln (52.5\ K/ (71.7\ K - 52.5\ K))) = 89.5\ min.$
$T_{End} = T_{Amb} + A = 21.2\ ºC + 118.5\ K = 139.7\ ºC.$ $R_{Th} = \Delta T/P = 82.8\ K / 145.2\ W = 0.570\ K/W.$

The test results were: R_{TH12} = 0.474 K/W, R_{TH24} = 0.559 K/W and R_{TH36} = 0.570 K/W.
And comparing with plain air, which had: R_{TH12} = 0.525 K/W, R_{TH24} = 0.542 K/W and R_{TH36} = 0.510 K/W.
Relative to plain air the insulation of the oven *increased / worsened* by: -10 %, +3 % and +12 %.

7.9. Measurement with the oven wrapped in a fibre duvet – with no solid insulation filling of the cavity.

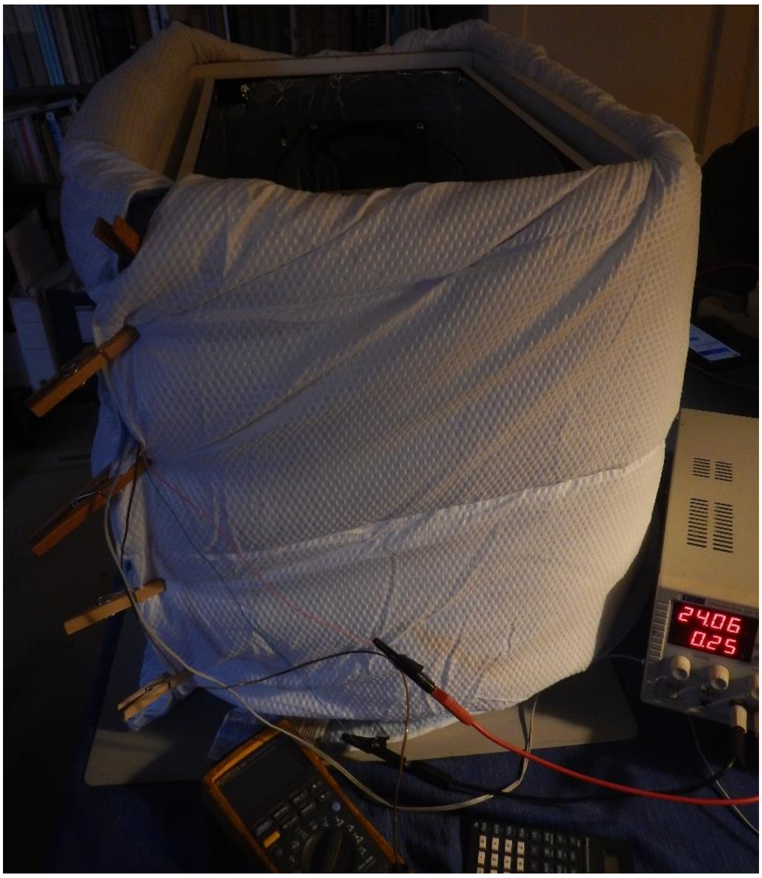

Fig. 14. The oven wrapped in – and externally insulated – with a fibre duvet.

The oven wrapped in a fibre duvet. Date: 2024.03.09.

A fibre duvet was bought from the company: Soveland, Mosegårdsvej 5, DK 8670 Låsby; CVR: 38759906.
The oven was placed on top of a box sized 260 x 405 x 300 mm, which was placed on my dining table.
The duvet sized 200 x 140 cm was wrapped around the oven. A rope constituted a belt tied around the periphery of the pane and resting at the top edges of the outer box (the edge could be regarded as the hips of the oven, the duvet its skirt and the rope as its belt). The duvet was folded over the rope, so in total two layers of duvet were wrapped around the oven, and the duvet did not cover any part of the top of the pane.

Two sets of measurements were taken; one for a dissipated power of 98.0 W and one for a power of 145.2 W.

Fan = 6,0 W; Heatsink dissipation 48.67 V / 1.89 A = 92.0 W. Fan + Heatsink = 6,0 W + 92.0 W = **98.0 W.**

No internal Insulation. Time:	11.30	12.00	12.30	13.00	13.30	14.00	14.30	15.00	15.30
Temperature in Oven T [ºC]	21.9	38.0	49.2	57.3	63.6	68.7	72.6	76.0	78.8
Ambient Temperature T_{Amb} [ºC]	22	22	22	22	22	22	22	22	22
Power dissipated in oven [W]	100.0	98.0	98.0	98.0	98.0	98.0	98.0	98.0	98.0
T - T_{Amb} [ºC]	0	16.1	27.3	35.4	41.7	46.8	50.7	54.1	56.9
Elapsed time [min.]	0	30	60	90	120	150	180	210	240
Column / Reading no.	0	1	2	3	4	5	6	7	8

Table 14. 2024.03.09. Wrapped in fibre duvet. Plain air – 98 W.

$A_{12} = T_1^2 / (2T_1 – T_2)$ = (16.1 K)^2 / (2 x 16.1 K - 27.3 K) = 52.9 K.
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1)))$ = (30.0 Min.) / (ln (16.1 K/ (27.3 K – 16.1 K))) = 82.7 min.
$T_{End} = T_{Amb}$ + A = 21.9 ºC + 52.9 K = 74.8 ºC. R_{Th} = ΔT/P = 52.9 K / 98.0 W = 0.540 K/W.

$A_{24} == T_2^2 / (2T_2 – T_4)$ = (27.3 K)^2 / (2 x 27.3 K - 41.7 K) = 57.8 K.
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2)))$ = (60.0 Min.) / (ln (27.3 K/ (41.7 - 27.3 K))) = 93.8 min.
$T_{End} = T_{Amb}$ + A = T_{End} = 21.9 ºC + 57.8 K = 79.7 ºC. R_{Th} = ΔT/P = 57.8 K / 98 W = 0.590 K/W.

$A_{36} = T_3^2 / (2T_3 – T_6)$ = (35.4 K)^2 / (2 x 35.4 K - 57.7 K) = 62.3 K.
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3)))$ = (90.0 Min.) / (ln (35.4 K/ (50.7 K - 35.4 K))) = 107.3 min.
$T_{End} = T_{Amb}$ + A = 21.9 ºC + 62.3 K = 84.4 ºC. R_{Th} = ΔT/P = 62.3 K / 98.0 W = 0.636 K/W.

$A_{48} = T_4^2 / (2T_4 – T_8)$ = (41.7 K)^2 / (2 x 41.7 K - 56.9 K) = 65.6 K.
$\tau_{48} = t_4 / (\ln (T_4 / (T_8 – T_4)))$ = (120.0 Min.) / (ln (41.7 K/ (56.9 K - 41.7 K))) = 118.9 min.
$T_{End} = T_{Amb}$ + A = 21.9 ºC + 65.6 K = 87.5 ºC. R_{Th} = ΔT/P = 65.6 K / 98.0 W = 0.669 K/W.

Fan = 6,0 W; Heatsink dissipation 60 V / 2.32 A; P = 139.2 W. Fan + Heatsink = 6,0 W + 139.2 W = **145.2 W.**

No Insulation. Time:	18.00	18.30	19.00	19.30	20.00	20.30	21.00	21.30	22.00	22.30
Temperature in Oven T [ºC]	23.3	48.9	65.0	76.7	85.2	91.9	96.9	101.1	104.3	-.
Ambient Temperature T_{Amb} [ºC]	23	23	23	23	23	23	23	23	23	-
Power dissipated in oven [W]	145.2	145.2	145.2	145.2	145.2	145.2	145.2	145.2	145.2	-
T - T_{Amb} [ºC]	0	25.6	41.7	53.4	61.9	68.6	73.6	77.8	81.0	-
Elapsed time [min.]	0	30	60	90	120	150	180	210	240	-
Column / Reading no.	0	1	2	3	4	5	6	7	8	-

Table 15. 2024.03.09. Wrapped in fibre duvet. Plain air – 145.2 W.

$A_{12} = T_1^2 / (2T_1 – T_2)$ = (25.6 K)^2 / (2 x 25.6 K - 41.7 K) = 69.0 K.
$\tau_{12} = t_1 / (\ln (T_1 / (T_2 – T_1)))$ = (30.0 Min.) / (ln (25.6 K/ (41.7 K – 25.6 K))) = 64.7 min.
$T_{End} = T_{Amb}$ + A = 23.3 ºC + 69.0 K = 92.3 ºC. R_{Th} = ΔT/P = 69.0 K / 145.2 W = 0.475 K/W.

$A_{24} == T_2^2 / (2T_2 – T_4)$ = (41.7 K)^2 / (2 x 41.7 K – 61.9 K) = 80.9 K.
$\tau_{24} = t_2 / (\ln (T_2 / (T_4 – T_2)))$ = (60.0 Min.) / (ln (41.7 K/ (61.9 K- 41.7 K))) = 82.8 min.
$T_{End} = T_{Amb}$ + A = T_{End} = 23.3 ºC + 80.9 K = 104.2 ºC. R_{Th} = ΔT/P = 80.9 K / 145.2 W = 0.557 K/W.

$A_{36} = T_3^2 / (2T_3 – T_6)$ = (53.4 K)^2 / (2 x 53.4 K – 73.6. K) = 85.9 K.
$\tau_{36} = t_3 / (\ln (T_3 / (T_6 – T_3)))$ = (90.0 Min.) / (ln (53.4 K/ (73.6 K - 53.4 K))) = 92.6 min.
$T_{End} = T_{Amb}$ + A = 23.3 ºC + K = 109.2 ºC. R_{Th} = ΔT/P = 85.9 K / 145.2 W = 0.592 K/W.

$A_{48} = T_4^2 / (2T_4 – T_8)$ = (61.9 K)^2 / (2 x 61.9 K - 81.0 K) = 89.5 K.
$\tau_{48} = t_4 / (\ln (T_4 / (T_8 – T_4)))$ = (120.0 Min.) / (ln (61.9 K/ (81.0 K - 61.9 K))) = 102.1 min.
$T_{End} = T_{Amb}$ + A = 23.3 ºC + 89.5 K = 112.8 ºC. R_{Th} = ΔT/P = 89.5 K / 145.2 W = 0.617 K/W.

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7.10. Measuring the heat leakage through the pane.

Up to this moment (2024.03.11) I had measured the thermal resistance between: A. The interior of the oven and the ambient for several different insulation materials inserted in the cavity - and B. For a duvet wrapped around the outside of the horizontal sides of the oven. The results of these measurements had only variated very little (in the order of 0.39 – 0,64 K/W for the entire oven). I now realized, that this indicated that power / heat must be leaking from somewhere else – i.e. not from the sides and the bottom of the oven.

In order to verify this, I found:
A. The power dissipated from the pane to the ambient (in form of convection and radiation).
B. Based on A I found the thermal resistance from the interior of the oven through the pane and to the ambient.
C. Having found the thermal resistance through the pane, I then compared it to the resistance of the entire oven.
D. And thereby evaluated the heat leakage through the pane.

These calculations were based on:

A. An internal oven temperature of 108.5 ºC.
B. An external temperature of 22 ºC.
C. A temperature of 39 ºC at the centre of the upper horizontal pane - and
D. The oven packed in the fibre duvet.
E. A total power dissipation of 145.2 W.

Under these conditions the power convection from the top side of the pane was calculated using the formula provided in section 8.3.2 in Part 1 – and power radiation was found using the formula provided in section 8.3.3.

The size of the glass area of the pane, which is available for the convection was 520 x 344 mm.
$P_{Convection} = K * A * \Delta T^{1.25} / L^{0.25}$
$= 1.78 \times (0.52\ m \times 0.344\ m) \times 17\ K^{1.25} / ((0.52\ m \times 0.344\ m)^{0.5})^{0.25}$ = 13,63 W

The size of the aperture (of the oven), which is available for radiation is 490 X 360 mm.

$P_{Net} = C_R * C_s * A * (T^4 - T_{Amb.}^4)$ - (In need of a better guess I have set $C_R = 1.0$)
$\Rightarrow 1.00 \times 5.67 * 10^{-8}\ W\ m^{-2}\ K^{-4} \times (0.52\ m \times 0.295\ m) \times ((273.15K + 39K)^4 - (273.15K + 22K)^4) = 16,57\ W$
The sum of the convection and the radiated power from the pane adds up to 30.20 W

And the thermal resistance from the top surface of the pane to the ambient is calculated:
$\Delta T = 39\ ºC – 22\ ºC = 17\ K$;
$R_{Pane} = \Delta T / P_{Pane} = 17\ K / 30.20\ W$ = 0.562 K/W

and compared to the entire thermal resistance from the interior of oven to the ambient:
$R_{Pane} = \Delta T / P = (108.5\ ºC - 22\ ºC) / 145.2\ W = 86.5K / 145.2\ W$ = 0.596 K/W

- which tracks within 5.7%.

This result shows, that virtually all the heat, leaked from the solar oven to the ambient, leaks through the pane.

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8. Comparing the tested insulation materials to plain air.

In Part 1, the thermal resistance between the interior of the solar oven (with plain air as insulation material) - and the ambient was calculated in two different ways (A and B) using "by eye" measurements;

A: $R_{Th\ AD} = \Delta T / P = (90.1^oC - 25^oC) / 125.1\ W$ = 0.52 K/W.

- and

B: $R_{Th\ AD} = ((R_{Th\ AB} + R_{Th\ BD})^{-1} + (R_{Th\ AC} + R_{Th\ CD})^{-1})^{-1}$

$= ((12.63\ K/W + 1.05\ K/W)^{-1} + (0.490\ K/W + 0.182\ K/W)^{-1})^{-1}$ = 0.64 K/W.

In order to compare the "by eye" measurement used in the Part 1 to the "mathematical" method, which is used in this Part 2 report, the first two tests using the "mathematical" method in this Part 2 report – were also measured with only plain air as insulation material.

These first two tests of Part 2 were made with:

1 test: A power dissipation P_1 = 104.5 W, => R_{TH12} = 0.57 K/W; R_{TH24} = 0.62 K/W; R_{TH36} = 0.62 K/W.

This *1. test* was erroneous, as the thermosensor was touching the inner side of the box.

2 test: A power dissipation P_2 = 145.4 W, => R_{TH12} = 0.53 K/W; R_{TH24} = 0.54 K/W; R_{TH36} = 0.51 K/W.

The result of the A calculation of Part 1 was = 0.52 K/W

– and the results of test B in Part 2 are: R_{TH12} = 0.53 K/W; R_{TH24} = 0.54 K/W; R_{TH36} = 0.51 K/W

None of the results from test B differs more than 0.02 K/W from the A calculation in Part 1 – corresponding to a deviation of 4%. A deviation of this magnitude must be characterised as very good and reassuring that the measurements are by far trustworthy.

Insulation	Power	A1	A2	A3	A_{Mean}	τ_{12}	τ_{24}	τ_{36}	τ_{Mean}	R_{TH12}	R_{TH24}	R_{TH36}
Units	[W]	[K]	[K]	[K]	[K]	[Min.]	[Min.]	[Min.]	[Min.]	[K/W]	[K/W]	[K/W]
Air	104.5	59.7	64.5	64.4	62.9	116	128	131	125	0.571	0.617	0.616
Air	145.4	76.4	78.8	74.1	76.4	96.0	100.2	97.2	97.8	0.525	0.542	0.510
Towel	145.4	58.8	65.1	67.5	63.8	68	78	81	75.7	0.411	0.448	0.462
Cardboard	143.6	56.8	53.5	64.8	58.4	70.0	78.3	85.3	77.9	0.396	0.392	0.451
Cardboard	143.0	62.1	74.0	77.9	71.3	68.5	89.4	85.3	81.3	0.434	0.517	0.545
Paper	143.6	59.1	69.6	73.4	67.6	60.2	78.1	86.9	75.1	0.412	0.484	0.511
Hey	143.6	64.5	75.5	82.0	74.0	58.4	75.5	88.3	74.9	0.449	0.526	0.571
Wool	143.6	66.9	77.7	80.8	75.1	66.1	83.2	90.0	79.8	0.466	0.541	0.562
Fabrics	143.6	52.0	73.8	80.8	68.9	43.0	79.6	93.9	72.2	0.363	0.514	0.563
Polystyrene	145.2	75.6	82.8	88.7	82.4	76.3	87.2	131.4	98.3	0.521	0.570	0.611
Popcorn	145.2	68.8	81.2	82.8	79.0	67	93.7	89.5	83.4	0.474	0.559	0.570
Ext. duvet	98.0	52.9	57.8	62.3	57.7	82.7	93.8	107.3	94.6	0.540	0.590	0.636
Ext. duvet	145.2	69.0	80.9	85.9	71.9	64.7	82.8	92.6	80.0	0.475	0.557	0.592

Table 16. The readings of rows starting in italic are doubtful, as the thermosensor might have touched the side of the box. Ext. duvet means that a dual layer of a fibre duvet is wrapped around the outside of the oven.

Looking for a pattern in the measurements, it is remarkable that for all the solid materials – except for the first erroneous readings for Cardboard – all the tests leads to that R_{TH24} is higher than R_{TH12} - and R_{TH36} is higher than R_{TH24}.

Comparing the measurements of the thermal resistance of plain air to the measurements of the solid insulation materials is disappointing. Only three, out of the seven "solid" insulation materials come out with a higher mean values of the thermal resistance (R_{Th}) - than the thermal resistance for plain air.

The three materials are: wool (1.0 %), popcorn (3.5%) and polystyrene – (10%). For all other solid insulation materials, their thermal resistance decrease – i.e. worsen – by increasing temperature.

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8.1. Polystyrene is the material, which comes out the best, i.e. with the highest increase in the thermal resistance between the inside of the oven and the ambient. Yet, the maximum increase is only in the order of 20%.
Polystyrene comes out with: R_{TH12} = 0.52 K/W; R_{TH24} = 0.57 K/W; R_{TH36} = 0.61 K/W
– compared to plain air, which came out with R_{TH12} = 0.53 K/W; R_{TH24} = 0.54 K/W; R_{TH36} = 0.51 K/W
– yielding a loss / an improvement of: -2% +6% and +20%.
- leave alone, that I still have my doubts as to how available polystyrene is in refugee camps.

8.2. Popcorn is the second best of the insulating materials, which were compared to plain air.
Popcorn comes out with: R_{TH12} = 0.47 K/W; R_{TH24} = 0.56 K/W; R_{TH36} = 0.57 K/W
– compared to plain air, which came out with: R_{TH12} = 0.53 K/W; R_{TH24} = 0.54 K/W; R_{TH36} = 0.51 K/W
– yielding a loss / an improvement of: -10% +3% and +12%.

Here it must be taken into account, that only a minor fraction of the sides of the oven were filled with popcorn – as was explained in section 7.8. Hence, an improvement of the insulation can be expected if the walls will be completely filled with popcorn. In this test I have used non salted popcorn, because I believe that salt is hydroscopic and could cause water to accumulate at the surface of the popcorn, and hence - I expect - could lead to an increased heat loss and fungi.

With ugali (= corn porridge) as one of the region's most prevailing meals, corn will be easy to find - and it will be cheap. Hence, why corn - to my opinion – will be the most promising of the tested insulating materials. However, be aware that there can be differences in the rate of the expansion of the corn, when it is popped - depending on the corn quality. This might cause varying insulation.

8.3. Wool is generally regarded as an excellent insulation material, but it disappointed in this test. I might not have stuffed it hard enough, but that does not explain the drop in the wools' thermal resistance R_{TH12}, compared to R_{TH12} for plain air. Wool comes out with: R_{TH12} = 0.47 K/W; R_{TH24} = 0.54 K/W; R_{TH36} = 0.56 K/W
– compared to plain air, which came out with: R_{TH12} = 0.53 K/W; R_{TH24} = 0.54 K/W; R_{TH36} = 0.51 K/W
–yielding a loss / an improvement of: -11% +0% and +10%.
Another issue is, that wool probably could be hard to find in many refugee camps.

My interpretation of the results is, that if an insulation material twists forth and back between the outer- and the inner- box in the solar oven, it will form "bridges", by which the heat will travel from the inner box to the outer box. The more the material will twist, the more "bridges" will be formed between the inner box and the outer box - and the shorter will the "bridges" be. This means an increase of heat lost by conduction.

That means that if / when the amount of heat lost by an increased conduction exceeds the reduction of the heat lost gained by less convection loss and less radiation loss, the total loss of heat from the oven will increase. This results in a lower thermal resistance - corresponding to a lower temperature in the oven.

9. Analysing the measurements.
As the absolute temperature of an item rises, so does its ability to radiate power rise by the absolute temperature to the power of four. This is the reason, why one would expect the thermal resistance between an item and its ambient to drop, as the temperature rises. This, complies with our test results for plain air. But if we look at the test results for all the solid insulation materials, we observe the opposite - that the thermal resistance rises toward the end of the heating graph!

I have no good explanation for this discrepancy. I have considered, if it could be due to the unlinearity of the thermal resistance caused mainly by the radiation and subsidiary by the convection. This unlinearity will become more dominant by an increase of the thermal span (the thermal span for the solar oven is in the order of 20 to 100 ^{o}C), and, hence, cause an increased deviation from a true exponential heating graph, which is a prerequisite for accurate results from the equations.

The fact - that for plain air, our measurements show that the thermal resistance between the oven and the ambient drops by increasing temperature – points to, that this discrepancy lies either by the heat conduction and / or by the convection – presumably by both the conduction and the convection.

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For a pipe or a tube, its resistance to a laminar flow decreases by an increasing pipe diameter to the power of three. I.e. if you reduce the diameter to the half - you will have eight times higher flow resistance. The flow resistance increases proportional to the length of the pipe.

Insulation materials such as wool, hay or fabrics consist of entangled fibres, where the space between the fibres forms a large number of narrow “pipes” connected partly in parallel – partly in series. The more entangled the fibres become - the narrower become the apertures / “pipes” between the fibres - leading to a higher flow resistance. And a higher flow resistance will curtail the power loss from the oven caused by the convection.

But, just as the insulation material will inhibit the power loss caused by convection – so will the insulation material, which touches both the inner and the other box, establish bridges / paths between the inner and the other box, which will allow for heat to be conducted out of the oven. As with other thermal resistances based on conduction, the resistance increases proportional to the length- and inversely proportional to the cross section of the conductor. Hence, for a solid insulation material goes: the lower the thermal conductivity - and the wider the gap between the inner and the other box – the less the conducted power loss. Hence, in short – when using solid insulation materials, one should aim for a broad gap between the inner and the other box.

For plain stagnant air the thermal conductivity is so low, that the conducted heat loss between the inner and the other box will be insignificant compared to the heat loss caused by the radiation. Thus, for an oven with only plain air as insulation material the size of the gap between the inner and the other box becomes less significant in terms of conduction loss.

But in terms of convection, with plain air as insulation material, the size of the gap between the inner and the other box becomes important. Convection is air, which flows along a surface. When such a flow takes place in the gap between the inner and the other box, it can be regarded as a laminar (i.e. slow) flow in a pipe. In order to minimize the convection, the airflow within the gap must be kept to a minimum, which calls for a narrow pipe – which for the oven means a narrow gap between the inner and the other box.

I have discussed this issue with an old bricklayer. Sometimes we can learn from old age and history. Up to approximate year 1800 most houses in Northern Europe were mainly made with solid walls, but from the early nineteenth century the use of cavity walls started to become common in order to improve the insulation of the houses. But for more than a century, the cavities were left empty. During that time people did have access to insulating material such as reed, hay, paper and gravel. One would expect that someone have tried to use these materials as insulators in their cavity walls. If the insulation materials had worked, they would presumably have caught on. Not until the nineteen thirties, when the mineral wool appeared on the market, did that scenario change.

I believe, that the reason for this is, that an insulation material must possess a high thermal resistance to minimize the heat conducted between the walls. Secondly, it must also possess a structure, which is strong enough to keep the material suspended, and to prevent it from falling down to the bottom of the cavity, where it might form bridges, which could act as a thermal short circuit between the outer- and the inner walls. Last - but not least - the material should be non-hydroscopic to prevent fungi.

Still, these are speculations - I am not able to come up with an appropriate explanation as to why the thermal resistance of the solid insulation materials increases by increasing temperature.

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10. Second thoughts concerning the construction of the solar oven.

Several causes can lead to variations in the power irradiated to the oven:
1. The stepwise adjustment of the oven to the trajectory of the sun over the day.
2. Clouds passing over the site.
3. People and animals passing by, casting shadows over the solar oven.

Earlier on, I have claimed that the most important property of a solar oven is its maximum temperature. That implies to maximize the thermal resistance from the interior of the oven to the ambient.

A second thought has led me to the following realization: The second most important physical property of a solar oven must be to have a short thermal time constant. Minimizing the thermal time constant will allow the oven to heat up more quickly - meaning that it will sooner reach a temperature, by which the food in the oven will be cooked - or the water in the oven will be sterilized.

A short time constant for the oven, means that the oven will not only heat up faster, but it will also cool off equally faster. Still - it is an advantage – for any given average temperature of the oven – to embrace the bigger temperature variations of the interior of the oven, which will be the result of a low thermal time constant of the oven. The reason why bigger variations are an advantage is found in Svante Arrhenius' Law.

Svante Arrhenius' Law tells us, that the speed of a chemical process will increase by 2.3 times by every teen degree the temperature is raised. The speed of the cooking (which is a chemical process), will increase more by a given temperature increase – than it will decrease by a corresponding decrease of the temperature. Let us look at the example below.

10.1. A calculated example of the impact of a lower thermal capacitance on the cooking time.

Let us assume that by 70 ^{o}C it takes ten hours to cook a meal in an oven, and that Svante Arrhenius' Law applies. Also, that the temperature of the oven can change instantly (i.e. its thermal time constant is zero).

During the first hour of the cooking the temperature is 90 ^{o}C.
During the second hour of the cooking the temperature is 50 ^{o}C.

During the first hour the temperature is (relative to 70 ^{o}C) raised by 2 x 10 ^{o}C to 90 ^{o}C.
– corresponding to 1 hour / 10 hours x 2.3 x 2.3 = 0.529 times the required cooking time by 70 ^{o}C.

During the next hour the temperature is lowered (relative to 70 ^{o}C) by 2 x 10 ^{o}C to 50 ^{o}C
– corresponding to 1 hour /10 hours x 2.3^{-1} x 2.3^{-1} = 0.0189 times the required cooking time by 70 ^{o}C.

Hence, during these two hours (with one hour at 90 ^{o}C - and one hour at 50 ^{o}C)
we have cooked 0.529 times + 0.0189 times = 0.548 times the required cooking time by 70 ^{o}C.

If the meal had maintained a constant temperature of 70 ^{o}C during the same two hours, it would have cooked 2 hours/ 10 hours = 0.200 times the required cooking time by 70 ^{o}C.

If the temperature of the meal is allowed to raise above - and to fall below the average temperature, we will gain more cooking time - than we lose in cooking time. In this case the meal will be cooked 0.548 / 0.2 = 2.74 times faster.

The thermal time constant of the oven is the thermal capacitance of the oven with its contents - multiplied by the thermal resistance between the interior of the oven and the ambient. We have now seen, that the thermal resistance should be as high as possible. Hence, to minimize the thermal time constant, the only mean we have is to minimize the thermal capacitance of the oven with its contents.

This is another reason, why I recommend that the oven should be made of plain wood.

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10.2. A calculated example of the impact of polystyrene on the cooking time.

Let us assume:

A solar irradiation I of 1000 W/m^2,

An ambient temperature of 21 ^oC.

A misalignment of the oven 15 degrees (~0.966),

An aperture A of the oven of 0.49 m x 0.29 m = 0.1421 m^2.

Our test result for the thermal resistance of the oven with plain air is ~0.54 K/W.

The oven temperature with plain air (R_{Th} ~ 0.54 K/W) = 21 ^oC + 74.1 ^oC = 95.1 ^oC.

The oven temperature with polystyrene is (R_{Th} ~ 0.57 K/W) = 21 ^oC + 78.2 ^oC = 99.3 ^oC.

$\Delta T = I \times A \times (R_{Polystyren} - R_{Plain\ Air})$ = 1000 W/m^2 x 0.1421 m^2 x (0.57 K/W - 0.54 K/W) = 4.27 K.

Using polystyrene as insulation will increase the temperature of the oven by approximate 4.3 K.

Appling the law of Svante Arrhenius, an increase of 4.3 ^oC will shorten the cooking time to approximate $(2.3^{0.43})^{-1}$ = 70% of the cooking time required with only plain air as insulation material.

10.3. Pivoting the oven, when aligning it to the sun.

The alignment of the oven - according to the trajectory of the sun over the day - was discussed in Part 1 section 7. If the oven is placed on a structure, which is easy to turn, the alignment can be made easier. I could suggest the hub of an old wheel from a bike might serve this purpose – the wheel does not need to be straight.

11. The conclusion.

The most important conclusion in Part 2 of the report is that virtually the entire heat flow out of the oven is lost through the double glazed pane. The verification of this assumption was obtained by calculating the convection loss and the radiation loss to- and from the pane. Based on convection- and the radiation losses the thermal resistance from the interior of the oven - through the pane – and to the ambient was compared it to the overall thermal resistance between the interior of the oven and the ambient. These two thermal resistances matched within less than 5% - meaning that virtually the entire heat leakage passes through the pane. Hence, an increase of the thermal resistance of the pane will have high priority.

Several reasons have occurred as to why the oven should *not* be made from chipboard but from plain wood. A thickness of 5 mm or more should yield a sufficient strength. I have only just learned that chipboard and plywood both contain formaldehyde, which is carcinogenic – and cause increased risk of leukaemia. Other reasons to ban chipboard are: Chipboard has a high density - i.e. it is heavy – and hence leads to a high thermal time constant for the oven. Chipboard is more hydroscopic than solid wood, which will last much longer.

The original aim of this Part 2 of the report was to find means to improve the efficiency of the solar oven, including testing various insulation materials. The following materials have been tested: plain air; towels; cardboard; paper balls; hay; wool; fabrics; polystyrene and popcorn. The insulating properties of the solid materials have been compared to the properties of plain air - using the insulating properties of plain air as yard stick. In the choice of materials, availability, safety, simple technology and low cost have had priority.

The test results of the measured thermal resistances of the solid insulation materials have disappointed. Rather than improving the thermal resistance - all the solid materials – except for popcorn, polystyrene and to some extent wool – turned out to reduce the thermal resistance, rather than to improve it. The revelation of the real culprit – the heat leakage through the pane – has altered the main focus from the insulation materials towards an improvement of the pane.

A positive outcome of Part 2 is that the two different ways of measuring the thermal resistance have been compared and found to yield compliable results between the measurements obtained be "by eye" and the measurements obtained the mathematical solution to the equations describing the heating graph.

The test results for the thermal resistance of the solid insulation material have shown some puzzling patterns, which I am unable to explain: For each material its thermal resistance was measured at the beginning, at the middle and at the end of the heating graph.

1. For all the tested materials apply, that the thermal resistance at the middle of the heating graph are higher than the thermal resistance at the beginning of the graph.
2. For the solid materials apply, that the thermal resistance at the high end of the heating graph are higher than the thermal resistance at the middle of the graph.
3. But for plain air, the thermal resistance at the high end of the heating graph is lower than the thermal resistance at the middle of the graph.

When my endeavours to improve and test the thermal resistance of the oven were of so little (<20%) avail, I tried to improve by wrapping good quality fibre duvet around the outside of the oven. That raised the resistance 4.3 % above the hitherto highest resistance, (which had been obtained for polystyrene) – but no substantial improvement was obtained. But that became the test, which turned the attention to the heat leakage through the pane.

I will uphold my recommendation to paint the inside of the inner box black, all other sides white and – if available - cover /glue aluminium foil on to the inner vertical sides of both boxes.

Last, but not least, I will repeat my recommendation to try to find- and / or to saw- a garment, which can be used as a coat or jacket around the sides of the oven. Preferable something, which is windproof on the outside and “woolly” at the inside. In case no such garment can be found the second best is to pile up twigs towards the sides of the oven and shelter the twigs with one or two old shirts or any fabrics available. Pretend that the oven is your baby, and it is freezing.

Insulation	Power	A1	A2	A3	A_{Mean}	τ_{12}	τ_{24}	τ_{36}	τ_{Mean}	R_{TH12}	R_{TH24}	R_{TH36}
Units	[W]	[K]	[K]	[K]	[K]	[Min.]	[Min.]	[Min.]	[Min.]	[K/W]	[K/W]	[K/W]
Air	104.5	59.7	64.5	64.4	62.9	116	128	131	125	0.571	0.617	0.616
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Cardboard	143.0	62.1	74.0	77.9	71.3	68.5	89.4	85.3	81.3	0.434	0.517	0.545
Paper	143.6	59.1	69.6	73.4	67.6	60.2	78.1	86.9	75.1	0.412	0.484	0.511
Hey	143.6	64.5	75.5	82.0	74.0	58.4	75.5	88.3	74.9	0.449	0.526	0.571
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Fabrics	143.6	52.0	73.8	80.8	68.9	43.0	79.6	93.9	72.2	0.363	0.514	0.563
Polystyrene	145.2	75.6	82.8	88.7	82.4	76.3	87.2	131.4	98.3	0.521	0.570	0.611
Popcorn	145.2	68.8	81.2	82.8	79.0	67	93.7	89.5	83.4	0.474	0.559	0.570
Ext. duvet	98.0	52.9	57.8	62.3	57.7	82.7	93.8	107.3	94.6	0.540	0.590	0.636
Ext. duvet	145.2	69.0	80.9	85.9	71.9	64.7	82.8	92.6	80.0	0.475	0.557	0.592

Table 17. The readings of rows starting in italic are doubtful, as the thermosensor might have touched the side of the box. Ext.= external duvet means that a dual layer of a fibre duvet is wrapped around the outside of the oven.

Aarhus, Denmark
Martz 16th. 2024.
Steen Carlsen

PS. Over the summer 2024, my friends Dina and Klaus Lynge have tried to cook with the oven. Klaus used a meat roasting thermometer placed at the bottom of the oven in a 4 mm hole in a clump of wood to read the temperature. The accuracy of the thermometer was verified in boiling water to be within +/-1 degree. Klaus took readings up to 110 ^{o}C, which differed too much to my reading of 83 ^{o}C to be accidental.

After months of speculating I have come to the conclusion, that my reading was the temperature at the top of the oven - just below the pane – where Klaus’ thermometer measured the temperature inside the wooden clump, which was placed in direct contact to the bottom of the inner box. Hence, the difference.

Steen Carlsen 09/08 2024.

APENDIX.

12. The connection between the Centigrade- and the Kelvin temperature scales.

Please note, that Centigrade refers to the temperature scale, which have the freezing- and the boiling point of water (at sea level) as fix-points. The Kelvin scale (K) has the absolute zero temperature (= -273.15 °C) as its reference point. Thus, 0 K = -273.15 °C and 273.15 K = 0 °C. The magnitude of one unit is the same for both of the scales; i.e. │K│=│ °C│.

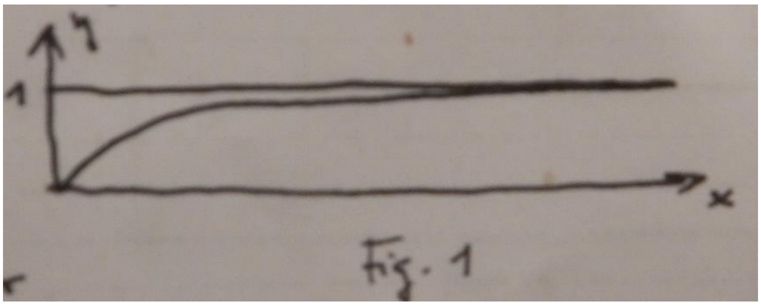
13. The power resistors used to heat the solar oven.

Data for the three 50 W power resistors used to heat up the heatsink in the solar oven:

Resistance	75 Ohm.
Power	50 W
Max. operating temperature	<200 °C
Temperature Coefficient	<100 ppm
Manufacture	ARCOL
Type	HS50
Manufactured	2003 week 44.

14. The mathematical solution to the final temperature of a heating graph - by Torkil and Gunnar.

The quality of a solar oven is determined by two properties: The temperature, which it will attain, when placed in the sun, and how long will it take to heat up. If we measure the time from the moment, when the oven is exposed to the sun, and the temperature of the oven - relative to the ambient temperature, then the temperature of the oven as a function of the time can be described by a graph, as the one shown at Figure 1. Here x is the time and y is the temperature.



If we define:

(1) $y = 1 - e^{-x}$ for $x \geq 0$,

we will get a graph, where

(2) $y = 0$ for $x = 0$

(3) $y \to 1$ for $x \to \infty$.

But this is not flexible enough. The horizontal asymptote should not be y = 1, but Y = A, where A is the temperature, which the oven approaches asymptotically. This is achieved by setting

(4) $y = T/A$ - yielding

(5) $T = A\,(1 - e^{-x})$ for $x \geq 0$,

where now it is T, which is the temperature.

But this is still not flexible enough, as the speed, by which the temperature rises, is

(6) $dT/dx = A\,(0 - (e^{-x})) = A\,e^{-x}$.

Hence, for any oven with a given A, the temperature will rise with the same slope. We also note that

(7) $dT/dx = A$ for $x = 0$.

Thus, at origo the slope of the graph will always be A.

We now define

(8) $x = t / \tau$,

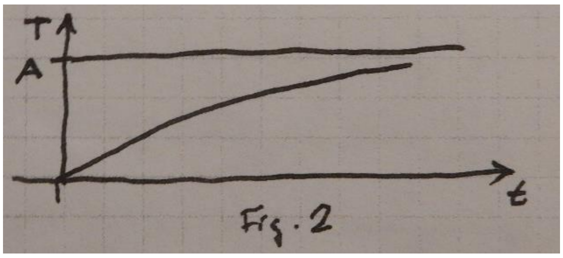
where τ is a positive constant; which gives us

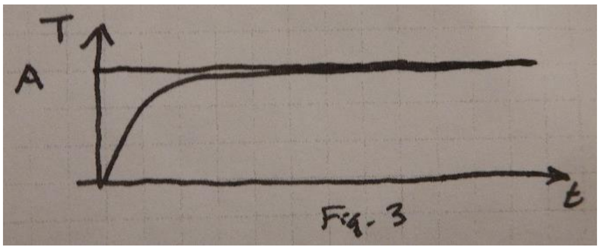
(9) $T = A\,(1 - e^{-t/\tau})$, $t \geq 0$.

Finding the slope of the graph by differentiation we get

(10) $dT/dt = dT/dx \cdot dx/dt = A\,e^{-x} \cdot 1/\tau = A \cdot e^{-t/\tau} \cdot 1/\tau$.

Thus, the graph is flat for large values of τ, and it is steep for small τ (- but always positive).





To evaluate a given solar oven, we wish to find A and τ, by placing the oven in the sun and observe T for various values of t. One single observation yields $T = T_1$ for $t = t_1$. Hence,

(11) $T_1 = A\,(1 - e^{-t_1/\tau})$.

This single equation is clearly not enough to find both A and τ.

A second observation yields $T = T_2$ for $t = t_2$, thus

(12) $T_2 = A\,(1 - e^{-t_2/\tau})$,

And we might be able to determine A and τ based on the two equations (11) and (12).

But it will not be simple, as A appears as a factor outside a bracket, while τ is hidden as the index in an exponential factor within the very same bracket. It will probably be a good idea to rearrange (9) a bit more before we insert t_1, T_1, t_2 and T_2. From (9) we find

(13) $A - T = A\,e^{-t/\tau}$ - hence,

(14) $(A - T)/A = e^{-t/\tau}$

(15) $1 - T/A = e^{-t/\tau}$

(16) $\ln(1 - T/A) = -t/\tau$

(We note that, as $T < A$ so $T/A < 1 \Rightarrow 1 - T/A > 0$. Thus the term $\ln(1 - T/A)$ does make sense.)

Finally, we rewrite (16) to

(17) $t = -\tau \ln(1 - T/A)$

Here we have an equation (17), into which we can insert t_1, T_1, t_2 and T_2.

Inserting t_1, T_1, t_2 and T_2. we obtain

(18) $t_1 = -\tau \ln(1 - T_1/A)$

(19) $t_2 = -\tau \ln(1 - T_2/A)$

Which seem much more manageable than (11) and (12). By division, we obtain

(20) $t_2 / t_1 = \ln(1 - T_2/A) / \ln(1 - T_1/A)$

If we could get rid of t_1 and t_2 we would be left with an equation with A, T_1 and T_2, in which we might be able to find A expressed by T_1 and T_2, which is what we wish for. And it is indeed possible, as we can choose the points in time t_1 and t_2 when we measure the temperatures T_1 and T_2. If we choose t_1 and t_2 so that $t_2 = 2\,t_1$, then

(21) $t_2 / t_1 = 2$

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which, together with (20) leads to

(22) $2 = \ln(1 - T_2/A) / \ln(1 - T_1/A)$.

Hence,

(23) $\ln(1 - T_2/A) = 2\ln(1 - T_1/A) = \ln((1 - T_1/A)^2) = \ln(1 - 2T_1/A + T_1^2/A^2)$

which leads to

(24) $1 - T_2/A = 1 - 2T_1/A + T_1^2/A^2 \Rightarrow$

(25) $-T_2 A = -2T_1 A + T_1^2 \Rightarrow$

(26) $(2T_1 - T_2) A = T_1^2 \Rightarrow$

(27) $A = T_1^2 / (2T_1 - T_2) \Rightarrow$

(Please observe, that the graph of equation (9) turns clockwise for increasing t. Hence, $2T_1 - T_2 > 0$.)

Based on (27) we have found A expressed by T_1 and T_2. Applying (18) or (19) and using (18) and $t_2 = 2\,t_1$, we find that

(28) $\tau = -t_1 / (\ln(1 - T_1/A))$

(Please note that, as $0 < (1 - T_1/A) < 1$, $\ln(1 - T_1/A) < 0$, causing $\tau > 0$.)

In (28) τ is expressed in term of A.

If this is unacceptable, you can insert (27) into (28) and will find

(29) $\tau = -t_1 / (\ln(1 - T_1 / (T_1^2 / (2T_1 - T_2))))$

$= t_1 / (-\ln(1 - ((2T_1 - T_2) / T_1)))$

$= t_1 / (-\ln(T_1 - 2T_1 + T_2) / T_1))$

$= t_1 / (-\ln((T_2 - T_1) / T_1))$.

And finally we get that

(30) $\tau = t_1 / (\ln(T_1 / (T_2 - T_1)))$

where τ is expressed only in t_1, T_1 and T_2.

As control we can insert (27) in (19), which yields

(31) $\tau = -t_2 / (\ln(1 - T_2 / (T_1^2 / (2T_1 - T_2))))$

(32) $= 2\,t_1 / (-\ln(1 - T_2(2T_1 - T_2) / T_1^2))$

(33) $= 2\,t_1 / (-\ln(T_1^2 - 2T_1T_2 + T_2^2) / T_1^2))$

(34) $= 2\,t_1 / (-\ln(T_1 - T_2)^2 / T_1^2))$

(35) $= 2\,t_1 / (\ln(T_1^2 / (T_1 - T_2)^2))$

(36) $= 2\,t_1 / (2\ln(T_1 / (T_1 - T_2)))$

(37) $= t_1 / (\ln(T_1 / (T_1 - T_2)))$

Which is the same as (30). The solution is found in (27) and (28) – or more fully in (27) and (30).

$A = T_1^2 / (2T_1 - T_2)$

$\tau = t_1 / (\ln(T_1 / (T_2 - T_1)))$

Translated from Danish by Steen Carlsen.

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15. The cross section of the end- and side- mouldings of the pane.
In Part 1, I forgot to include the cross section of the mouldings, which constitute the frame around the pane. Here it comes.

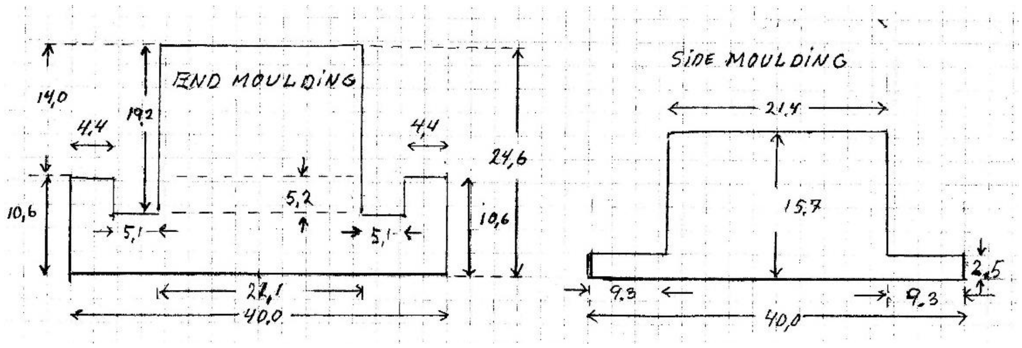

Fig. 15.

16. The problems of measuring the time constant and the final temperature T_{Final} in solar-ovens.

If you want to measure a thermal resistance between two matters / items, the two matters will always have some finite masses, and both the matters will present some finite thermal capacitance. This thermal capacitance will cause a slowdown in the changes of the temperatures of the two matters. And though the deviation from the final temperature becomes smaller and smaller over time, the rate - at which the matter (asymptotically) approaches its final value - also becomes smaller and smaller. In fact, if the system is left undisturbed, it will never attain its final value. In other words, to measure the thermal resistance between any two matters, theoretically we will have to wait infinitely long before we can make the required measurements of the temperature.

Infinitely long, is a long time to wait to finish a measurement. Yet, if we assume that all the thermal components in a system would behave linearly – which does not hold true - it can mathematically be shown, that the heating graph (i.e. the temperature of the oven as function of time) will follow an exponential curve.

As stated earlier, one of the most important properties of a solar oven is the final temperature (i.e. the temperature, which the oven would attain in equilibrium i.e. after eternal long time). Rather than having to wait for ever, it would be nice to be able to calculate the final temperature based on temperature readings, which could be made within a practical length of time after the time (t_0) when the heating of the oven has started.

If we assume that temperature of the oven rises exponentially and we measure the temperature when the heating of the oven starts and later at two points in time, that can be perceived as three points on the same heating graph. Mathematically it can be expressed as two exponential equations with two unknowns. In 2022 I tried to solve the exponential equations, for any such three readings - taken at any points in time. I had to face, that I was unable to find a general solution valid for such two readings, taken at any points in time.

My friend Torkil and his pal Gunnar are mathematicians. They are both in their nineties and do mathematics together in their leisure time. They managed to solve the equations in the specific case where (t_2 - t_0) = 2 x (t_1 - t_0). I have translated their solution into English, which can be found above in section 14 of this appendix.

They solved the equations under the condition, that the time from the start of the heat up (t_0) to the last reading time (t_2) would be twice the time from the start of the heat up (t_0) to the first reading time (t_1).

Torkil and Gunnar, proved that (for an exponential rise in temperature) - if:
1. At a time $t_0 = 0$ a solar oven starts to heat up from the temperature $T_0 = 0$ °C.
2. At a time t_1 the solar oven has reached the temperature T_1.
3. At a time t_2 the solar oven has reached the temperature T_2.
4. And time t_2 is equal to two times $t_{1;}$ ($t_2 – t_0 = 2$ x (t_1 - t_0))

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then the final temperature T_{End} of the solar oven can be expressed by the equation:
$T_{End} = T_1^2 / (2T_1 – T_2)$
and the time constant $\tau = t_1 / (\ln (T_1 / (T_2 – T_1)))$

- where the time constant τ is the time it will take from:
A. The start of the heating of the oven - to
B. The time where the temperature has reached 63.2 % of the span between the final temperature (T_{End}) minus the starting temperature (T_0).

17. Compensating for the ambient temperature.
At the start of a recording of a heating graph for a solar oven, the oven must be in equilibrium with (i.e. have the same temperature as) the ambient (i.e. the surroundings). That condition will be fulfilled (to within an error of less than 1% of the temperature span of the oven) if – before the heating is started – the oven has been kept out of the sun and in the same surroundings for a time equal to 5-6 times the time constant of the oven.

Generally, the time constant of the oven will be less than two hours. Hence, when making more measurements on an oven, it is recommendable to leave the oven in the shadow - and at the site, where the next measurements are to be made - overnight, to settle the temperature of the oven between each measurement.

If the temperature of the solar oven and the ambient temperature - at the time when the oven starts to heat up is not $T_0 = 0$ ºC (degrees Centigrade) but e.g. 27 ºC - then the readings, which we take at the t_1, and t_2 must be compensated for this off set value (27 ºC). That means we must subtract the 27 ºC from the temperature we read in the oven at t_1 in order to get T1. Likewise, we must subtract 27 ºC from the temperature we read at t_2 in order to get T2.

When we have found the (compensated) values of T_0, T_1 and T_2, we can now use T_1 and T_2 to find the final temperature by using and the equation $T_{End} = T_1^2 / (2T_1 – T_2)$.
We can also use T_1 and T_2 to find the thermal constant τ by using the equation $\tau = t_1 / (\ln (T_1 / (T_2 – T_1)))$.

Finally, to find T_{Final}, we have to reverse the compensation by adding the start-up temperature T_0 to T_{End} in order to find the oven's final temperature T_{Final}. Thus, the final temperature, which a given solar oven will reach, will always depend on the ambient temperature, in which it is used.

For practical reasons, we have, denoted the total increase in the interior temperature of the solar oven - relative to the ambient temperature – as A (i.e. $A = T_{End} - T_0$). A is proportional to the thermal resistance between the interior of the oven and its surroundings (the ambient) multiplied by the heat / power leaving the oven.

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18. The unlinearity of a thermal resistance, which comprises conduction, convection and radiation.
Section 17 applied to systems, comprising linear thermal resistances. That a system is thermally linear, means that the thermal power transmitted from point A to point B is proportional to the difference in temperature between point A and point B.

As described in Part 1, the thermal resistance is composed of the three components:
1. The thermal conduction. 2. The convection and 3. The radiation.

1. *The thermal conduction* is very seldom a problem – it is – by far - nice and linear.

2. *The power convection* is determined by $P_{Convection} = K * A * \Delta T^{1.25} / L^{0.25}$ - where:
   ΔT is the difference in temperature between the body and the ambient air in units of [K or °C].

In the equation above, which describes a convection, the parameters are:

For the top side:
L [m] = is the square root of the product of the largest- and the smallest- measurements.
A is the area of the top side [in m^2].

For the vertical sides:
L [m] = is /are the height(s) of the vertical sides.
A is the sum of the areas of the vertical sides [in m^2].

For the underside:
L [m] = is the square root of the product of the largest- and the smallest- measurements.
A is the underside area [in m^2].

K is a constant, which for the top side it is 1.78; for the vertical sides it is 1.37 and for the underside it is 0.96.

The equation describing the convection shows that the power P is proportional to the temperature difference raised to the power of 1.25 = $\Delta T^{1.25}$. The power of 1.25 is not linear, but the power of 1.25 does not present a severe unlinearity either.

3. The power radiation is determined by $P_{Radiation} = P = C_R * C_s * A * T^4$
=> $T = (P / (C_R * C_s * A))^{-4}$
where:

C_s is the radiation coefficient (= $5.67 * 10^{-8}$ W m^{-2} K^{-4} for an absolute black body)
A is the area [m^2] of the surface of the body, which radiates the heat.
T is the absolute temperature of the body in Kelvin [K] (i.e. the temperature in °C + 273.15 K).
$T_{Amb.}$ is the absolute temperature of the ambient in Kelvin [K] (i.e. the temperature in °C + 273.15 K).
C_R is a constant (between 0.0 and 1.0) depending on the surface of the body / material.

C_R describes the reflection from a surface of a body, i.e. the ability of that surface to absorb and radiate heat.
It is 1.0 for an absolute black body.
For a blank (fully reflecting) surface / body (like a mirror) C_R is 0.
For white bodies C_R is nearly (almost) 0.

If the temperature of a body is T and the ambient temperature is $T_{Amb.}$, the net heat radiation P_{Net} from the body will be the difference between the radiated and the irradiated heat / power from the body - and from the ambient into the body.

$$\text{i.e. } P_{Net} = C_R * C_s * A * (T^4 - T_{Amb.}^4).$$

Hence, for the radiation the power is proportional to the absolute temperature raised to the power of four. As the temperature between the oven and the ambient can reach 70 – 90 K, it can imply a significant unlinearity.

19. Cooling down the oven.
Just as it takes eternal long time for the oven to heat up to its final temperature, so does it take eternal long time for the oven to cool off. Let us assume, that the temperature of the oven has reached a temperature of A = 60 K above the ambient temperature and that the oven has to cool down to a temperature of one degree above the ambient temperature.

How long time (t) will it take for the oven to cool off, if we assume that the temperature of the oven will follow a true exponential temperature curve $T(t) = A\ e^{(-t / \tau)}$, and the thermal time constant τ of the oven is 90 minutes?

$T(t) = A\ e^{(-t / \tau)}$ =>
$T(t) / A = e^{(-t / \tau)}$ =>
$\ln (T(t) / A) = \ln (e^{(-t / \tau)})$ =>
$\ln (T(t) / A) = -t / \tau$ =>
$-t / \tau = \ln (T(t) / A)$ =>
$t / \tau = \ln (A / T(t))$ =>
For τ = 90 minutes; A = 60 K and T(t) = 1 K – we obtain
t = 90 minutes x ln (60 K / 1 K) = 368 minutes ~ 6 hours.

To shorten the cooling time of the oven, I established a forced cooling by switching off the power supplied to the three power resistors, while I maintained the power to the fan - and removed the lit from the oven. After an hour - or so – of forced cooling I then switched off the fan in order for the system to find its equilibrium without any supply of power.

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