DESIGN OF GAS-FILLED FLAT PLATE SOLAR COLLECTORS

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Abstract

With a suitable gas filling used between cover glass and absorber in a flat plate solar collector, it is possible achieving better thermal performance at the same time as the distance between absorber and glass can be reduced. Though, even if there is no vacuum inside the box, there will be potential risks for exhaustion due to stresses depending on the gas volume varies as the temperature varies. This study found out that it is possible build such a collector with less material in the absorber and the tubes and still getting better performance, without risks for exhaustion.

Keywords: Solar collectors – Modelling – Mechanical stresses – heated cavity

1. Introduction

Sealed, flat plate solar collectors filled with a suitable gas can have advantages compared to common, open, air filled constructions: the thermal performance is better at the same time as the distance between absorber and glass can be reduced [1]. Another advantage is the prevention of ageing of the selective surface on the absorber due to the absence of humidity and dust. This paper concentrates on constructions soft enough to accommodate the gas with a pressure near ambient air without expansion vessel. This brings about that the glass and absorber will move and bend as the gas volume changes. The bends will cause stresses in the material and it is important that the construction is designed so the actual stresses always is lower than the allowable ditto. A dimensionless factor is used in this context, called Factors of Safety (FoS), defined as in equation 1. As the formula is defined, the FoS must be > 1 for getting a construction that lasts.

$$FoS = \frac{Allowable\ stress}{Actual\ stress} \qquad (1)$$

Vestlund et al [2] showed that the FoS raised with shorter distances between glass and absorber and bigger areas. The relation between height and width also had some influence; the FoS raised when the absorber was long in the same direction as the tubes was placed, i.e. it was preferable using fewer, long tubes parallel to the longest side of the collector instead of increased number of tubes parallel to the shortest side of the collector. This work concentrates on thermal as well as mechanical performance. This paper will show that by using a suitable gas it is possible achieving state of the art performance or even better at the same time as the material usage is reduced and the FoS is satisfactory Figure 1 visualizes such a collector turned upside down; the tubes (upmost) are fixed on the absorber and the absorber is formed as a tray and fixed in the glass.

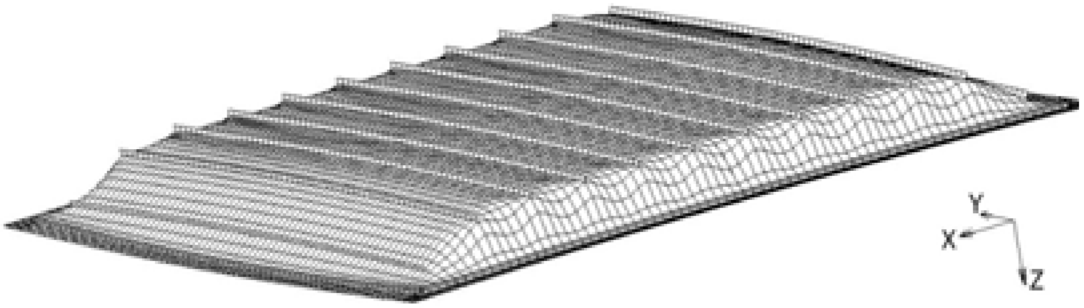

Figure 1: A sealed, gas filled flat plate solar collector seen from upside down. The tubes, (meshed as rods) is upmost in the figure. The tubes are attached to the absorber. The absorber is formed as a tray, and is in its turn attached to the glass. The deviation of absorber to glass distance is exaggerated 10 times. Insulation, frame and pipe connection is not shown.

2. Method

2.1. Factor of safety analysis

Factors of safety were calculated by setting up the models of solar collectors in a Finite Element Analysis program called "MSC.Marc Mentat 2005r2". The way of calculating the factor of safety can be read in Vestlund et al 2010 [2].

2.2. Thermal performance calculation

All heat transfer relations in the model uses functions possible to find in normal used books about heat transfer. This paper is built on formulas from Holman [3] except a refinement of the Nusselt number in sealed, inclined layers from Hollands et al [4]. Material data comes from a measurement series Alvares [5], Lide [6], Holman [3], Air-Liquide [7] and Sundström [8]. The thermal performance calculation also takes in to account the distribution of distance changes due to temperature variations.

Table 1:Thermo physical properties and geometries used in the mathematical model.

Simulating conditions	**Value**		
Ambient Pressure (kPa)	100		
Ambient temperature (°C)	25		
Irradiance (W/m^2)	1000		
Wind (m/s)	0		
Massflow in tubes (kg/s,m^2)	0.05		
Properties of materials in solar collector			
Glass transmittance, emmittance glass (-, -)	0.95, 0.88		
Absorber absorbance emmittance (- , -)	0.95, 0.05		
Thermal conductance, insulation (W/m,K)	0.04		
Geometrical properties	Ref 1	Ref 2	Models
Area solar collector absorber (m^2)	2.12	2.50	2.02

Angle arctan(height/width) (°)	62	30	46
Thickness of the copper absorber (mm)	0.25	0.25	0.1..0.3
Thickness of the aluminium absorber (mm)			0.2..1.0
Tube spacing, d_{tt} (mm)	90	120	103..144
Tube outer diameter (mm)	12	12	12
Tube thickness references (mm)	0.75	0.75	0.5 (1.0)
Slope (°)	45	45	45

2.3. Validating model

Results from a model were compared with two commercial solar collectors. Reference 1, was a Argon filled, sealed collector. Reference 2, was a open, air filled, collector. As far as possible the reference models had the same geometrical properties as the real collectors. The thermal validation can be seen in table 1 and shows that the model has an error of up to about 2%.

Table 2: Deviations when validating the model.

	ηcounted – ηtested		
Collector	**T_w=25 °C**	**T_w=50 °C**	**T_w=75 °C**
Reference 1, Argon, sealed cavity	2.1%	1.7%	2.1%
Reference 2, Air, open cavity	1.8%	1.1%	-0.6%

3. Results

3.1 Optimal gas volume

The efficiency of collector depending of gas volume shows a local maximum at shorter distances than normally used. This is gas dependant and table 3 shows the different local maximums of efficiency for different gases and different temperature differences between heat transfer media and ambience.

Table 3: Local maxima of efficiency for different gases.

	Air	**Ar**	**Kr**	**Xe**
Optimal gas volume for best efficiency [nl/m^2]	9.3	8.6	5.7	3.9

N.b. the gas volume is expressed as normal litres (nl) per m^2 absorber area, where 1 nl is the volume of the gas when the gas is 25 °C. The values shows the volume for best performance at $T_w = T_a = 25$ °C.

3.3 Optimization of copper absorbers

It is possible optimizing the thermal performance with respect to usage of copper per absorber area. If the absorber is thinner than the usual 0.25 mm, it is possible getting the tubes closer with the same usage of material. The η0 and FoS as a function of copper usage can be studied in Figure 2. The x-scale is the total amount of copper used in a solar collector (i.e. absorber + tube) per square meter absorber area. The tube has an outer diameter of 12 mm and a material thickness of 0.5mm.

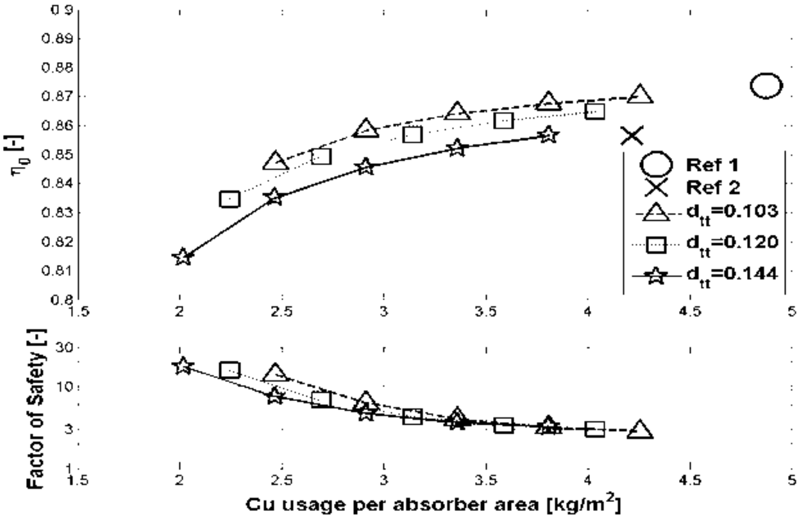

Figure 2: Dependencies of copper usage (gas=Ar)

The figure shows the result for an Argon filled collector; if the gas is changed there will only be some scale differences; but the internal order will remain.

As can be seen in the figure, there is higher performance of using shorter distances between the tubes (d_{tt}) in all cases; For example the rightmost dot (d_p = 0.30 mm) of the d_{tt} = 144 mm curve, shows the same efficiency as the middle dot (d_p = 0.20 mm) of the d_{tt} = 120 mm curve, and the second dot (d_p = 0.15 mm) of the d_{tt} = 103 mm curve, but the total mass is 3.8, 3.1 and 2.9 kg/m^2 respectively. The analyse will in the following concentrate on the shortest distance, i.e. d_{tt}=103 mm for copper absorbers.

As also can be seen in the figure, the FoS is increasing with lowering usage of copper: When the absorber gets softer the gas pressure drops and then the stresses gets lower and the FoS higher.

3.4 Efficiencies for different gases

Argon shows better performance than air, but Argon is by no mean the ultimate gas. Figure 3 shows efficiency curves for 3 gas filled solar collectors with 0.1 mm thick absorber and a tube to tube distance of 103 mm; one with Argon, one with Krypton and one with Xenon. The references (Argon and air filled respectively) are also shown for comparison.

The total copper usages for the tested objects are 2.5 kg/m^2 compared to the references usages of 4.9 kg/m^2 (ref. 1) and 4.2 kg/m^2 (ref. 2) respectively. Withstanding the test objects only have 40% as thick absorber as the references, it can be seen that at η_0, where the fin efficiency has the most affection, the test collectors still are useful; they have a efficiency that is up to 3 percent lower than reference 1 and up to about 1 percent lower than reference 1. At higher temperature differences between T_w and T_a, the gas filled collectors just getting better compared to the references. Interestingly also the Argon filled test object becomes a slight more efficient than reference 1. Mainly, this can be explained by a more appropriate chosen d_{pc} in the test collector.

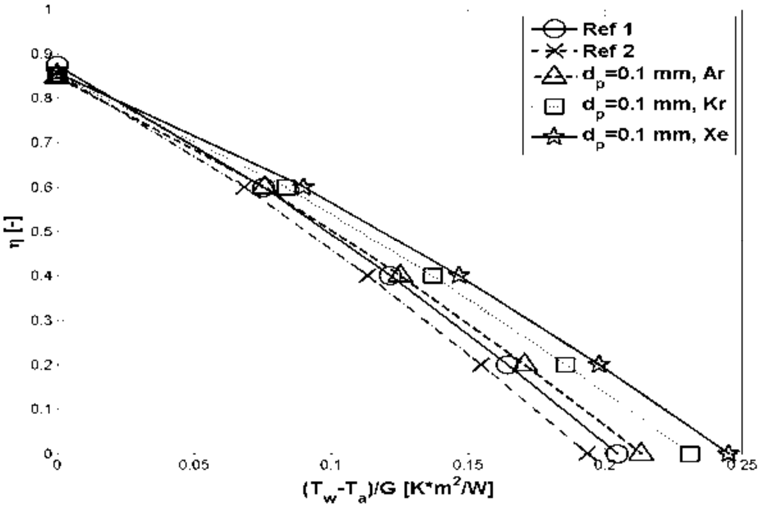

Figure 3: Efficiency curves for gas filled solar collectors with a copper absorber thickness of 0.1mm, compared with the two reference collectors.

3.5 Aluminium absorber

An effective method of minimizing the usage of copper is to change the absorber material into aluminium. In this case it was interesting use a longer centre to centre distance of the tubes, d_{tt}, and by that minimize the copper usage furthermore. d_{tt} was set to 144 mm and the thickness of tubes, d_{mt}, was 0.5 mm. The dependencies of the absorber thickness and gas can be seen in Figure 4.

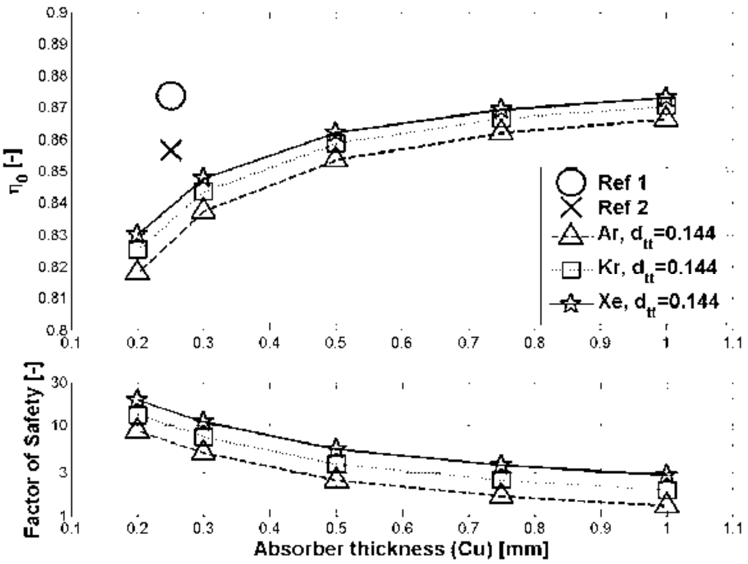

Figure 4: Dependencies of gas and thickness of aluminum absorber solar collectors.

N.B: The references have absorbers made of copper, the test objects are made of aluminium.

As can be seen, the aluminium collectors are getting the same η_0 as the ref 2 from at about d_{tt} = 0.5 mm and the same as ref 1 at about 1 mm. In terms of material usage; 4.2 kg/m^2 copper (ref 2) is as efficient as 1.1 kg/m^2 copper (for the tubes) and 1.1 kg/m^2 aluminium (for the absorber). The FoS limits however the usage of thick aluminium absorbers and they can be doubtful together with Argon.

3.7 Aluminium collectors at higher temperatures

A solar collector does not only work at η_0, and if the absorber is 0.5 mm or thinner, the advantages of the thermal performances of the suitable gases soon will be seen as the temperature difference between heat transfer media and ambience rises. There will be almost an copy of the curves in the efficiency diagram in Figure 4, if a 0.5 mm aluminum absorber is used together with 0.5 mm tubes with a cc-distance of 144 mm with the difference that the first will use 2.5 kg copper / m^2 and the latter will use 1.1 kg copper and 1.4 kg aluminium per square meter.

3.8 Total performance

All the factors for the curve in a efficiency diagram is shown in Table 4 for the previously analyzed collectors (i.e. 0.1 mm copper collectors with a d_{tt} of 103 mm and the 0.5 mm aluminium collectors with 144 mm d_{tt}), and compared with the references.

Table 4: Factors for analyzed collectors

Collector	**Ref 1**	**Ref 2**	**Cu,Ar**	**Cu,Kr**	**Cu,Xe**	**Al,Ar**	**Al,Kr**	**Al,Xe**
Gas	Argon	Air	Argon	Krypon	Xenon	Argon	Krypon	Xenon
η_0 [-]	0.874	0.857	0.847	0.852	0.856	0.853	0.859	0.862
η(Tw-Ta/G = 0.25) [-]	0.793	0.773	0.777	0.784	0.796	0.784	0.795	0.802
η(Tw-Ta/G = 0.50) [-]	0.701	0.676	0.695	0.714	0.727	0.701	0.720	0.733
a1 [W/m^2,K]	3.40	3.54	3.01	2.76	2.56	3.02	2.76	2.57
a2 [mW/m^2,K^2]	4.29	4.60	4.56	4.07	3.80	4.58	4.10	3.83
Gas volume / area [nl/m^2]	22	40	8.6	5.7	3.9	8.6	5.7	3.9
Closed cavity?	Yes	No	yes	yes	yes	Yes	yes	yes
Absorber material	Cu	Cu	Cu	Cu	Cu	Al	Al	Al
Absorber thickness [mm]	0.25	0.25	0.10	0.10	0.10	0.50	0.50	0.50
Tube material	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu
Tube to tube distance [mm]	90	120	103	103	103	144	144	144
Tube thickness [mm]	0.75	0.75	0.5	0.5	0.5	0.5	0.5	0.5
Cu Mass absorber and tube [kg/m^2]	4.9	4.2	2.5	2.5	2.5	1.1	1.1	1.1
Al Mass absorber [kg/m^2]	0	0	0	0	0	1.4	1.4	1.4

As can be seen, the test objects are 1 to 3% less efficient at η_0 as the references, because of their lesser use of material. However, the test objects has lower a1 and a2 values, thanks to the thermal properties of the gases, especially krypton and xenon, and therefore they persists the reduction of efficiency better at higher temperature differences between T_w and T_a. An example of the advantage of a gas filling gets better the higher temperature difference: Reference 1 is 1.5 % more efficient than the Al,Kr in table 4 at η_0, but at Tw-Ta/G = 0.25 it is only 0.2 % ahead, and at Tw-Ta/G = 0.50 it is 1.9 % behind the krypton filled collector. Then it should be remembered: Reference 1 uses 4.9 kg/m^2 copper and an argon filling; Al,Kr uses 1.1 kg/m^2 copper, 1.4 kg/m^2 aluminium and an krypton filling.

4 Discussion

The deviations between the calculation model and measurement of the existing collectors are presented in the validation of the model and showed good agreement. The deviations that yet are left can be explained as the sum of four reasons. The first reason is lack of precision in the formulas that explains the physics and is out of scope for this paper. The second is lack of adequate information about the references. Som data was presented as a range by the manufacturer and then the middle point was used. For properties with no data specified at all, commonly values have been used. The third reason is uncertainties of the measurements of the references. Efficiency data for reference 1, the gas filled, comes from a sheet from the manufacturer [9]. For reference 2, the air filled, the figures comes from a test protocol [10]. The fourth part of deviations is deviations in the model itself. The more nodes in the model, the less change in result. It was found out that the number of absorber nodes per tube node was more important than number of tube nodes. The model achieved good resolution when the number of absorber nodes per tube node was 4 and the number of tube nodes was 2. This indicates that the fin efficiency is more important than the unlinear heating of the heat transfer media in the flow direction.

Two factors that can influence the factor of safety on the different components in the collector were taken in to account: the volume changes in the gas and the pressure inside the tubes. Other factors influencing the FoS that was not taken into account was for example possible snow and/or wind loads; in lack of reasonable values they are omitted. It should also be remembered that free room is needed under the absorber for the gas to expand, otherwise, if the absorber reaches the insulation, the stresses in the construction will increase in an unpredictable way and the FoS will be unknown.

5 Conclusion

It is possible reducing the usage of copper by 50% in an collector built with copper in absorber and tubes and still get a descent performance; a few percent lower at $\eta 0$, and a few percent better in the more normal working point range (η(Tw-Ta/G = 0.25..0.50)), though that requires a proper gas, such as Krypton or Xenon.

It is also possible reducing the usage of copper usage furthermore to less than 50% and still achieve a good performance: an absorber made of aluminium, tube made of copper and a proper gas in the cavity. Such a collector behaves in a similar way as the 50% copper collector described above; i.e. a few percent lower performance at $\eta 0$, and a few percent better in the more normal working point range.

Collectors with thin absorbers requires free movement ability for the absorber.

6. References

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Nomenclature

A	Area (m^2)
a1	loss coefficient when mean temperature of heat transfer medium is the same as the ambience (W/m^2, K)
a2	temperature dependant loss coefficient (mW/m^2, K^2)
d	distance (m)
FoS	Factor of Safety (-)
G	Irradiance (W/m^2)
s	Sensitivity(-)
T	Temperature (K)
η	Efficency (-)

Subscripts

0	When $T_w - T_a = 0K$
a	Ambient
c	Cover glazing
f	Film; used in temperatures describing the arithmetic mean between the wall and the free stream in boundary layers or the mean between the two walls in enclosed spaces.
m	Material, Mean
p	Absorber plate
p0	When the pressure is 0
w	Heat transfer medium