

EVALUATION OF FLAT PLATE SOLAR COLLECTOR WITH INTEGRAL FIN EXTRUDED ALUMINIUM TUBES

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Abstract

Flat plate collector (FPC) is a central component of any solar water heating system. The efficiency of FPC is determined by performance of absorber plate. Absorber plate has conventionally been comprised of copper tubes with brazed fins. The present study is an attempt to investigate the possibility of replacing copper-based absorber system with aluminium and thereby reduce cost significantly. The extra thermal resistance caused by introducing aluminium is compensated by avoiding a fin-tube weld joint with the help of extruded fin-tube arrangement. Thermal resistance analysis of the commercially available collector and modified AI-FPC has been carried out which suggests that the latter has nearly same overall heat loss coefficient as former one. Extruded aluminium fin-tube modules have been fabricated followed by performance testing on commercial and modified collector for over two month period. Performance testing results show that under same solar irradiation and weather conditions the modified collector performs as efficiently as the conventional one. Extrusion process limits the minimum fin thickness possible resulting in considerable increase in the use of aluminium in absorber plate.

Keywords: flat plate collector, bond conductance, extruded aluminium fin-tube.

1. Introduction

Since the first flat plate collector systems were developed in the 1950s, absorber plates and tubes for FPC systems worldwide, have historically been made from copper. Copper has been favored because of the combination of high thermal conductivity, resistance to atmospheric and water corrosion, reasonable mechanical strength and ease of joining by soldering, brazing etc. Aluminum was not given a serious consideration in spite of being cheaper and lighter than copper, mainly because of its lower thermal conductivity, lower resistance to aqueous corrosion (especially in presence of chloride ions) and problems associated with welding at that time. However, since mid-2000s there has been a very sharp increase in the prices of copper while the increase in aluminum prices has been modest [1, 2]. As a result, while absorber material and other metal costs was about 36% of total FPC collector manufacturing cost in 1995, the material costs have increased to about 65% in 2011 [3]. Hence the case for cost reduction of FPC collectors by replacing copper with aluminum becomes all the more pertinent. It is expected that such a replacement can also benefit other segments of industry such as electrical windings and refrigeration by making more copper available.

There is a significant potential for cost reduction of FPC based solar water heater systems by replacement of copper based solar water heater systems by replacement of copper plates and tubes with aluminum since the price of aluminum is about 25-30% of that of copper [4]. Seemingly disadvantageous position of conductivity of aluminium is annulled by the immense contact resistance between the absorber plate and tubes of copper

collectors. In addition, the cost and time of manufacturing copper absorber plate is high because of the need for a good joint between the risers and plates. With significant design changes for aluminum via the use of integral fin extruded sections (fig. 1), joining is required only at the headers.

This work aims to theoretically and experimentally study the effect of bond conductance and riser tube material on the overall efficiency of the flat plate collector in order to ascertain the feasibility of replacing copper with aluminium as absorber plate material. Following section offers an overview of the research work conducted in the past in this area.

1.1. Bond Conductance

The fin-tube heat transfer efficiency in a solar collector is determined by the bond conductance value of the joint.

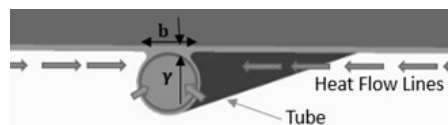


Fig. 1. Cross sectional view of fin-tube module

It is defined as

$$C_b = \frac{\kappa_b b}{\gamma} \quad (1)$$

where κ_b = conductivity of bond material in W/m-K

Lack of knowledge of precise values of κ_b and γ for a given bond poses difficulty in measuring bond

conductance using a direct equation. However, it is possible to calculate it based on temperature measurement across the bond and knowledge of heat supply. In the past, several studies have been carried out to measure the bond conductance of different fin-tube joints. Khan et. al [5] found the average values of three bond conductance as follows: $C_{b,wired}=3.47$ W/m-K; $C_{b,soldered}=25.84$ W/m-K; $C_{b,duPont} = 4.61$ W/m-K. It concludes that the soldered bond is an excellent joint and duPont adhesive is unsuitable from the thermal point of view. Badran et al. [6] has compared five specimens of fin-tube configurations and found that bond conductance for welded joint has highest value (30 W/m K) as compare to press fit and partial contact between fin-tube. Shariah et al [7] theoretically studied the effect of thermal conductivity of the absorber plate of a solar collector on the performance of a thermosiphon solar water heater. Their study showed that replacing copper with aluminium in absorber plate has no significant impact on the efficiency of collector. Literature survey suggests that suitability of 'extruded aluminium fin-tube' arrangement in FPC has never been theoretically studied or experimentally tested in the past. The present work makes unique contribution in this area.

2. Design and Fabrication of Modified Al-FPC

It is found that thermal performance of solar collector depends on bond conductance between tube and plate. The better the bond conductance faster is the heat transfer between plate and tube. Tube and plate when fabricated as a single module by an extrusion process results in virtually zero contact resistance, thereby increasing collector performance. If absorber plate and integrated tubes are divided based on geometric repeatability, it does not affect thermal performance of collector. A single module is easy to extrude therefore the conventional copper absorber plate can be replaced with the series of equally spaced extruded fin-tube modules having same length as collector. It is important to consider both aspects i.e. the thermal performance and ease of extrusion of the desired shape, while deciding dimensions of module to be extruded. Following section briefly illustrates one such consideration i.e. extrusion thickness.

2.1 Effect of Fin Thickness on Thermal Performance

Mathematically, fin efficiency is given by

$$\phi = \frac{\tanh[m(W-D_o)/2]}{m(W-D_o)/2}; m = \sqrt{\frac{U_l}{k_p \delta_p}} \quad (2)$$

Where k_p and δ_p are thermal conductivity and thickness of absorber plate respectively, W is center-to-center distance between tubes (m), D_o is outer diameter of riser tube.

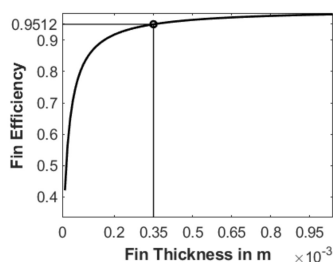


Fig. 2. Fin efficiency vs fin thickness graph

Increase in fin-tube thickness results in reduction of overall resistance, thereby improving collector efficiency. However beyond 0.35 mm magnitude, fin thickness has no substantial impact on the fin efficiency as shown in Fig. 2. Therefore extruded module of 0.35 mm thickness is optimum from thermal and material point of view.

During extrusion tube thickness should be kept close to plate thickness in order to avoid defects like non-uniform material flow. Figure 3 shows the final dimension of a module that has been extruded after considering thermal, manufacturing, weight and economic point of view.

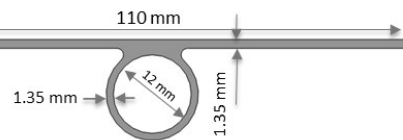


Fig. 3. Dimensions of extruded fin-tube Al-FPC fabricated for performance testing (not to scale)

3. FPC Performance Testing

'Draft Indian standard' [8] test procedure has been followed to compare performance of Cu-FPC and Al-FPC. The test method is based on a lumped capacitance model, where it is assumed that average water temperature in the storage tank characterizes the behavior of the whole system whether the storage is well-mixed or stratified. The test procedure envisages characterizing the thermal performance of the system without any withdrawal of hot water from the storage tank. This strategy is adopted because the performance of the solar water heating system strongly depends on the pattern of withdrawal of hot water from the storage tank, and there could be wide variation in the withdrawal pattern. The system performance is evaluated in two parts corresponding to its performance during daytime and during nighttime. Usually, the storage tank in solar water heating systems which are designed to work on the principle of thermosiphonic flow is located at higher level than the top edge of the solar collector with a view to suppress reverse flow during night. In such a case, the solar collector and part of piping would not play role in losing heat from the tank during night as it does during the day. However, night time test would account for all thermal losses from the system.

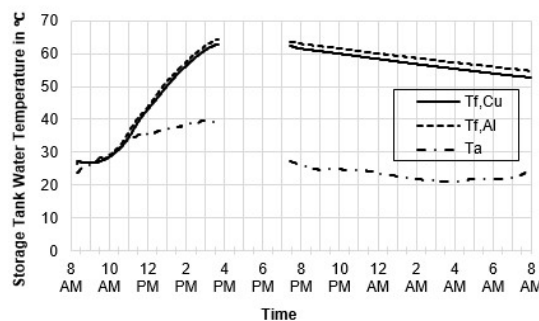


Fig. 4. FPC performance recorded on 17th April 2018

As shown in Fig. 4, storage tank water temperature measurement for both the collectors showed that the Al-FPC performs as efficient as Cu-FPC under same irradiation and weather conditions. This gives conclusive evidence of feasibility of Al in place of copper as fin-tube material. However extruded aluminium fin thickness of 1.35 mm is quite high as compared to copper absorber plate thickness of 0.35 mm.

4. Thermal modelling results

Thermal analysis of FPC is divided into four steps which involve solar insolation calculation, evaluation of radiation absorbed by absorber plate, loss calculations and finally evaluating performance parameters [9]. Experimental values of storage tank water temperature are in close agreement with simulations results validating the adopted modelling algorithm. As bond conductance increases the overall resistance decreases until bond conductance reaches critical value (~30 W/m-K) where other heat loss coefficient become predominant. This can be inferred from the following equation of overall resistance to heat transfer in top direction in FPC.

$$R_o = \frac{1}{U_1[D_o+(W-D_o)\phi]} + \frac{\delta}{2k_{plate}D} + \frac{1}{C_b} + \frac{\ln(D_o/D_i)}{2\pi k_{pipe}} + \frac{1}{\pi D_i h_f} \quad (3)$$

Where U_1 is overall heat loss coefficient, D is riser tube average diameter, D_o and D_i is outer and inner diameter of riser tubes respectively, h_f is convective heat transfer coefficient at the tube and water interface, δ is thickness of absorber plate.

Fig. 5 graphically shows the effect of increasing bond conductance on the overall heat resistance network.

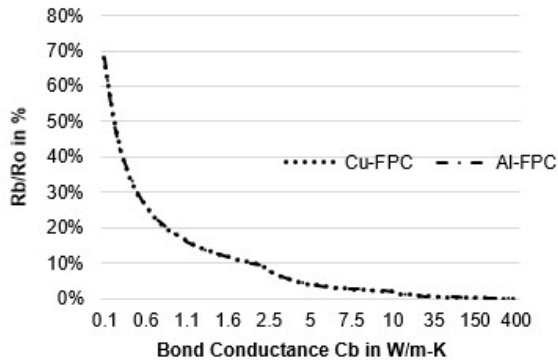


Fig. 5. Contribution of bond resistance R_b or $(1/C_b)$ in overall resistance R_o for varying bond conductance

Following are the key findings of thermal analysis of the flat plate collector:

1. If bond conductance exceeds value of 30 W/m-K, the collector efficiency is solely dictated by optical losses. Consequently, further increase in bond conductance cease to have any effect on efficiency of collector as shown in the Fig 5.

References

- [1] <http://www.infomine.com/investment/metal-prices/copper/all/>
- [2] <http://www.infomine.com/investment/metal-prices/aluminum/all/>
- [3] Stephanie Banse and Joachim Berner, Lowering costs, maintaining efficiency; Conference report in Sun & Wind Energy (SMEThermal 2012).
- [4] Solar Flat Plate Collector Analysis, Sunil.K.Amrutkar, Satyshree Ghodke, K. N. Patil; IOSR Journal of Engineering, Vol. 2 (2), pp 207 (Feb 2012).
- [5] Ehsan Ullah Khan, "Bond Conductance in Various Tube-in-Strip Types of Solar Collector", Pakistan Council of Scientific and Industrial Research, West Regional Laboratories, Lahore

2. Resistance offered by riser tube walls is insignificant as compared to other dominant resistances like the fin-tube resistance, optical losses, convective loss from all the sides of collector etc. Hence the use of aluminium tube instead of copper does not affect the overall heat loss coefficient.

Cu-FPC differs from Al-FPC only in terms of fin-tube joint and riser/header tube material. Since riser tube material has little impact on overall heat loss coefficient this suggests that fin-tube joint in the conventional collector is in fact beyond 30 W/m-k value and is already oversized from thermal point of view.

5. Conclusion

Literature review revealed that there has been usage of aluminium material in commercial FPCs along with copper. However, the absorber plate made purely out of aluminium is entirely new for the FPCs. Storage tank water temperature data for fifty days have been recorded and characteristic parameters such as overall efficiency, heat loss coefficient and bond conductance have been determined. The key findings are

1. Time taken for both the collectors to reach steady state is almost same when subjected to same irradiation. This result implies that thermal heat capacity of the system is not affected significantly by the absorber plate material.
2. Efficiency of Al-FPC is almost same as that of commercial Cu-FPC considering the degree of uncertainty in experimental measurements. Hence, aluminium is a viable option to replace copper in FPCs.
3. Large thickness of extrusion has offset the benefit of lightweight aluminium. More investigation needs to be done in this direction to ascertain its feasibility.
4. Modeling outcome combined with performance testing results suggests that commercial Cu-FPC bond conductance value is beyond 30 W/m-K. Hence, it is as efficient as extruded Al-FPC.

Acknowledgments

The authors acknowledge the support of the Indian Institute of Science in conducting this research and the assistance received from DST as grant under DST/TM/SERI/DSS/277(G). The authors also thank Aditya Birla Science and Technology Company for carrying out extrusion of solar collector fin-tube modules.

- [6] Badran, Ali A., et al. "On the measurement of bond conductance in solar collector absorber plate." Energy Conversion and Management 49.11 (2008): 3305-3310.
- [7] Shariah, A. M., et al. "Effect of thermal conductivity of absorber plate on the performance of a solar water heater." Applied Thermal Engineering 19.7 (1999): 733-741.
- [8] Draft Indian Standard: "Test Procedure for Thermosiphon –Type Domestic Solar Hot Water Heating Systems" ICS 27.160; 91.140.65; 97.100.99
- [9] Duffie J, Beckman W., "Solar engineering of thermal processes". 2nd ed. NY: John Wiley; 1991.