Translucent cover design of solar energy equipment for manufacturing of prefabricated concrete components

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Abstract. Translucent cover is one the main design features of solar energy equipment like solar collector. Its material and layers number influence on overall translucency of the cover and, as a result, on efficiency of the equipment. Formwork, equipped by translucent cover, can be considered as solar energy equipment like solar collector due to similar thermal-physical processes, taking place in it. Such equipment can be used during manufacturing of prefabricated concrete components to speed up the curing process by heating the structures using solar energy. The aim of our research work is determination of optimal layers’ number of translucent cover. The research was made in various climatic conditions. The obtained results testify to certain influence of translucent cover design on efficiency of solar energy equipment. However, this influence depends on climatic conditions.

Keywords: Translucent cover, solar energy equipment, precast concrete structures, heat treatment, renewable energy resources.

1. Introduction

The research on development of various types of solar energy equipment is made in different countries [1-3]. At present, the most common type is a solar collector. Solar collectors are widely used in different fields, such as household equipment systems, hot water production [4-7].

Concrete, as the most common construction material in the world, and prefabricated concrete components have considerable energy requirements for their manufacturing, including energy expenses for heat treatment of concrete to speed up the curing process of its curing. Fossil fuels, such as natural gas, oil, coal are required for this purpose [8]. Possibility to obtain temperature of heater about 60-80 °C in the solar energy equipment allows using solar energy for heat treatment of concrete during manufacturing of prefabricated concrete components [9].

Formwork, which is used during manufacturing of prefabricated concrete components, can be equipped by translucent cover and considered as solar energy equipment. Such equipment is comparable with solar collector for thermo-physical processes, taking place in it.

Such method of heat treatment of the concrete components can be made on condition of placement of the formwork with translucent cover on open air. Concrete is direct heated by solar energy in the daytime and stores heat in the night time.

Our research results show that this technology can be used for manufacturing of prefabricated concrete elements using solar energy within 5 months for Moscow region (ϕ=56° N) and 7 months for South of Russia (ϕ=45° N). The manufacturing period does not exceed 24 hours during this time [10].

However, the efficiency of heat treatment of the concrete components in the solar energy equipment depends on design features of such equipment. Design of translucent cover as one the main design features influences on amount of solar radiation, which can be absorbed by heater during the daytime, and heat loss to environment [11-13]. Taking into account the above, the aim of this research work is the determination of optimal layers’ number of translucent cover.
2. Materials and methods of research

The increase of the layers’ number reduces the amount of heat, consumed by concrete, due to reduction of coefficient of the solar radiation transmission and the growth of the shaded area of the concrete component (Equation 1).

\[
C_{tr} = C_{shad} + C_{dust} \cdot C_{cover} - 1
\]

where \( C_{tr} \) – coefficient of the solar radiation transmission; \( C_{shad} \) – coefficient of shading; \( C_{dust} \) – coefficient of dusting; \( C_{cover} \) – integral coefficient of the translucent cover transmission (it depends on incidence angle of direct solar radiation, number of layer and material of the cover).

At the same time, the increase of the layers’ number reduces heat loss from concrete in the environment through the translucent cover (Equation 2).

\[
U_{loss} = \frac{1}{h^c_{con} + h^e_{rad} + \sum_{i=1}^{n} h^{\varepsilon-t}_{con} + \sum_{i=1}^{n} h^{\varepsilon-t}_{rad}} + \frac{1}{h^{e-t}_{con} + h^{e-t}_{rad}} + \frac{1}{h^c_{con} + h^e_{rad}}^{-1}
\]

where \( U_{loss} \) – coefficient of heat loss through the translucent cover, W/(°C·m²); \( h^c_{con} \) – convective coefficient of heat transfer between the translucent cover and the environment, W/(°C·m²); \( h^{\varepsilon-t}_{con} \) – radiation coefficient of heat transfer between the translucent cover and the environment, W/(°C·m²); \( h^{\varepsilon-t}_{rad} \) – radiation coefficients of heat transfer between layers of the translucent cover, W/(°C·m²); \( h^{e-t}_{con} \) – convective coefficient of heat transfer between the concrete component and the translucent cover, W/(°C·m²); \( h^{e-t}_{rad} \) – radiation coefficient of heat transfer between the concrete component and the translucent cover, W/(°C·m²).

The calculation and experimental research were carried out to determine temperature and strength of concrete, curing in formwork, equipped by translucent cover, in different climate conditions under various design of the cover.

The experimental research in laboratory conditions was made to verify the above calculation model. The temperature conditions of humid subtropical climate were simulated in climatic camera. Walls, floor and roof of the camera were insulated. The electric reflector lamps were used for imitation of solar radiation intensity. They were placed on a special panel on the roof of the camera. The passage of the airflow above the lamps allowed keeping the necessary air temperature. The air temperature in the camera was controlled by digital potentiometer with help of thermocouple. The air humidity was controlled by digital hygrometer.

The intensity of solar radiation changed according to parabolic law with the maximum value of 1300 W/m² in the camera. The air temperature changed according to sine law in the range of 24-50 °C, the air humidity – 6-39% in the camera.

The research of the concrete strength was made for standard methodic with the employment of series laboratory equipment. Concrete B25 was used in the research. The reference standard to compare the obtained concrete strength was concrete, curing within 28 days in normal conditions.

We made the research of materials of translucent cover. The main materials were the following: glass, polymer foil, polycarbonate, acrylic glass. Polymer foils had a number of advantages as compared with other materials, the main are: the price and usability.

Polyethylene-terephthalate foil with integral coefficient of the transmission of 0.88-0.85 and polyethylene foil with integral coefficient of the transmission of 0.92-0.94 were chosen as the most suitable types after the comparison of the polyethylene foils characteristics.

Single layer and double layer design of translucent cover was chosen in the research because the increase layers’ number more than two layers cause considerable reduction of amount of solar radiation, which can be consumed by heater [10].
3. Results and discussion

The calculation of concrete temperature and strength was carried out for various climatic conditions of Russian Federation in summertime (July): humid subtropical climate (Krasnodar region) and humid continental climate (Moscow region). The results are shown in table 1 and table 2.

**Table 1.** Concrete curing in formwork, equipped by single and double layer translucent cover, in humid subtropical climate conditions: Krasnodar region, Russia.

| Time of day | $Q_{abs}$ [kJ] | $U_{loss}$ [W/(°C·m²)] | $Q_{loss}$ [kJ] | $t_{concrete}$ [°C] | Time of day | $Q_{abs}$ [kJ] | $U_{loss}$ [W/(°C·m²)] | $Q_{loss}$ [kJ] | $t_{concrete}$ [°C] |
|-------------|----------------|-------------------------|-----------------|---------------------|-------------|----------------|-------------------------|-----------------|---------------------|
| 10:00       | 93.7           | 1.15                    | 8.7             | 21                  | 10:00       | 68.7           | 0.39                    | 7.5             | 21                  |
| 11:00       | 109            | 1.18                    | 9.9             | 23.3                | 11:00       | 93.3           | 0.4                     | 7.8             | 23                  |
| 12:00       | 118            | 1.2                     | 12.3            | 25.9                | 12:00       | 112            | 0.4                     | 9.2             | 25.4                |
| 13:00       | 121            | 1.22                    | 16              | 28.8                | 13:00       | 127            | 0.45                    | 11.7            | 28.2                |
| 14:00       | 126            | 11.04                   | 37.8            | 31.7                | 14:00       | 100            | 2.96                    | 68.4            | 31.2                |
| 15:00       | 123            | 9.27                    | 107.7           | 34.5                | 15:00       | 79.5           | 3.26                    | 63              | 33.2                |
| 16:00       | 107            | 8.97                    | 113.3           | 36.5                | 16:00       | 54.2           | 3.42                    | 56.3            | 35.1                |
| 17:00       | 82             | 8.85                    | 116.7           | 38.8                | 17:00       | 20.8           | 3.57                    | 46.7            | 37.4                |
| 18:00       | 49.5           | 8.82                    | 116.6           | 40.7                | 18:00       | -              | 3.69                    | 44.1            | 39.5                |
| 19:00       | 20.7           | 8.81                    | 117.5           | 42.4                | 19:00       | -              | 3.79                    | 53.6            | 41.4                |
| 20:00       | 3.4            | 8.82                    | 123.9           | 43.6                | 20:00       | -              | 3.91                    | 66.3            | 43.6                |
| 21:00       | -              | 8.77                    | 133.2           | 44.4                | 21:00       | -              | 3.96                    | 71              | 45.1                |
| 22:00       | -              | 8.83                    | 142.7           | 45.2                | 22:00       | -              | 4.01                    | 77              | 46.2                |
| 23:00       | -              | 8.83                    | 145.7           | 44.5                | 23:00       | -              | 4.03                    | 81              | 46.4                |
| 24:00       | -              | 8.83                    | 146.9           | 43.7                | 24:00       | -              | 4.05                    | 84.2            | 46.6                |
| 1:00        | -              | 8.82                    | 146.2           | 42.9                | 1:00        | -              | 4.07                    | 86.2            | 46.7                |
| 2:00        | -              | 8.81                    | 143.5           | 42.2                | 2:00        | -              | 4.07                    | 87.1            | 46.8                |
| 3:00        | -              | 8.81                    | 138.9           | 41.4                | 3:00        | -              | 4.07                    | 86.8            | 46.9                |
| 4:00        | -              | 8.8                     | 132.5           | 40.7                | 4:00        | -              | 4.06                    | 85.4            | 47                  |
| 5:00        | -              | 8.8                     | 124.7           | 40.1                | 5:00        | -              | 4.05                    | 83.1            | 47.2                |
| 6:00        | 3.4            | 8.8                     | 116.6           | 39.6                | 6:00        | -              | 4.03                    | 80.1            | 47.3                |
| 7:00        | 20.2           | 8.8                     | 114.9           | 39.2                | 7:00        | -              | 4.01                    | 76.6            | 47.5                |
| 8:00        | 49.5           | 8.81                    | 120.7           | 39.1                | 8:00        | 1.1            | 3.98                    | 73.5            | 47.8                |
| 9:00        | 82.4           | 8.81                    | 130.4           | 39.3                | 9:00        | 37.4          | 3.96                    | 89.8            | 48.1                |

Maturity of concrete [°C-hours] 909 Maturity of concrete [°C-hours] 968
Relative age of concrete [days] 4 Relative age of concrete [days] 4.2
Strength of concrete 61 Strength of concrete 64
[ % from reference standard] [ % from reference standard]

Note: size of concrete sample 30x30x30(h) cm; temperature ($t_{concrete}$) is in the middle of concrete sample; reference standard is concrete C25 (compressive strength in the age of 28 days is 29.8 MPa); material of transparent cover is polyethylene-terephthalate foil.

$Q_{abs}$ and $Q_{loss}$ in the tables are the amount of heat, absorbed by concrete during the day time and lost through the translucent cover.

The analysis of the research results shows that concrete is heated more intensively under single layer translucent cover during the day time. Its maximum temperature is 1.5-2 °C more than under double layer translucent cover. However, concrete temperature under single layer cover starts decreasing after sundown, while it continues increasing under double layer cover.

The coefficient of heat loss ($U_{loss}$) of double layer cover decreases almost in two times as compared with single layer cover. The temperature of concrete decreases slower under double layer cover at
night time. The maximum excess of the concrete temperature is from 3-5 °C (table 1) until 8-10 °C (table 2) as compared with single layer cover.

Table 2. Concrete curing in formwork, equipped by single and double layer translucent cover, in humid continental climate conditions: Moscow region, Russia.

| Time of day | Single layer translucent cover | Double layer translucent cover |
|-------------|--------------------------------|--------------------------------|
|             | $Q_{abs}$ [kJ] | $U_{loss}$ [W/(°C·m²)] | $Q_{loss}$ [kJ] | $t_{concrete}$ [°C] | $Q_{abs}$ [kJ] | $U_{loss}$ [W/(°C·m²)] | $Q_{loss}$ [kJ] | $t_{concrete}$ [°C] |
| 10:00       | 36.7           | 1.13                        | 7.5            | 21                     | 10:00          | 28.6           | 0.42                        | 5.8            | 21                     |
| 11:00       | 44.1           | 1.15                        | 8.2            | 23.9                    | 11:00          | 40.1           | 0.42                        | 6.0            | 22.8                    |
| 12:00       | 53.6           | 15.2                        | 20.5           | 27.1                    | 12:00          | 43.4           | 2.62                        | 27.6           | 25.3                    |
| 13:00       | 60.2           | 11.2                        | 49.9           | 30.2                    | 13:00          | 51.1           | 3.38                        | 33.2           | 27.3                    |
| 14:00       | 57.9           | 10.5                        | 51.2           | 32.3                    | 14:00          | 42.8           | 3.61                        | 31.5           | 29.4                    |
| 15:00       | 52.7           | 10.1                        | 52.9           | 34.2                    | 15:00          | 32.9           | 3.74                        | 29.1           | 31.4                    |
| 16:00       | 44.8           | 9.93                        | 53.7           | 36.1                    | 16:00          | 21.9           | 3.84                        | 26.6           | 33.2                    |
| 17:00       | 33.7           | 9.83                        | 52.9           | 37.4                    | 17:00          | 7.4            | 3.94                        | 22.7           | 35.3                    |
| 18:00       | 20.4           | 9.77                        | 50.7           | 38.3                    | 18:00          | 4.8            | 4.03                        | 21.7           | 37.7                    |
| 19:00       | 7.2            | 9.74                        | 48.1           | 38.1                    | 19:00          | 3.5            | 4.11                        | 25.3           | 38.2                    |
| 20:00       | 2.6            | 9.72                        | 49.6           | 38.9                    | 20:00          | 2.1            | 4.18                        | 28.7           | 38.9                    |
| 21:00       | 0.7            | 9.7                         | 52.1           | 38.3                    | 21:00          | 0.6            | 4.23                        | 31.6           | 39.6                    |
| 22:00       | -              | 9.68                        | 52.9           | 37.5                    | 22:00          | -              | 4.26                        | 33.7           | 40.6                    |
| 23:00       | -              | 9.68                        | 52.5           | 35.8                    | 23:00          | -              | 4.29                        | 35.2           | 40.3                    |
| 24:00       | -              | 9.68                        | 51.5           | 34.3                    | 24:00          | -              | 4.3                        | 36.2           | 39.9                    |
| 1:00        | -              | 9.68                        | 49.6           | 32.6                    | 1:00           | -              | 4.31                        | 36.6           | 39.4                    |
| 2:00        | -              | 9.69                        | 47             | 31.2                    | 2:00           | -              | 4.3                        | 36.1           | 39                     |
| 3:00        | -              | 9.72                        | 43.8           | 29.7                    | 3:00           | -              | 4.28                        | 35             | 38.5                    |
| 4:00        | -              | 9.77                        | 39.9           | 28.5                    | 4:00           | -              | 4.26                        | 33.7           | 38.2                    |
| 5:00        | 0.7            | 9.85                        | 35.5           | 27.3                    | 5:00           | 0.6            | 4.24                        | 32             | 37.9                    |
| 6:00        | 2.4            | 9.99                        | 31             | 26.4                    | 6:00           | 2.1            | 4.21                        | 29.9           | 37.5                    |
| 7:00        | 6.9            | 10.21                       | 28.2           | 25.8                    | 7:00           | 3.6            | 4.17                        | 27.7           | 37.3                    |
| 8:00        | 19.7           | 10.57                       | 30.8           | 25.8                    | 8:00           | 5              | 4.13                        | 25.4           | 37.1                    |
| 9:00        | 32.5           | 11.06                       | 34.7           | 26.3                    | 9:00           | 11.9           | 4.08                        | 27.8           | 37.1                    |

Note: size of concrete sample 20x20x20(h) cm; temperature ($t_{concrete}$) is in the middle of concrete sample; reference standard is concrete C25 (compressive strength in the age of 28 days is 29.8 MPa); material of transparent cover is polyethylene foil.

Maturity of concrete (3), which is total sum of numerical values of concrete temperatures over the period of concrete curing, is almost the same in both climatic conditions, but under double layer cover it is more than under single layer cover.

$$
M_{concrete} = \sum_{i=1}^{n} t_{concrete} \Delta t_i
$$

where $\Delta t_i$ – time between the measurements of the concrete temperature.

Nevertheless, it is more for the concrete samples, curing under double layer cover in humid continental climate conditions (table 2). The same situation is for relative age of concrete, which depends on the average concrete temperature and intervals between its measurements.
The results of calculation and experimental research of the concrete temperature in conditions of subtropical climate are shown in fig. 1. The similarity of graphs, obtained by the calculation and the experimental research, testifies to adequacy of chosen calculation model and the assessment of the process, taking place during heat treatment of the concrete components using solar energy.

![Temperature of concrete sample, curing in formwork, equipped by single and double layer translucent cover in subtropical climate conditions: φ = 44° N, in July.](image)

1 – experimental concrete temperature under single layer cover (climatic camera); 2 – calculated concrete temperature under single layer cover; 3 – experimental concrete temperature under double layer cover (climatic camera); 4 – calculated concrete temperature under double layer cover; 5 – actual air temperature during the experiment (climatic camera); 6 – calculated air temperature.

Strength of concrete, curing in formwork, equipped by double layer translucent cover, is better in both climate conditions. However, the difference in the values of the concrete strength decreases with increasing the average air temperature and intensity of solar radiation.

4. Conclusion
The obtained research results testify to the increase of translucent cover layers in humid subtropical climate (Krasnodar region) does not improve the values of strength, maturity and relative age of concrete. It testifies to inefficiency of double layer cover in such climate conditions.

In spite of better values of strength, maturity and relative age of concrete, curing in formwork, equipped by double layer translucent cover in humid continental climate (Moscow region), we have to admit its inefficiency. This is because we have to take into account the economic component, connected with the equipment costs. The increase of the concrete strength by 1-4% does not justify the increase of the equipment price, connected with addition of one more layer of translucent cover at the time of manufacturing and operation of the equipment.
References

[1] Farjana S H, Huda N, Parvez Mahmud M A and Saidur R 2018 Solar process heat in industrial systems – A global review Renewable and Sustainable Energy Reviews 82(3) pp 2270-2286

[2] Abdullah M A, Muttaqi K M and Agalgaonkar A P 2015 Sustainable energy system design with distributed renewable resources considering economic, environmental and uncertainty aspects Renewable Energy 78 pp 165-172

[3] Foster E, Contestabile M, Blazquez J, Manzano B, Workman M and Shah N 2017 The unstudied barriers to widespread renewable energy deployment: Fossil fuel price responses Energy Policy 103 pp 258-264

[4] Fudholi A and Sopian K 2019 A review of solar air flat plate collector for drying application Renewable and Sustainable Energy Reviews 102 pp 333-345

[5] Hu J and Zhang G 2019 Performance improvement of solar air collector based on airflow reorganization: A review Applied Thermal Engineering 155 pp 592-611

[6] Shafieietan A, Khadiani M and Nosrati A 2018 A review of latest developments, progress, and applications of heat pipe solar collectors Renewable and Sustainable Energy Reviews 95 pp 273-304

[7] Kalogirou S A, Karellas S, Brainakis K, Stanciuc C and Badescu V 2016 Exergy analysis of solar thermal collectors and processes Progress in Energy and Combustion Science 26 pp 106-137

[8] Li Z, Shen G Q and Xue X 2014 Critical review of the research on the management of prefabricated construction Habitat International 43 pp 240-249

[9] Benammar B, Mezghiche B and Guettala S 2013 Influence of atmospheric steam curing by solar energy on the compressive and flexural strength of concretes Construction and Building Materials 49 pp 511-518

[10] Koroteev D D, Kharun M and Stashevskaya N A 2017 Manufacturing of concrete elements on mobile polygons with the using of solar energy International Journal of Advanced and Applied Sciences 4(10) pp 10-14

[11] Egolf P W, Amacker N, Gottschalk G, Courret G, Noume A and Hutter K 2018 A translucent honeycomb solar collector and thermal storage module for building facades International Journal of Heat and Mass Transfer 127(A) pp 781-795

[12] Dowson M, Pegg I, Harrison D and Dehouche Z 2012 Predicted and in situ performance of a solar air collector incorporating a translucent granular aerogel cover Energy and Buildings 49 pp 173-187

[13] Paneri A, Wong I L and Burek S 2019 Transparent insulation materials: An overview on past, present and future developments Solar Energy 184 pp 59-83

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