ISSN 0003-701X, Applied Solar Energy, 2016, Vol. 52, No. 4, pp. 251–255. © Allerton Press, Inc., 2016.
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Improvement of the Flow Distribution Uniformity Over Riser Pipes of the Beam-Absorbing Heat Exchanger of a Solar Water Heating Plate-Type Collector with Forced Circulation

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Received December 12, 2015

Abstract—Quantitative ratios and calculated dependences between design parameters allowing improvement of the flow distribution uniformity over riser pipes of the beam-absorbing heat exchanger of the solar water heating plate-type collector with forced circulation were determined.

DOI: 10.3103/S0003701X16040137

STATEMENT OF PROBLEM

Calculations of the thermal parameters of the solar water heating collector (SWC) are usually based on assumption of the uniform distribution of the flow rate over riser pipes both in a single collector and SWC bank [1—3]. With nonuniform flow distribution in some SWC parts, riser pipes with low flow rates may have temperatures considerably exceeding the temperature of parts with higher fluid flow. That is why the hydraulic calculations of both hydraulic channels (delivery and collecting) of a separate SWC and connecting pipes in the system containing several SWC are of great importance for provision of high thermal efficiency of both collector and the SWC bank.

Analytical and experimental studies of this problem were carried out in [4—6]; the influence of a nonuniform flow distribution in the SWC system on the heat generation at different (small, medium and high) specific flow rates and collector interconnection diagrams were assessed. It is of particular importance for large systems with forced circulation because the systems with natural circulation are, to some extent, self-regulating and such a problem is not critical for them [1].

A review of some studies concerning the uniformity of flow rate distribution in SWCs is given in [4]; the analytical calculation method for flow distribution and its experimental verification are also given.

Results of the analytical and experimental studies concerning the influence of the flow distribution over riser pipes of the beam-absorbing SWC plate-type heat exchanger on heat generation are given in [5]. Tests were carried out in natural conditions on one of the solar unit sections designed for the hot water supply to a hotel and containing ten parallel branches in four series connected in each branch of the SWC. The variation range of the liquid specific flow rate, both with the diagonal layout of the inlet and outlet branches (Z-diagram) and with the location of those branches from one side of the section (Π- scheme), was g = 5—30 kg/(m^2 h). The outlet temperature on each branch of the SWC section, showing the heat transfer efficiency from the SWC, was measured during experiments. Temperature differences between branches of the SWC section show the deficiency of the uniformity of the flow distribution because cold tap water of equal temperature was supplied at the inlet of each branch.

Nearly uniform flow distribution by separate branches of the SWC section was observed for the Z-schemes at low g (5.15 kg/(m^2 h)) and average g (10.6 kg/(m^2 h)) specific flows and for the Π-scheme at low g (4.96 kg/(m^2 h)) specific flows only; negligible temperature differences (±2—3°C) was found at the outlet of the parallel branches. For the Z-scheme at high g (29.4 kg/(m^2 h)), and for Π-scheme at low g (20.0 kg/(m^2 h)) and high g (30.4 kg/(m^2 h)) specific flows, the considerable flow distribution nonuniformity was observed via extreme 9 and 8 SWC sections where the temperature difference was up to ±4—5°C as compared with the average value, and if compared with the most extreme ten branch, they differed by 8—10°C. It is mentioned in [5] that for this unit the influence of the flow distribution nonuniformity on the heat generation is negligible and may be ignored. It is clear that high hydraulic resistance in riser pipes supported by a series connection of four SWCs in each

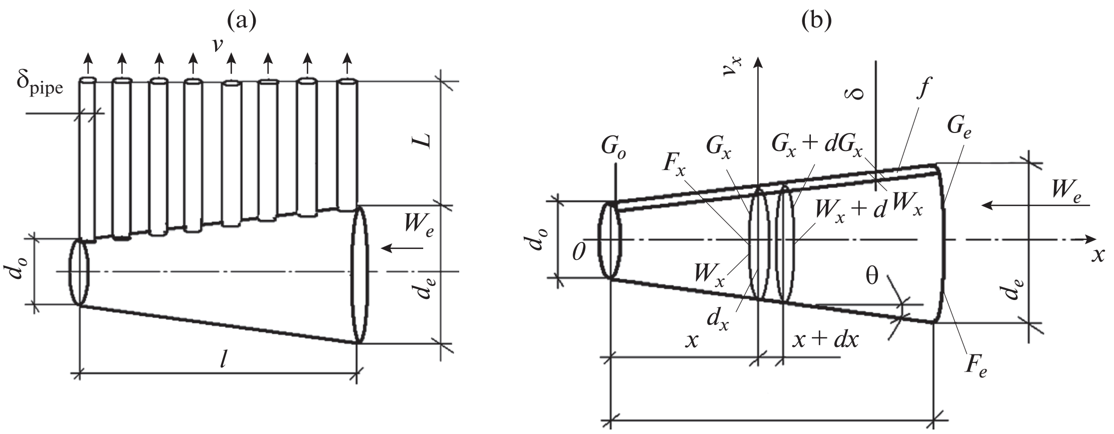

Fig. 1. Scheme of the cone hydraulic channel with the in-line beam of riser pipes (a) and with conditional slot of constant width (b).

branch leads to the flattening of the flux between branches at quite large diameters of the delivery and collecting pipelines (no information in [5]). There were no practical recommendations for improvement of the flow distribution uniformity in the SWC system in [5].

Results of temperature measurement at low, average and high specific flows for the package containing 12 SWCs connected in parallel are given in [6]. According to experimental data, the temperature difference between the central part and extreme parts of the package at high flow is 22°C, and with the decrease of specific consumptions via SWC, the same as in experimental data [5], the temperature difference decreases. However, this difference is quite important and that is why it exerts strong influence on the general heat efficiency of the SWC package. So, based on the test results in [6] it is recommended to apply hydraulic channels of large diameter in order to have the pressure drop mainly in the riser pipes. As for SWC packages with forced circulation, with more than 24 pipes, it is recommended to use series-to-parallel connections or parallel-series connections instead of the parallel one.

Thus, results from tests carried out in [5] and [6] show that the flow distribution nonuniformity, both in the single collector and in the SWC system, decreases with the decrease in the specific liquid flow, with the increase of the diameter of delivery and collector hydraulic channels and with the decrease in the number and diameter of riser pipes. It is seen that nonuniformity of flow distribution over riser pipes of the beam-absorbing heat exchanger of the SWC plate-type exerts considerable influence both on the pure operating parameters (specific liquid flow via SWC) and on structural parameters (ratio of the delivery and collector channels diameter with the riser pipe diameter).

During design and development of some collectors and SWC packages with the given nonuniformity of the flow distribution, it is required to know the quantitative interconnection between the above structural parameters, which is not available in these works. It should be mentioned that one more effective structural method for equalizing the flow supply over riser pipes, which is not discussed in [5, 6], is possible in principle. This is profiling of the hydraulic channels by length [7], i.e., change in their cross-section according to a certain law providing similar dynamic pressure in all riser pipes. The aim of this work is to improve the uniformity of the flow distribution in the solar collector system under forced circulation based on the qualitative interconnection between structural parameters influencing on the flow distribution in the SWC with different levelling methods.

Mathematical model of the process

Let us consider the process of the water supply by the cone hydraulic channel of length l, with the entry diameter d_e, and the outlet diameter d_o, along which the package of the riser pipes with similar diameter d_{pipe} is located (Fig. 1a).

Let us specify the reference point at the capped end of the channel (Fig. 1b) and direct the X axis toward the water flow. Let us replace riser pipes to the conditional slot of constant width δ; at its outlet, the pressure losses in local resistances are equal to the pressure losses due to friction along the length of the riser pipe bank; and let us draw in the channel two cross-sections at a distance x and $x + dx$ from the capped end (Fig. 1b).

It is clear that a decrease in the water flow inside the channel from section $x + dx$ to the section x equals the water flowing out via conditional slot between these sections.

By indicating the water flow in the section x as G_x and in the section $x + dx$ as $G_x + dG_x$ and the normal velocity of water outflow from the slot in the section x as v_x, we may write down the following:

$$dG_x = v_x \delta \frac{dx}{\cos\theta}. \quad (1)$$

Proceeding to the derivative we have the following:

$$G_x' = \frac{v_x \delta}{\cos\theta}. \quad (2)$$

Normal water velocity in the slot:

$$v_x = \mu\sqrt{\frac{2}{\rho}(p_x - p_0)} = \mu\sqrt{\frac{2}{\rho}\Delta p_x}. \quad (3)$$

Let us make Bernoulli's equation applicable to sections x and x + dx:

$$\Delta p_x + d\Delta p_x + \frac{\rho W_x^2}{2} + d\left(\frac{\rho W_x^2}{2}\right) = \Delta p_x + \frac{\rho W_x^2}{2} + \frac{\lambda}{d_x}\frac{\rho W_x^2}{2}dx.$$

Canceling identical terms in the left- and right-hand sides of the equation and proceeding to derivatives we have the following:

$$\Delta p_x' + \rho W_x' W_x - \frac{\lambda}{d_x}\frac{\rho W_x^2}{2} = 0. \quad (4)$$

Let us express $\Delta p_x'$; W_x and W_x' in terms of volumetric consumption G_x. The following results from equations (3) and (2):

$$\Delta p_x' = \left(\frac{\rho v_x^2}{2\mu^2}\right)' = \frac{\rho}{2\mu^2}\left(\frac{G_x'^2\cos^2\theta}{\delta^2}\right)' = \frac{\rho\cos^2\theta}{\mu^2\delta^2}G_x'G_x''.$$

The quantity $W_x = \frac{G_x}{F_x}$; and taking the derivative we have $W_x' = \frac{G_x'F_x - G_xF_x'}{F_x^2}$, where F_x is the square of the channel cross-section in section x.

By substituting the value $\Delta p_x'$, W_x into equation (4) W_x' and dividing by $\rho\cos^2\theta/\mu^2\delta^2$, we obtain:

$$G_x''G_x' + \frac{\mu^2\delta^2}{F_x^2\cos^2\theta}G_x'G_x - \frac{\mu^2\delta^2}{F_x^2\cos^2\theta}\left(\frac{F_x'}{F_x} + \frac{\lambda}{2d_x}\right)G_x^2 = 0. \quad (5)$$

Let us introduce notations:

$$\bar{G}_{\bar{x}} = G_x/G_H;\ \bar{F}_{\bar{x}} = F_x/F_e;\ \bar{d}_{\bar{x}} = d_x/d_e;\ \bar{x} = x/l.$$

Then

$$G_x = G_H\bar{G}_{\bar{x}};\ F_x = F_e\bar{F}_x;\ d_x = d_e\bar{d}_{\bar{x}};\ x = l\bar{x};$$

$$G_x' = \frac{dG_x}{dx} = \frac{G_e}{l}\frac{d\bar{G}_{\bar{x}}}{d\bar{x}} = \frac{G_e}{l}\bar{G}_{\bar{x}}';$$

$$G_x'' = \frac{dG_x'}{dx} = \frac{G_e}{l^2}\cdot\frac{d\bar{G}_{\bar{x}}'}{d\bar{x}} = \frac{G_e}{l^2}\bar{G}_{\bar{x}}'',$$

$$F_x' = \frac{dF_x}{dx} = \frac{F_e}{l}\bar{F}_{\bar{x}}'.$$

Substituting the found values G_x, G_x', G_x'', F_x and F_x' in (5) and multiplying by l^3/L_h^2, we have the following differential equation:

$$\bar{G}_{\bar{x}}''\bar{G}_{\bar{x}}' + \frac{\mu^2\bar{f}^2}{\bar{F}_{\bar{x}}^2}\bar{G}_{\bar{x}}'\bar{G}_{\bar{x}}' - \frac{\mu^2\bar{f}^2}{\bar{F}_{\bar{x}}^2}\left[\frac{\bar{F}_{\bar{x}}'}{\bar{F}_{\bar{x}}} + \frac{\lambda\bar{l}}{2\bar{d}_x}\right]\bar{G}_{\bar{x}}^2 = 0, \quad (6)$$

where

$$\bar{f} = \frac{f}{F_e} = \frac{\delta l}{F_e\cos\theta};\ \bar{l} = \frac{l}{d};\ \bar{d}_0 = \frac{d_0}{d_e},$$

$$\bar{d}_x = \frac{d_x}{d_e} = \frac{d_0 + 2x\ \tan\theta}{d_e} \quad (7)$$

$$= \frac{d_0 + 2x\frac{d_e - d_0}{2l}}{d_e} = \bar{d}_0 + (1 - \bar{d}_0)\bar{x};$$

$$\bar{F}_{\bar{x}} = \bar{d}_{\bar{x}}^2 = \left[\bar{d}_0 + (1 - \bar{d}_0)\bar{x}\right]^2, \quad (8)$$

$$\bar{F}_{\bar{x}}' = 2\left[\bar{d}_0 + (1 - \bar{d}_0)\bar{x}\right](1 - \bar{d}_0). \quad (9)$$

Let us introduce boundary conditions

$$\text{at}\quad \left.\begin{matrix}\bar{x} = 0 & \bar{G}_0 = 0\\ \bar{x} = 1 & \bar{G}_e = 1\end{matrix}\right\}. \quad (10)$$

Hereinafter, the value $\mu\bar{f}$ will be called the parameter of the conditional slot and $\lambda\bar{l}$, the channel parameter.

Equation (6) and conditions (10) give mathematical formulation for the considered boundary value problem.

Let us assume that it is solved, i.e., the relative volumetric water flow $\bar{G}_{\bar{x}}$ is found inside the hydraulic channel.

$$\bar{G}_{\bar{x}} = \varphi(\mu\bar{f}, \lambda\bar{l}, \bar{d}_o, \bar{x}). \quad (11)$$

In this case the relative velocity of the water outflow from the conditional slot is as follows:

$$\bar{v}_{\bar{x}} = \frac{v_x}{v_{cp}} = \frac{G_x'\cos\theta}{\delta v_{cp}} = \frac{G_e\cos\theta}{\delta l v_{cp}}\bar{G}_{\bar{x}}' = \bar{G}_{\bar{x}}'. \quad (12)$$

Let us note that at uniform distribution $\bar{v}_{\bar{x}} = 1$, and relative volumetric water flow inside the channel is $\bar{G}_{\bar{x}} = \bar{x}$, i.e., linearly decreasing along its length from the beginning ($\bar{G}_{\bar{x}=1} = 1$) to the end of the channel ($\bar{G}_{\bar{x}=0} = 0$). Because of this, the deviation of the non-uniform water supply from the uniform is as follows:

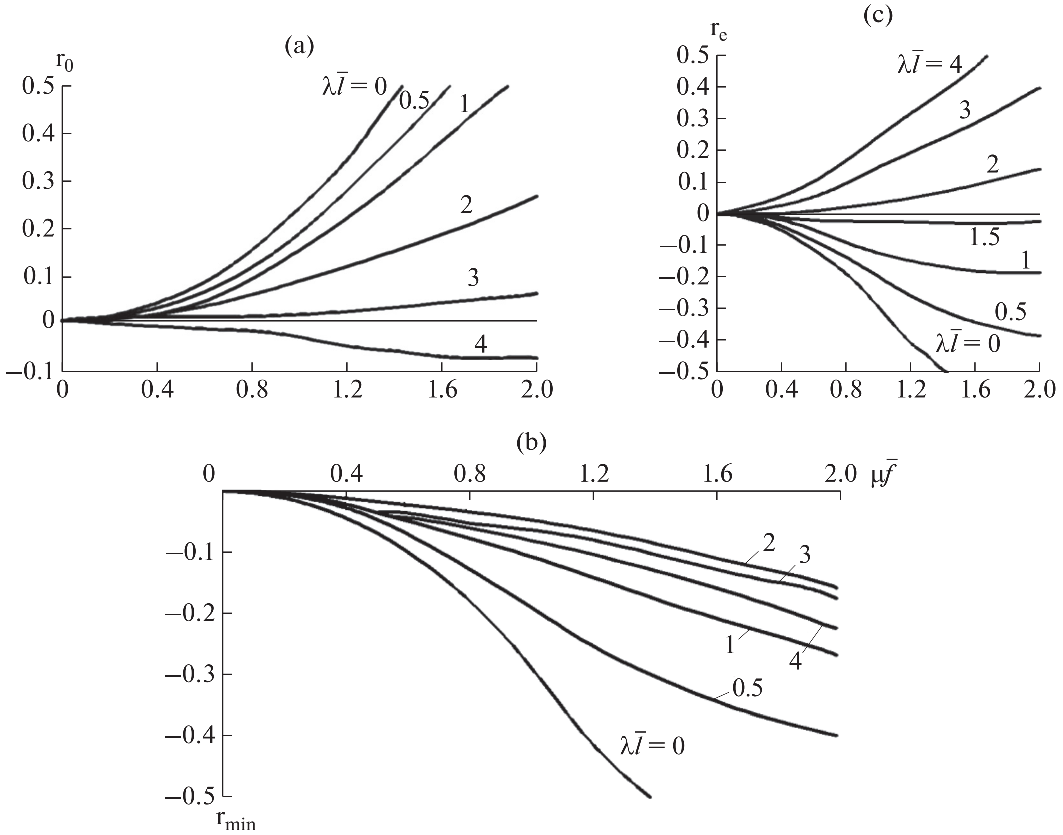

Fig. 2. Variance graph of the relative deviation at the end (a), in the section with the minimum flow velocity (b) and at the beginning (c) of the cone channel with the longitudinal slot at $\bar{d}_o = 0.8$.

$$r_{\bar{x}} = \bar{v}_{\bar{x}} - 1. \quad (13)$$

Let us find the dependence of $r_{\bar{x}}$ on values $\mu\bar{f}$, $\lambda\bar{l}$, $\bar{d}_o$ and $\bar{x}$.

The analytical solution of the nonlinear differential equation (6) with the boundary conditions (10) is quite difficult. Therefore, its integration was carried out by a numerical method. Tables with the change of $r_{\bar{x}}$ depending on $\bar{x}$ at different values $\mu\bar{f}, \lambda\bar{l}$ and $\bar{d}_o$ were obtained after calculation.

The relative deviation of the nonuniform water supply as against the uniform along the channel $r_{\bar{x}}$ changes in general in the following way: r_0 is important at the outlet of the channel $r_{\bar{x}}$, then with the increase of $\bar{x}$ the value $r_{\bar{x}}$ decreases and approaches its minimum $r_{\min}$, after that with the further increase of $\bar{x}$ the value $r_{\bar{x}}$ increases and approaches the value r_h at the channel head.

Diagrams of the relative deviation at the end, in the cross-section with the minimum outflow velocity and at the channel head, were made based on calculation results: r_0, $r_{\min}$, and r_h. Thus, the minimum deviation was shown by the channels $\bar{d}_o = 0.8$. That is why the deviation diagrams r_0, $r_{\min}$, r_h are given for the channels with such tapering (Fig. 2).

As seen from diagrams (Fig. 2) the absolute valuesr_0, $r_{\min}$, r_h increase with the increase in the slot parameter $\mu\bar{f}$. The deviation r_h at $\lambda\bar{l} = 0$ is negative; and with the increase in the parameter $\lambda\bar{l}$, it first decreases reaching a minimum at $\lambda\bar{l} = 1{,}5$ and then increases. Deviation $r_{\min}$ is always negative and with the increase in the channel parameter $\lambda\bar{l}$, it decreases. Deviation r_0 at $\lambda\bar{l} = 0$is positive and with the increase of the parameter $\lambda\bar{l}$, it first decreases reaching a minimum at $\lambda\bar{l} = 3$, and then increases.

Thus, the slot parameter $\mu\bar{f}$ is the most important value; with the decrease in its numeric value the relative deviation $r_{\bar{x}}$of the nonuniform water distribution as against the uniform one, along the length of the cone channel, decreases, i.e., as $\mu\bar{f} \to 0,\ r_{\bar{x}} \to 0$.

That is why during the design and development of both separate collectors and SWC systems, the following condition must be satisfied:

$$\mu\bar{f} \to \min. \quad (14)$$

Fulfilment of condition (14) is possible at $\mu \to \min$ and at $\bar{f} \to \min$. Let us consider both cases in more detail.

It follows from (3) that

$$\mu = \frac{v_x}{\sqrt{\frac{2\Delta p_x}{\rho}}}. \qquad (15)$$

The following may be written down from the condition of change of the riser pipes by the conditional slot; at the slot outlet, the pressure losses in local resistances are equivalent to the friction pressure losses along the length L of the riser pipes,

$$\Delta p_x = \frac{\lambda_{\text{pipe}}}{\delta_{\text{pipe}}} L \frac{\rho v_x^2}{2}.. \qquad (16)$$

Substituting (16) in (15), we obtain the following

$$\mu = \sqrt{\frac{\delta_{\text{pipe}}}{\lambda_{\text{pipe}} L}}. \qquad (17)$$

From (17), as $\mu \to \min$ as the diameter of the riser pipes decrease, δ_{pipe}, and with the increase of the length L, i.e., with the increase in their hydraulic resistance, which corresponds to recommendations given in [6].

It is seen from condition

$$\bar{f} = \frac{f}{F_e} \to \min, \qquad (18)$$

that the sectional area of the hydraulic channel F_e shall considerably exceed the total area of riser pipes f, which also corresponds to recommendations given in [6].

The profiling of the hydraulic channel by length in the form of its cone tapering from the initial d_e to the final d_o diameter also contributes to the leveling of the flow distribution along its length. The minimum uniformity of the flow distribution is obtained by the ratio of the final d_o and initial d_e diameters of $\bar{d}_o = 0.8$. This diameter ratio is recommended during the development and design of both separate collectors and SWC banks. Thus, in order to simplify the SWC structure, the uniform flow distribution may be obtained by applying composite hydraulic channels of uniform cross-section, but of different diameters by length.

CONCLUSIONS

Improvement of the flow distribution uniformity over riser pipes of the beam-absorbing heat exchanger of the SWC plate-type collector under forced circulation may be obtained by the following procedures:

1) Increase in the cross-section area (diameters) of the delivery and collector hydraulic channels;

2) Increase in the hydraulic resistance of the riser pipes with a decrease in their diameter and increase in length;

3) Profiling of the hydraulic channels by length by their tapering in the flow direction.

Quantitative ratios and calculated dependences between structural parameters influencing the flow distribution for three feasible leveling procedures were determined. They may be used for the development of the numerical procedure of separate collectors and SWC banks with the determined nonuniformity of the flow distribution under forced circulation of the coolant.

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Translated by E. Grishina

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