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Studying the Change of the Coefficient of Hydraulic Resistance in a Solar Air Collector With a Turbulator

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ABSTRACT: Solar air collectors are widely used because they are convenient, cheap and easy to operate for solar energy. Many studies are conducted on theoretical and experimental research of the hydraulic resistance coefficient based on the acceleration of thermal-hydrodynamic processes in solar air collectors with turbulators. In this research work, the procedure for calculating the coefficient of hydraulic resistance when using turbulizers in solar air collectors, the results obtained on hydraulic resistance, the results of comparing the experimental results with the model results, as well as the empirical relationships for determining the hydraulic resistance in solar air collectors are presented. These results can be used in the development of solar air collectors with high energy efficiency.

I. INTRODUCTION

Solar air collector (SAC) is one of the most important and effective means of collecting solar energy. The operation of this device is based on convective, conductive and radiative heat transfer. Improving heat transfer using forced convection is the most effective way to increase SAC efficiency. The most common way to improve SAC efficiency is to use turbulizers. Due to the increase in turbulent speed, the heat transfer coefficient increases, the boundary layer breaks and the heat transfer rate increases. However, increased turbulence causes additional pressure loss. In order to establish a rational relationship between frictional resistance and heat transfer in SAC with a turbulator, in-depth experimental studies are required.

Pressure loss and heat transfer when using turbulizers of different geometric shapes were experimentally and theoretically studied in a large number of research works [1, 2, 3]. Aoues and others [4] conducted an experimental study of the SAC with ribs of different geometric shapes to improve the characteristics of the SAC. The cooling air stream passes through a 25 mm gap between the absorber plate and the galvanized steel plate on top of the insulation. In this space there are thin metal barriers welded perpendicular to the air flow. The angle of inclination of these barriers varies from 60 to 120° and they are installed with an interval of 10 and 5 cm. The number of obstacles was equal to 152 and 256. Chabane and others [5, 6, 7] conducted an experimental study of heat transfer in SAC of a new design. In this case, a rib was fixed under the absorber plate and the obtained results were compared with the results of a simple SAC. The maximum UWC was 40.02, 51.50% and 34.92, 43.9% for the finned and non-finned SAC when the air mass consumption was 0.012 and 0.016 kg/s, respectively.

Singh et al [8] checked with a CFD model and conducted an experimental study of the bent SAC (bend angle varied in the range of 25...50°). According to the results, the heat transfer coefficient, Nusselt number and temperature are significantly increased compared to the conventional SAC. It was determined that the thermal-hydrodynamic efficiency increased by 43% and 31%, and the Nusselt number by 7 and 6%, respectively, in the bubble and concave construction. Abuska [9] proposed a new design SAC with a conical surface of the absorber plate. In this study, three mass consumptions were used. According to the results, the thermal UWC value of the modified cone-surfaced SAC is 6.0, 9.8, and 10.6% higher than that of the conventional SAC when the mass consumption is 0.04, 0.08, and 0.1 kg/s. was. Sawhney and others [10] conducted an experimental study of the heat transfer and friction coefficient in the SAC channel with triangular turbulizers on the absorber plate. According to the results, when Re=4000, the Nusselt number increased by 223% compared to the normal plate. Baissi et al. [11] modified the absorber plate using two longitudinally bent delta-shaped pile generators and conducted experimental studies to determine the increase in the thermal characteristics of the SAC. A correlation relationship is proposed to determine the Nusselt number and friction coefficients depending on the

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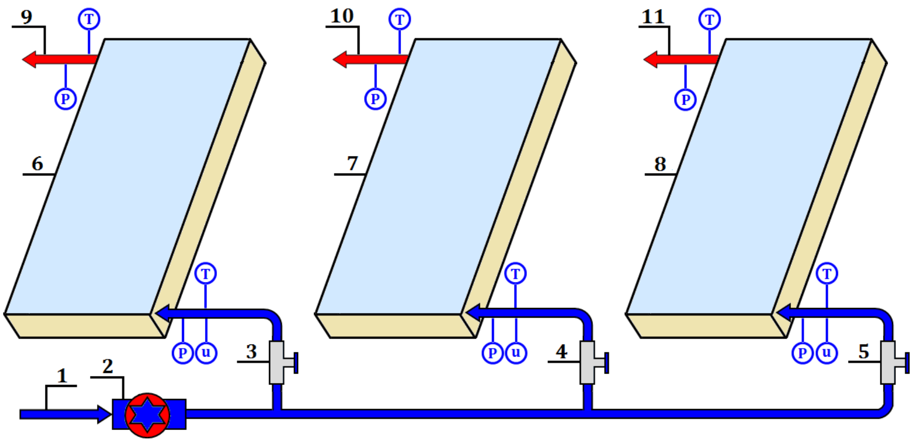
Reynolds number and the turbulence parameter. Gilani and others [12] used bulge-shaped turbulizers on the absorber plate to increase the efficiency of small-capacity convective SACs. According to the results, the thermal UWC was 26.5% higher when the turbulizer pitch was 16 mm than the normal SAC.

II. MATERIALS AND METHODS

As it can be seen from the analysis of the literature, there have been no experimental studies on the determination of the friction coefficient in SACs with hole turbulizers and confusor turbulizers. Taking into account the above, experimental-industrial samples of six theoretically researched models were developed and built on the basis of the educational and scientific laboratory of the Karshi Institute of Engineering and Economics, Department of “Heat Energy”. The general view of the experimental device is shown in Fig. 1 and the scheme is shown in Fig. 2. The developed experimental device allows to study the effect of the properties of the turbulizer absorber on the characteristics of the SAC (air pressure loss, air outlet temperature, thermal-hydrodynamic efficiency of the SAC). SAC with turbulizer, air inlet and outlet holes, metal body with insulating layer on the sides, absorber and light-transmitting glass cover placed parallel to each other in the body, turbulizers installed in the absorber at the same height as the body, and truncated pyramid-shaped baffles attached to the turbulizers formed.

Fig.1. Overview of the SAC experimental setup



1-air transmission; 2-fan; 3, 4, 5-valves; 6, 7, 8-solar air collectors; 9, 10, 11-hot air outlet; T-thermometer; P-differential manometer, u-anemometer

Fig. 2. Schematic of the SAC experimental setup

SAC with a turbulator works in the following order, atmospheric air with a temperature of 10...30℃ is sucked in by a fan, through valves and anemometers, using a pipe-shaped inlet hole installed on the side of the SAC body, parallel to each other absorber and directed to the air channel between the glass cover. The directed air stream moves in the S-shaped direction in the SAC air space and, as a result of washing the absorber, its temperature increases to 80...85℃. The required speed of the air flow is adjusted using valves and controlled using an anemometer. In the system, polyethylene pipes are used as transmission pipes that provide air movement. Experimental studies were conducted to determine the change in

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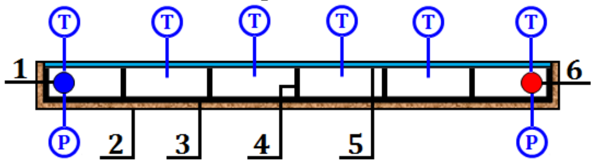
air temperature along the length of the SAC and to determine the hourly change in outlet air temperature. Experimental studies were conducted from 8^{00} to 18^{00} hours for four days. The installation scheme of the measurement and control devices used in the experimental research is shown in Figure 3.



1, 6-air inlet and outlet; 2-isolation; 3-absorber; 4-turbulizers; 5-transparent coating; T-thermometer; P-differential manometer

Fig.3. Measurement and control scheme of SAC with a turbulator

During the experiments, the necessary data are recorded according to the standard with the help of various measuring and control devices. However, there are uncertainties associated with measurement and control devices, measurement points, instrument indicators, experimental conditions, and the influence of the external environment. Therefore, in order to achieve a clear result in experimental research, it is necessary to first estimate the uncertainty of each control-measuring instrument and the general error during the research. If we denote variable uncertainties $u_1, u_2, \dots, u_n$, independent variables $z_1, z_2, \dots, z_n$ and the result by R, then the total error (1) is determined by the expression:

$$U_R = \left[\left(\frac{\partial R}{\partial z_1}u_1\right)^2 + \left(\frac{\partial R}{\partial z_2}u_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial z_n}u_n\right)^2\right]^{0,5} \quad (1)$$

Table 1 lists all measurement errors that occurred when measuring various parameters in experimental studies.

Table 1

Errors in measuring various parameters

Parameter	**Calculation**	**Error**
Solar radiation (R8180)	$U_{\mathrm{R8180}} = \sqrt{1^2 + 1^2}$	1,41
Temperature (DC-1)	$U_{DC-1} = \sqrt{1^2 + 1^2 + 1^2}$	1,73
Temperature (GM1361)	$U_{GM1361} = \sqrt{1^2 + 1^2 + 1^2}$	1,73
Temperature (HT-9815)	$U_{\mathrm{HT-9815}} = \sqrt{0{,}5^2 + 0{,}5^2 + 0{,}5^2}$	0,87
Pressure (FU-P1)	$U_{\mathrm{FU-P1}} = \sqrt{1{,}5^2 + 1{,}5^2 + 1{,}5^2}$	2,60
Pressure (QX-1201)	$U_{\mathrm{QX-1201}} = \sqrt{0{,}5^2 + 0{,}5^2 + 0{,}5^2}$	0,87
Anemometer (UT363)	$U_{DC-1} = \sqrt{1^2 + 1^2 + 1^2}$	1,73
Total error, %	$U_t = \sqrt{\begin{matrix}1{,}41^2 + 1{,}73^2 + 1{,}73^2 + 0{,}87^2 + \\ +2{,}60^2 + 0{,}87^2 + 1{,}73^2\end{matrix}}$	4,39

The air channel of the SAC with a turbulizer is a channel of a difficult shape, and the characteristic of the flow movement in such channels is explained by the presence of convective transfers due to the large cumulative and secondary flows that occur. This situation and the varying tortuosity of the channel wall lead to an uneven distribution of the frictional resistance at the flow boundaries. In order to achieve an accurate calculation of the coefficient of hydraulic resistance in such channels, the averaged flow characteristics (average velocity, average Reynolds number, average relative turbidity) over the channel cross-section to the local characteristic (local relative turbidity) turbulence, local Reynolds number, local hydraulic resistance coefficient) is necessary to pass. Therefore, the total pressure loss along the length of the SAC channel is:

$$\Delta P_t = \xi_t \frac{\rho u^2}{2} = \left(\lambda_l + f_f\right)\frac{\rho u^2}{2} \quad (2)$$

where ξ_t is the total hydraulic resistance; ρ-air density, kg/m^3; u is velocity of the air, m/s; λ_m is total local resistance coefficient in the SAC channel; f_f is SAC channel friction coefficient.

It is known that the total local resistance coefficient of SAC consists of the sum of the resistances of all obstacles encountered in the direction of air movement in the air duct, in our case there are the following local resistances: sharp expansion, sharp narrowing, narrowing of the transition section, flow through hole and confusor etc. When the local resistance coefficient is 500≤Re≤3300 during the sharp expansion of the cross-section when the air flow enters the SAC [241; 158-159-b]:

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$$\lambda_m = -8{,}44 - 26{,}16(1 - F_1/F_2)^2 - 5{,}38(1 - F_1/F_2)^4 + \\ + lgRe[6{,}01 + 18{,}54(1 - F_1/F_2)^2 + 4{,}01(1 - F_1/F_2)^4] + \\ + (lgRe)^2[-1{,}02 - 3{,}09(1 - F_1/F_2)^2 - 0{,}68(1 - F_1/F_2)^4] \quad (3)$$

When 10≤Re≤500:

$$\lambda_m = 3{,}62 + 10{,}74(1 - F_1/F_2)^2 - 4{,}41(1 - F_1/F_2)^4 + \\ + \frac{1}{lgRe}[-18{,}13 - 56{,}78(1 - F_1/F_2)^2 + 33{,}4(1 - F_1/F_2)^4] + \\ + \frac{1}{(lgRe)^2}[30{,}85 + 99{,}95(1 - F_1/F_2)^2 - 62{,}78(1 - F_1/F_2)^4] + \\ + \frac{1}{(lgRe)^3}[-13{,}22 - 53{,}95(1 - F_1/F_2)^2 + 33{,}80(1 - F_1/F_2)^4] \quad (4)$$

where F_1 and F_2 are the area of narrow and wide sections, m^2.

The local resistance coefficient when the air stream flows through the hole turbulizer is determined as follows [241;]

$$\lambda_l = \left[0{,}5\left(1 - \frac{F_1}{F_2}\right)^{0{,}75} + \left(1 - \frac{F_1}{F_2}\right)^{1{,}375} + \left(1 - \frac{F_1}{F_2}\right)^2\right]\left(\frac{F_1}{F_2}\right)^2 \quad (5)$$

The coefficient of local resistance when the air stream flows through a turbulizer with a confusor is determined as follows [241;]:

$$\lambda_l = \frac{A}{Re} \quad (6)$$

where $5° \leq \alpha \leq 40°$, $A = \frac{20{,}5}{n_0^{0{,}5}(tg\alpha)^{0{,}75}}$, $n_0 = F_1/F_2$.

The coefficient of frictional resistance in the SAC air channel is determined using the correction factor depending on the shape of the cross-sectional surface of the channel:

$$f_f = k_t \frac{64}{Re} \quad (7)$$

where the k_c is correction coefficient is determined depending on the ratio of the sides of the rectangle, for example, in the laminar flow regime, it can be determined according to the following table:

a/b	0	0,1	0,2	0,4	0,6	0,8	1,0
k_t	1,10	1,08	1,06	1,04	1,02	1,01	1,0

III. RESULTS AND DISCUSSION

As can be seen from the calculation formulas given above, the calculation of the total hydraulic resistance based on the values of local and friction resistance coefficients for all elements of the SAC is quite difficult and requires a large amount of computational work. These problems can be solved by experimentally determining the total pressure drop in the SAC. Experimental studies to determine the pressure loss in SAC with a smooth absorber and a turbulizer were conducted separately for each model in the experimental device shown in Figures 1 and 2. Based on the pressure loss results, the overall hydraulic resistance coefficient of SAC was determined and the results were compared. Experimental studies were carried out in the following ranges of the main parameters: air flow speed $u = 4 \ldots 20\ m/s$, Reynolds number Re=500...2100. Table 2 shows the results of determining the pressure loss in SACs with smooth absorbers and turbulizers.

Table 2
Pressure loss in SAC at different air velocities

№	**Model**	**Pressure loss at different speeds $\Delta P, Pa$**				
		$4\ m/s$	$8\ m/s$	$12\ m/s$	$16\ m/s$	$20\ m/s$
1	QHK	1,3	5,8	10,3	24,0	35,0
2	T4	11,9	46,5	106,1	191,2	295,5
3	T5	12,7	50,4	116,2	206,6	327,2
4	TT4	3,5	13,4	30,6	54,8	84,0
5	TT5	2,3	7,9	17,0	32,7	48,6
6	KT4	3,6	13,7	30,9	53,4	79,7
7	KT5	2,1	7,7	16,8	29,7	45,7

Based on the results presented in Table 2 above, the overall hydraulic resistance coefficient of the SAC was determined and the results obtained for each model were compared with the results of the smooth absorber SAC. Figure 4 shows the

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theoretical and experimental results of the change of hydraulic resistance depending on the Reynolds number in each model of SAC.

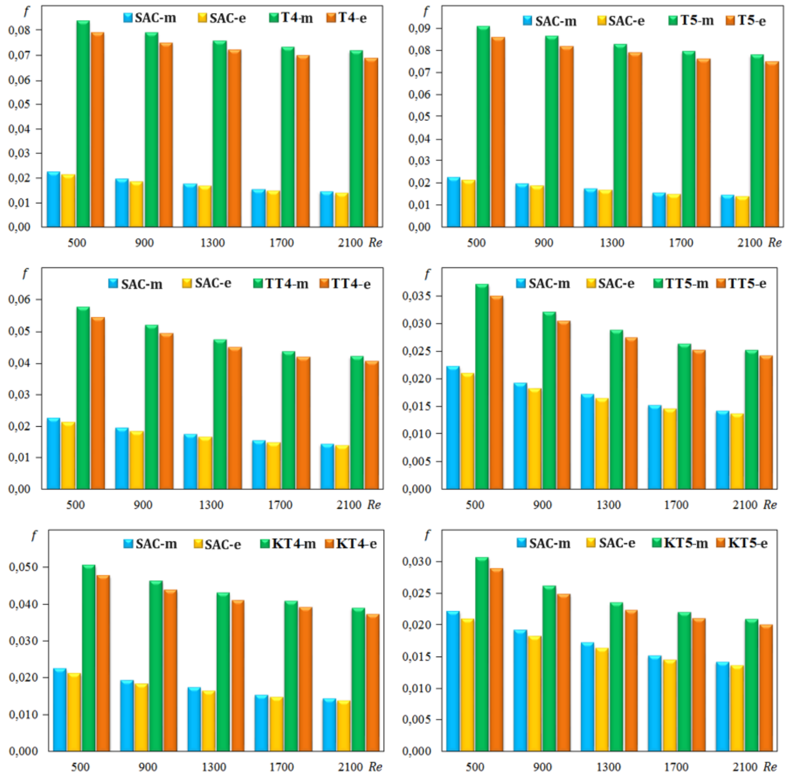

Fig. 4. Results of change of hydraulic resistance coefficient of SAC depending on Reynolds number
(m-theoretical, t-experimental)

As can be seen from the results presented in Figure 4, the coefficient of hydraulic resistance decreased with the increase of Reynolds number in all models. The coefficient of hydraulic resistance is the highest in the T5 model and the smallest in the KT5 model, which is in full agreement with the theoretical results. The value of the coefficient of hydraulic resistance compared to SAC with a smooth absorber is on average 4.5 times in the T4 model, 4.8 times in the T5 model, 2.8 times in the TT4 model, 1.7 times in the TT5 model, 2.5 times in the KT4 model and 1.4 times in the KT5 model. The character of the change of the theoretical and experimental results obtained on hydraulic resistance is the same, and when the validation of the results is checked by the reliability of approximation, $R^2 = 0{,}952$ for the T4 model, $R^2 = 0{,}973$ for the T5 model, and $R^2 = 0{,}958$ for the TT4 model, $R^2 = 0{,}981$ for TT5 model, $R^2 = 0{,}968$ for KT4 model, for KT5 model $R^2 = 0{,}987$. The deviation of experimental results from theoretical research results was 4.8%.

Based on the generalization of the experimental results on the coefficient of hydraulic resistance in SACs with smooth absorbers and turbulizers, the following empirical relationships were obtained:

For T4 model:

$$f = \frac{0{,}146}{Re^{0{,}0996}} \tag{8}$$

For T5 model:

$$f = \frac{0{,}157}{Re^{0{,}098}} \tag{9}$$

For TT4 model:

$$f = \frac{0{,}204}{Re^{0{,}213}} \tag{10}$$

For TT5 model:

$$f = \frac{0{,}181}{Re^{0{,}265}} \tag{11}$$

For KT4 model:

$$f = \frac{0{,}138}{Re^{0{,}171}} \tag{12}$$

For KT5 model:

$$f = \frac{0{,}143}{Re^{0{,}259}} \tag{13}$$

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Empirical correlations (8)-(13) given above apply to the proposed six models, and the calculation error according to empirical correlations is 0.21%, 0.38%, 0.93%, 0, respectively. .68%, 0.51% and 0.56%. The adequacy of the identified empirical models was tested by Fisher's test. At a confidence level of 0.05, the table value of the Fisher criterion was 0.0062. The estimated value of the Fisher criterion was 0.0024 for the T4 model, 0.0039 for the T5 model, 0.0025 for the TT4 model, 0.0031 for the TT5 model, 0.0048 for the KT4 model, and 0.0019 for the KT5 model. It can be seen that in all cases the calculated value of Fisher's criterion is smaller than the table value, which means that the models are adequate. Thus, the results obtained on the basis of theoretical and experimental studies on determining the hydraulic resistance of SAC and empirical relationships allow determining the total hydraulic resistance of SACs with flat, perforated and confusing turbulizers and the necessary fan power for driving air.

IV. CONCLUSION

The scheme of the experimental device, which allows experimental research of hydrodynamics and heat exchange processes in SAC with a smooth absorber and a turbulizer, was developed, and a pilot-industrial sample was built and tested.

When the total pressure loss and hydraulic resistance coefficients in SAC with smooth absorber and turbulizer were determined experimentally, the average value of hydraulic resistance coefficient compared to SAC with smooth absorber was 4.5 times in T4 model, 4.8 times in T5 model, 2.8 times in TT4 model, TT5 it was found to be 1.7 times higher in model KT4, 2.5 times higher in model KT5 and 1.4 times higher in model KT5.

The results determined on the value of the coefficient of hydraulic resistance in the SAC were summarized, and empirical relationships were obtained that allow determining the coefficient of hydraulic resistance in the SAC with a smooth absorber and a turbulizer with a calculation error of 4.8%.

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