DAMAGE OF INSULATION IN FLAT PLATE SOLAR COLLECTORS BY STOPPAGE OF FLUID FLOW

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This communication presents an analysis of the rise in temperature of the plate and insulation of flat plate solar collectors, when the flow of fluid in the collector stops (accidentally) and the fluid is drained off. The equation of heat conduction in the insulation is solved along with the equations representing the energy balance to obtain an explicit expression for the temperature of the plate (i. e. the top layer of the insulation) as a function of time.

It is concluded that under typical hot and sunny conditions in the deserts of India and West Asia, the temperature of the top layer of the insulation (for typical parameters of a collector) may exceed the maximum service temperature in about 1000 seconds (when inexpensive insulation e.g., polyurethane foam is used). Hence the possibility of occurence of accidental stoppage of fluid flow and draining of fluid for periods exceeding about 20 minutes rules out the use of inexpensive foam insulation. The theory is in good agreement with a low temperature experiment.

INTRODUCTION

IT has been observed that during stoppage of fluid flow in a solar collector under conditions of high atmospheric temperature and intense solar radiation (which occurs frequently in tropical deserts) inexpensive insulation below the plate gets damaged. In this communication, we present a straight forward analysis of the rise in the temperature of the plate (i. e. the top layer of the insulation), occuring after the accidental stoppage of the fluid flow and draining of fluid ; when this temperature exceeds the maximum service temperature the insulation gets damaged. We have solved the equation of heat conduction in the insulation along with the energy balance equations to obtain an explicit expression for the temperature of the plate (i. e. top layer of the insulation) as a function of time. For low values of thermal conductivity of insulation (e. g. polyurethane foam), the plate temperature reaches 92% of the stagnation temperature in 1000 seconds and then asymptotically approaches the stagnation temperature. For relatively higher values of thermal conductivity of insulation, similar behaviour corresponding to a larger time scale is predicted.

It is seen that for typical collector parameters and typical conditions of intense solar radiation and high atmospheric temperature, frequently encountered in tropical deserts in summer, the temperature of the top layer of insulation (if an inexpensive insulation like polyurethane foam is used) may exceed the maximum service temperature in a period of the order of 1000 seconds. Hence the use of inexpensive insulation is ruled out by the possibility of occurrence of accidental stoppage of fluid flow for long periods (twenty minutes or more).

The theory is in good agreement with the observed rise in temperature of a simulated solar collector, experiment corresponding to a stagnation temperature of 87°C.

Theoretical Analysis

Steady State Plate Temperature : The steady state energy balance of the plate in a flat plate collector can be expressed as :

$$Q = h_1 (T_{p0} - T_c) + h_f (T_{p0} - T_{fm}) + \lambda_e (T_{p0} - T_a), \quad \ldots (1)$$

where Q is the absorbed solar energy per unit time per unit area of the absorbing plate, h_1 is the heat loss coefficient between the absorbing plate and the glass cover, T_{p0} is steady state absorbing plate temperature, T_c is glass cover temperature, h_f is heat transfer coefficient between the surface of the absorbing plate and the fluid, $T_{f,m}$ is the arithmetic mean temperature of the fluid passing through the absorbing plate, λ_e is the heat loss from the absorbing plate to the ambient air through the edges of the insulation per unit area of plate per unit difference of temperature and T_a is ambient air temperature.

The above expression assumes an infinite thickness of insulation below the plate. This is, of course, a poor assumption for the steady state but as shall be seen later a reasonably good one for studying transient phenomena in a time interval of the order of 1000 seconds. Since our aim is to examine the transient nature of the phenomena, we shall retain this assumption.

The energy balance of the glass cover assumed to have negligible thickness is given by Duffie and Beckman (1974)

$$h_1 (T_{p0} - T_c) = h_0 (T_c - T_a), \quad \ldots (2)$$

where h_0 is heat loss coefficient from the glass cover to the ambient air.

The mean fluid temperature is determined from the condition following Threlkeld (1970)

$$h_f (T_{p0} - T_{fm}) = \frac{\dot{m}_f c_f}{A} (T_{f0} - T_{fi})$$

$$= \frac{2\dot{m}_f c_f}{A} (T_{fm} - T_{fi}) \quad \ldots (3)$$

where $T_{f,0}$ is fluid outlet temperature, $\dot{m}_f$ is mass flow rate of the fluid, C_f is specific heat of the fluid, A is area of the absorbing plate and $T_{f,i}$ is fluid inlet temperature.

From eqns. (1), (2) and (3), the steady state platet emperature T_{p0} is given by ;

$$T_{p0} = \frac{\left[Q + (U_t + \lambda_e)\, T_a + \frac{2\dot{m}_f}{A} \frac{C_f h_f T_{fi}}{\left(\frac{2\dot{m}_f C_f}{A} + h_f \right)} \right]}{\left[U_t + \lambda_e + \frac{\frac{2\dot{m}_f C_f h_f}{A}}{\frac{2\dot{m}_f C_f}{A} + h_f} \right]}, \quad \ldots (4)$$

where

$$U_t = \frac{h_0 h_1}{h_0 + h_1}$$

which is overall top loss coefficient between the absorbing plate and the ambient air.

The above analysis is based on the simplified model discussed by Threlkeld (1970) and neglects temperature gradients along the plate.

Growth of plate temperature after stoppage of fluid flow — The equation of heat conduction in the insulation is

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t},$$

where α is the thermal diffusivity of the insulation, $T(x,t)$ is temperature distribution in the insulation, x is position coordinate along the thickness of the insulation and t is time. The appropriate boundary conditions are

$$T(0,t) = T_p \quad \ldots (6)$$

and

$$T(x,0) = T_{p0}, \quad \ldots (7)$$

where T_p is plate temperature and

$$-K\left(\frac{\partial T}{\partial x}\right)_{x=0} = Q - h_1 (T_{x=0} - T_e) - H_e \left.\frac{\partial T}{\partial t}\right|_{x=0} - \lambda_e (T_{x=0} - T_a)$$

$$= Q - U_L [T(x=0) - T_a] - H_e \left.\frac{\partial T}{\partial t}\right|_{x=0} \quad \ldots (8)$$

where $U_L = U_t + \lambda_e$ is the overall heat loss coefficient between the absorbing plate surface and the ambient air, K is thermal conductivity of the insulation and H_e is effective heat capacity the absorbing plate and the remaining fluid per unit area of the plate when the flow ceases. The glass cover temperature in this case is again determined by eqn. (2) on replacing T_{p0} by T_p or $T(x = 0)$.

The characteristic lengths associated with equations (5) and (8) corresponding to a time interval Δt are

$$L_1 = (K \Delta T/\rho c)^{1/2}$$

and

$$L_2 = \left[\frac{(H_c/\Delta t) + U_t + \lambda_e}{K} \right]^{-1},$$

where ρ and C are density and specific heat of the insulation respectively and Δt is the time interval with typical collector parameters ;

(i) For glass wool and polyurethane foam and $\Delta t = 1000$ secs. and (ii) for asbestos and $\Delta t = 2000$ sec., the characteristic lengths are less than 3 cms. Hence the assumption of infinite thickness of the insulation is appropriate for thicknesses larger than 10–15 cms.

Now we proceed to consider the two cases separately.

Case A : Low thermal conductivity $K < 2\,(U_L\,\alpha\,H_c)^{\frac{1}{2}}$

Using the Laplace Transform technique the solution for the temperature (in this case) as a function of distance and time can after a little simplification be written as,

$$\begin{aligned} T(x,t) = T_{p0} + \frac{\{Q - U_L\,(T_{p0} - T_a)\}}{\alpha\,H_c\,(\alpha_1^2 + \beta_1^2)} \Bigg[\Bigg\{ erfc \left(\frac{x}{2\sqrt{\alpha t}} \right) \\ + \frac{(\alpha_1^2 + \beta_1^2)^{1/2}}{\beta_1} \exp\,(\alpha t\,(\alpha_1^2 - \beta^2_1) - \alpha_1 x \Bigg\} \Bigg] \\ [\{A \sin\,(\phi - \Psi + \beta_1 x + 2\alpha t\,\alpha_1\,\beta_1) \\ - B \cos\,(\phi - \Psi + \beta_1 x + 2\alpha t\,\alpha_1\,\beta_1)\}], \qquad \ldots (9) \end{aligned}$$

where

$$\alpha_1 = -\left(\frac{K}{2\alpha H_c}\right), \; \beta_1 = \tfrac{1}{2}\left(\frac{4U_L}{\alpha H_c} - \frac{K^2}{\alpha^2 H_c^2}\right)^{\frac{1}{2}},$$

$$A = -\left[\frac{\exp\,(-x'^2)}{2\pi\,x'}\left(1 - \cos\,(2x'y')\right) + \frac{2}{\pi}\exp\,(-x'^2),\right.$$

$$\left. \times \sum_{n=1}^{\infty} \frac{\exp\,(-n^{2'}4)}{(n^2 + 4x'^2)}\,fn\,(x', y') - erfc\,(x')\right]$$

$$B = -\left[\frac{\exp\,(-x'^2)}{2\pi x'}\sin\,(2x'y') + \frac{2}{\pi}\exp\,(-x'^2)\right.$$

$$\left. \sum_{n=1}^{\infty} \frac{\exp\,(-n^{2'}4)}{(n^2 + 4x'^2)}\,\text{In}\,(x', y')\right],$$

$$\begin{aligned} fn\,(x',y') = [2x'\,(1 - \cosh\,(ny')\cos\,(2x'\,y') \\ + n \sinh\,(ny')\sin\,(2x'y')] \end{aligned}$$

$$\begin{aligned} \text{In}\,(x',y') = [2x'\cosh\,(ny')\sin\,(2x'\,y') \\ + n \sin h\,(ny')\cos\,(2x'\,y')] \end{aligned}$$

$$x' = \left(\frac{x}{2\sqrt{\alpha t}}\right) - \alpha_1 \sqrt{\alpha t}\,,\ y' = \beta_1 \sqrt{\alpha t}\,,$$

$$\phi = \tan^{-1}\left\{\frac{\alpha_1^2 - \beta_1^2}{2\alpha_1\ \beta_1}\right\} \text{ and } \Psi = \tan^{-1}\left(\frac{\alpha_1}{\beta_1}\right)$$

Case B — Relatively high thermal conductivity $K > 2\,(U_L\ \alpha\ H_c)^{1/2}$ The solution for the temperature $T\,(x,\,t)$ after using the Laplace Transform technique in this case is given by

$$T(\alpha,\,t) = T_{p0}\Bigg[\ 1 + \frac{\{Q - U_L\,(T_{p0} - T_a)\}}{\alpha H_c\,T_{p0}\,\alpha'_1\beta'_1}\Bigg\{ erfc\left(\frac{x}{2\sqrt{\alpha t}}\right)$$

$$+ \frac{\beta_1'}{(\alpha_1' - \beta'_1)}\exp\left(-\alpha'_1 x + \alpha'^2_1\,\alpha t\right)$$

$$erfc\left(\frac{x}{2\sqrt{\alpha t}} - \alpha'_1\sqrt{\alpha t}\right) + \frac{\alpha'_1}{\beta_1' - \alpha'_1}\ \exp-(\beta'_1 x + \beta'^2_1\alpha t)$$

$$erfc\left(\frac{x}{2\sqrt{\alpha t}} - \beta_1'\sqrt{\alpha t}\right)\Bigg\}\Bigg]\,, \qquad \ldots \quad (10)$$

where

$$\alpha'_1 = -\left(\frac{K^2}{2\alpha H_c}\right) + \tfrac{1}{2}\left(\frac{K^2}{\alpha^2 H_c^2} - \frac{4U_L}{\alpha H_c}\right)^{1/2}$$

and

$$\beta'_1 = -\left(\frac{K}{2\alpha H_c}\right) - \tfrac{1}{2}\left(\frac{K^2}{\alpha^2\ H_c^2} - \frac{4U_L}{\alpha H_c}\right)^{1/2}$$

The temperature of the plate in each case can be obtained by putting $x = o$ in eqns. (9) and (10). We see that in both cases $T_p\ (t \to \infty) = \dfrac{Q + U_L\,T_a}{U_L} = T_s$ is the stagnation plate temperature.

Experiment

To have an experimental verificatiou of our theory, we have performed a simple low temperature experiment. The experimental set up consists of a wooden box (31 cms $\times$ 21.5 cms $\times$ 19 cms), fitted with a glass cover at the top and a blackened copper plate (of thickness 2 mm), placed 2 cms below the glass cover; below the copper plate is a layer of glass wool of thickness 15 cms. One junction of a copper-constantan thermocouple was soldered to the centre of the lower surface of the plate and the other one was outside the box in air (shade). The box was brought from a room, in the sun at 11.45 a. m. on September 13, 1977 and the temperature of the plate recorded by means of the thermocuple and a millivoltmeter at intervals of two minutes.

The relevant parameters of the experimental set up are ; Intensity of the solar radiation (I) = 853 W/m^2 (constant as measured by calibrated solar cell), Absorptance of the copper plate (α_0) = 0.9, Transmittance of the glass cover (τ) = 0.9, Density of copper (ρ_p) = 8954 Kg/m^3, Specific heat of copper plate (C_p) = 0.3831,

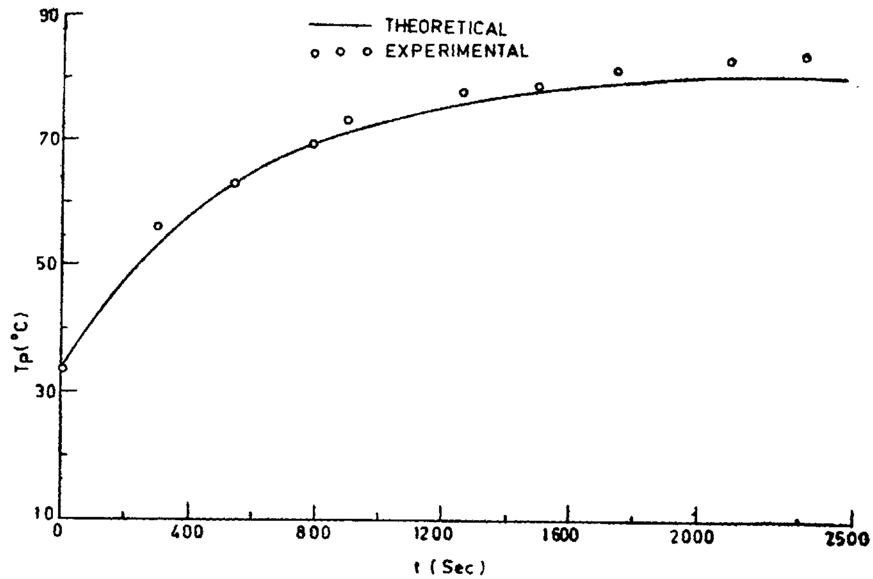

Fig. 1. Variation of the plate temperature with time; the solid curve indicates theoretical results while experimental points are denoted by [o]

KJ/kg°C, Thickness of the ocopper plate (l) = 0.002 m, Density of the glass wool insulation (ρ) = 200.2 Kg/m^3, Specific heat of the glass wool (C) = 0.67 KJ/Kg°C, Thermal conductivity of the glass wool = 0.04 W/m°C, $Q = \alpha_0 \tau I =$ 691 W/m^2, $H_c = l \rho_p C_p$ = 6.86 KJ/m^{2}°C and Ambient air temperature (T_a) = 31.5°C.

The rise of the plate temperature as obtained experimentally for glass wool as insulation is shown by [o] in Fig. 1. From the behaviour of experimental point in Fig. 1 the stagnation temperature $T_s = T_p (t \rightarrow \infty)$ can be seen to be 87°C. For the experimental conditions mean Q = 691 W/m^2, mean T_a = 31.5°C. and T_s = 87°C, We obtain U_L =12.45 W/m^{2}°C. Using this value of U_L we have calculated T_p (t) from eqn. (9) for the experimental parameters; the solid curve in Fig. 1 represents the theoretically calculated results. It must be mentioned here that the conditions of our experiment (e. g. Intensity of solar radiation, heat transfer from absorbing plate to glass cover and glass cover to ambient air) were such as to give a low stagnation temperature (~ 87°C). Therefore, we could not observe the damage of insulation. However, the observed variation of the plate temperature with time agrees well with the theoretically calculated results for the experimental parameters. This establishes the validity of the theoretical model .

Numerical Results and Discussion

To have a numerical appreciation of the importance of the present theory under more stringent conditions of the solar collectors we have computed the rise of plate temperature with time in three typical insulation cases as specified in Table (I); in case III the stagnation temperature is higher than the service temperature of the insulation.

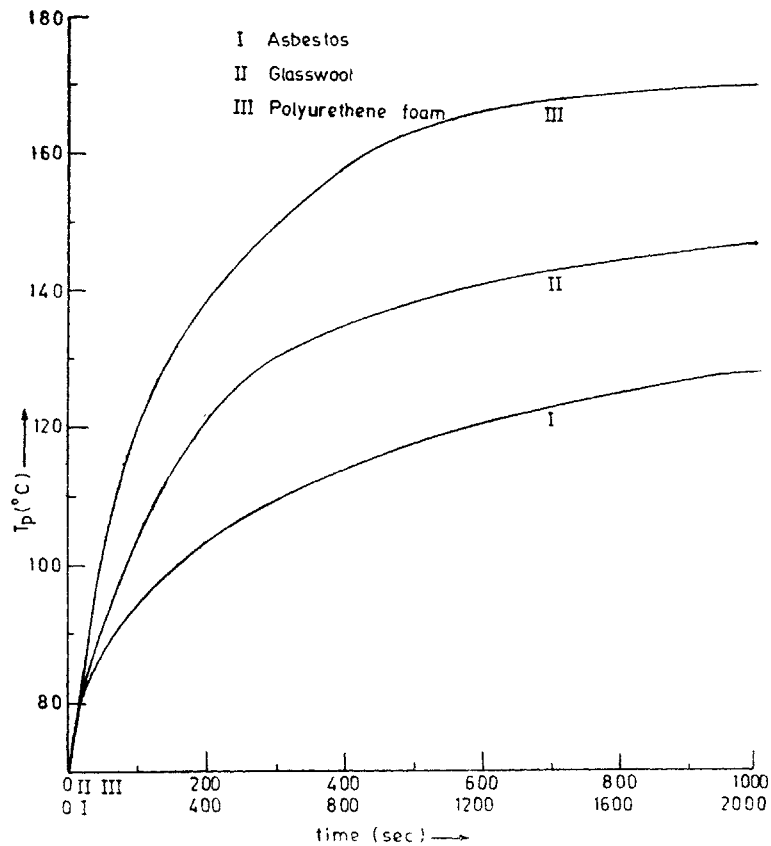

Fig. 2. Rise of plate temperature (the three cases refer to Table I); different time scales have been used for the three cases.

The numerically evaluated variation of plate temperature (i.e., temperature of top of insulation) with time for the three cases is shown in Fig. 2. It is seen that in all cases the plate temperature approaches the stagnation temperature asymptotically; the approach is the fastest for polyurethane foam (least K) and slowest for asbestos (largest K).

It is seen from Fig. 2 that the maximum service temperature for polyurethane foam is reached in 1024 seconds. Beyond this temperature, the insulation gets irreversibly damaged and the properties get drastically changed; thus there is no point in continuing the calculation further. Thus we conclude that when inexpensive insulation with relatively low value of maximum service temperature is used in flat plate solar collectors, the stoppge of fluid flow for even 20 minutes can damage the insulation irreversibly. Thus the possibility of accidental stoppage of fluid flow for long periods rules out the use of insulation with relatively low maximum service temperature. It must be mentioned here that some other inexpensive insulations (e.g. polystyrene

TABLE I

Parameters for three cases

Case	Insulation	K $(w/m\,°c)$	ρ (k_g/m^3)	C $(kjm^2\,°c)$	U_L $(w/m^2\,°c)$	T_{p0} $(°c)$	T_s $(°c)$	Tm† $(°c)$	Δt (Sec)
I	Asbestos	0.192	576.0	0.816	8.33	70	165	128	2000
II	Glass-wool	0.04	200.2	0.67	8.33	70	165	143	729
III	Polyurethane Foam*	0.023	32.04	1.21	7.14	70	185	170	1024

In all these cases we have assumed collector parameters

H_c†† = 1.213 Kj/m² °C, $T_{fi} = T_a = 45\,°C$, $Q = 10^3$ W/m²

$C_f = 4.19$ KJ/Kg °C $\left(\frac{\dot{m}_f}{A}\right) = 0.004$ Kg/m² Sec.

$h_f = 1500$ W/m² °C.

*Maximum service temperature 170 °C.
+Tm is the plate temperature after a typical long period.
++Corresponds to an aluminium sheet of thickness 0.5 mm, with liquid drained off.

foam) have even a much lower maximum service temperature (~ 90°C — 120°C) and hence the possibility of damage of insulation in these insulations is more pronounced.

REFERENCES

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Threlkeld, James L. (1970). *Thermal Environmental Engineering*. Prentice Hall. Inc., New Jersey.