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Increase in Dependability and Efficiency of Self-Draining Water Systems of Solar Heat Supply

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Abstract—It is shown in the paper that the reliability and efficiency of self-draining systems of the drainback syphon type depend on the atmospheric pressure and heating temperature of the heat carrier in the solar collectors, which affect the value of the allowable drop of the atmospheric pressure in the upper point of the system after it is filled with the heat carrier and achieves the specified heat operation mode. In such systems, the drop of the atmospheric pressure and growth of the heating temperature of the heat carrier lead to an increase in the power consumption for the heat carrier circulation owing to the interruption of the jet in the syphon because of boiling of the heat carrier. An improved structure of the self-draining solar circuit with an active element in the form of a Venturi tube was developed in which there are no such drawbacks under atmospheric pressure, and as compared to the common self-draining system of the drainback syphon type, the power consumption for the heat carrier circulation is reduced to 65–80%. The calculated dependences are given to define the necessary degree of the flow contraction in the Venturi tube and its resistance coefficients.

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STATE OF THE PROBLEM AND GOAL SETTING

The main element of the solar heat-supply water systems (SHS) is the solar collector (SC), which serves for conversion of the solar energy into the heat energy removed from the collector by the heat carrier—water. It is known that the solar collector operates under conditions of strong nonuniformity of the solar radiation intake and significant outdoor temperature fluctuations: from lower negative values in winter to high positive values in summer. Such operating conditions can lead to the failure of the solar collector. For example, in winter at night, failure can occur owing to freezing of water in the collector, and in summer in the daytime, failure can occur owing to its boiling and rapid increase in the pressure of the overheated water vapor (or antifreeze) to dangerous values when in the stagnation mode (circulation stop) the temperature inside the solar collector can rise to 200°C in flat collectors and to 300°C in vacuum collectors [1, 2].

One of the directions of improvement of the structures of solar heat-supply water systems is application of self-draining systems in them with the discharge of the solar collector when the circulation pumps stop [3, 4]. This engineering solution makes it possible to avoid both water freezing in the solar collector in winter and its boiling in summer in the absence of the heat carrier circulation in the system.

It should be noted that such self-draining systems can be divided into two variants: the systems including an intake air valve in the upper point of the system (Fig. 1) [3] and systems without an air valve (drainback systems) (Fig. 2), which we call syphon-type systems.

At the start and stop of the circulation pump, the operation of the self-draining solar plants in both variants of systems is similar to each other. When there is no solar radiation and the pump is deactivated, the heat carrier flows by gravity from the solar collector and is accumulated in a special tank (Fig. 3a). In case of presence of solar radiation, after the pump is activated, the solar collectors are filled with the accumulated heat carrier from the tank and the solar plant operates under normal conditions (Fig. 3b).

With the working pump, the principal difference of the systems consists in different distribution of the hydrostatic pressure along the water circulation system, which affects the required capacity of the pump and electric energy consumed by it.

It is shown is [5] that the presence of the intake air valve in the upper point of the system leads to interruption of the flow jet in this point during operation of the pump and to the necessity of constant moving against the hydrostatic pressure defined by the height H (Fig. 1a), even after filling of the system with water, because when discharging to the tank for drainage the potential energy of the water is uselessly lost owing to

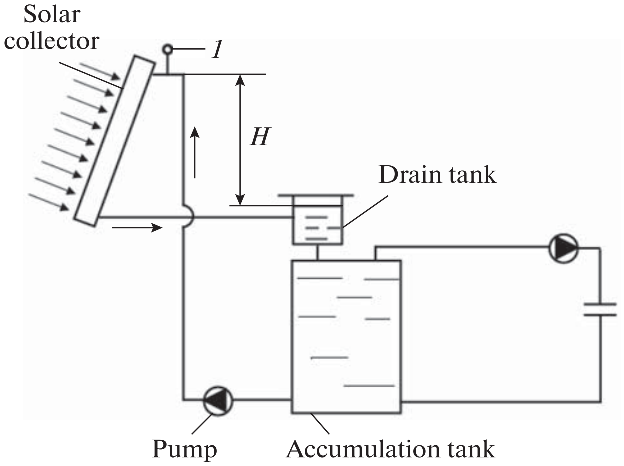

Fig. 1. Diagram of the self-draining solar plant with an air intake valve [3]: *1*—air intake valve; *H*—difference of the water levels in the solar collector and expansion tank.

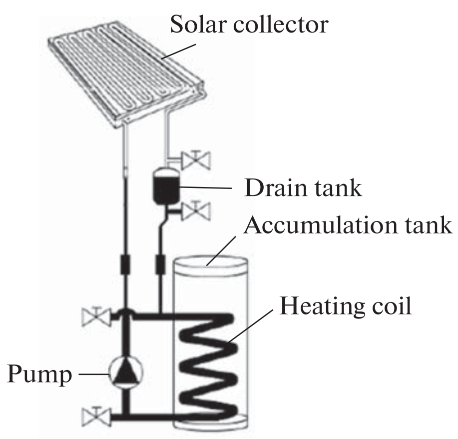

Fig. 2. Diagram of the self-draining solar plant of the syphon type (drainback systems) without an air intake valve [4].

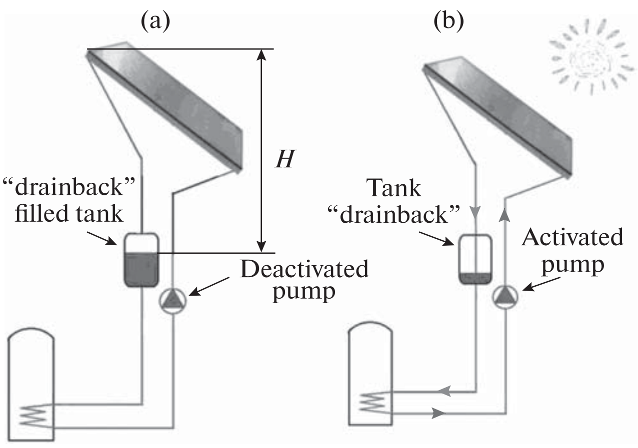

Fig. 3. Operating modes of the self-draining solar plant of the syphon type with the pump deactivated (a) and activated (b).

operation of the gravity pipeline by the partial section. That is why this system requires the maximum capacity of the pump and increased electric energy consumption also after filling of the system with water.

In a self-draining solar plant of the syphon type (drainback systems) (Fig. 2), the pressure significantly decreases in the upper part of the system after it is filled with water owing to the absence of the air intake valve. That is why it is enough for the pump to lift water not to the full height H after filling of the system, but only to the height H excluding the value of the allowable pressure drop in the syphon $(h_{vac})_{add}$, which for water under the normal atmospheric pressure and temperature 20°C is $(h_{vac})_{add}$ = 6–7 m.w.c. [6].

Therefore, it may seem that the syphon-type solar plant has an apparent advantage as compared to the system with the air valve in the upper point of the system. But, as is known [6], the value of the allowable pressure drop in the syphon, as in the suction pump pipe, depends on the temperature and liquid type under normal atmospheric pressure. With the increase in the temperature of the liquid, the value of the allowable pressure drop is reduced since with the increase in the temperature formation of areas in the flow filled with the air and heat carrier vapor intensifies owing to a growth of the "pressure of the saturated vapor" [6]. For example, at the water temperature of 60°C, the allowable pressure drop acquires already a negative value, i.e., becomes higher than the atmospheric pressure [6]. If the water heating temperature in the solar collectors of the self-draining solar plant after their heating with the solar beams is assumed equal to 60°C and higher, then both variants of the systems will turn out to be equal from the point of view of the required capacity of the pump and electric energy consumed by it owing to the pressure change in the syphon because of boiling of the heat carrier.

Thus, it is possible to make a conclusion that the self-draining solar plants of the syphon type under atmospheric pressure can have some advantages as compared to the system with the air valve in the upper point of the system only in the "cold" condition of the solar circuit, i.e., to the water temperature not exceeding 20°C.

After the system achieves the design heat operation mode (more than 60°C), the pump capacity consumption and electric energy consumption in both variants of the systems become maximal owing to the jet interruption. It follows that the heating temperature of the heat carrier in the solar collector and atmospheric pressure have a significant influence on the reliability and efficiency of operation of the self-draining systems of the drainback syphon type.

In [7], the solar heat-supply water system of a residential house constructed in the city of Linkoping (Sweden) is shown where some special cylinders filled with nitrogen creating a slight excess pressure in the system as compared to the atmospheric air are installed instead of the intake air valve 1 (Fig. 1) in order to protect the solar collectors from corrosion and provide more reliable water draining after the stop of the pump. It is evident that connection of the cylinders with nitrogen to the upper point of the self-draining solar plant does not introduce any changes to the operating mode of the circulation pump before and after filling of the system with water because the jet interruption will still be observed in this point under the operating pump. Application of the engineering solution in the self-draining solar plant of the drainback syphon type where the nitrogen cylinders can be connected to the upper part of the drain tank appears to be interesting (Fig. 2). This will create excess pressure in the solar circuit (higher than the atmospheric pressure) and favorable conditions for operation of the syphon because this makes it possible to avoid boiling of the heat carrier in the upper point of the syphon during heating in the solar collector higher than 60°C. However, this engineering solution requires a comprehensive detailed study because in this case a significant excess pressure (approximately not less than 1 atm per each 10 m of the height H of the solar plant) is required. At the same time, the requirements on the strength properties of the system and its impermeability increase, and also problems can appear with the nitrogen dissolved in the heat carrier, the absorbed amount of which is proportional to its pressure according to Henry's law [8]. Then, besides boiling of the heat carrier in the upper point of the syphon, the problem of emission and accumulation of the nitrogen dissolved in the heat carrier additionally appears during the pressure drop, which can lead to the jet interruption.

Owing to their simplicity, the self-draining systems operating under atmospheric pressure are widely used in practice [1, 2]. Thus, for example, in [9], the characteristics of self-draining solar plants of 16 world leading producers are represented. The main differences of these solar plants consist in the structure of the drain tank (separate or combined with the accumulating tank); length of the solar circuit (from 20 to 40 m) and its geometric height, i.e., differences of elevations H (from 5 to 25 m, see Fig. 3a); area of the solar collector; and type of heat carrier.

The drainback systems have many advantages as compared to other types of solar water heaters. Because the system needs some air space for the gravity-flowing drainage of the heat carrier, the circuit is not under pressure. Fewer requirements are made on the soldered joints, screwed fittings, and gaskets. If the heat carrier circuit unseals, it will flow slower than it would under pressure. In addition, there are no motorized valves, and the system does not depend in the voltage supply to support protection from freezing. If the electric energy is switched off, the pump is shut down and the heat carrier drains from the collectors to the tank.

The use of the circuit without pressure means that the numerous components required in the systems under pressure are not necessary. The expansion tank, back valve, pressure gauge, air-relief valve, and air separator are not required.

However, in spite of all advantages and widespread use, the drainback self-draining systems also have the following disadvantages.

As the heat carrier is in the tank and the collector is empty at the start of the pump, the latter should overcome the hydrostatic head H and lift the heat carrier from the lowest level to the upper point in the system (Fig. 3a). This requires a more powerful pump consuming more electric energy. As was shown above, the pump power is required not only within a short period of time after its activation in the mode of filling with water but also during water circulation in the filled system, after it achieves the design heat mode (60°C and more), because upon the physical height of the solar circuit exceeding the value of the allowable pressure drop in the flow pipe (syphon) in the upper point, the jet interruption occurs because of boiling of the heat carrier.

Therefore, in the American drainback system, the pump models Taco 009 (Canada) and Grundfos UP26-64 and UP26-96 (Denmark) are popular owing to their proven dependability and capability to lift the heat carrier to the height of more than 9 m in the open circuit. These pumps in the drainback systems consume more energy than they do in the glycolic systems under pressure. For the systems with a very high upper point (more than 10 m), the required pump cannot be selected. In this respect, in some cases, several pumps are installed in series, but if one pump is out of service, the heat carrier can fail to achieve the upper part of the collector, which makes it vulnerable to freezing. Many drainback systems use the second pump to provide the circulation of the domestic hot water through the heat exchanger to the tank, thereby increasing the power consumption by the system. The drainback system with two pumps can often consume threefold or more electric energy for the pumps as compared to the glycol systems with one circulation pipe. For example, the circulation pump in the glycol system can use about 85 W, while the total capacity of two pumps of comparable size of the drainback system can be 260 W or more. In some cases, the additional consumed electric energy can reach 2 kWh per day during days with high solar activity, which makes the drainback plants unavailable in the systems with a self-contained power supply.

Thus, as the operating practice shows, the existing drainback systems can be characterized by such disadvantages as low dependability and significant consumption of electric energy by the pump for the heat carrier circulation.

The aim of this work is to increase the dependability and efficiency of operation of the self-draining water

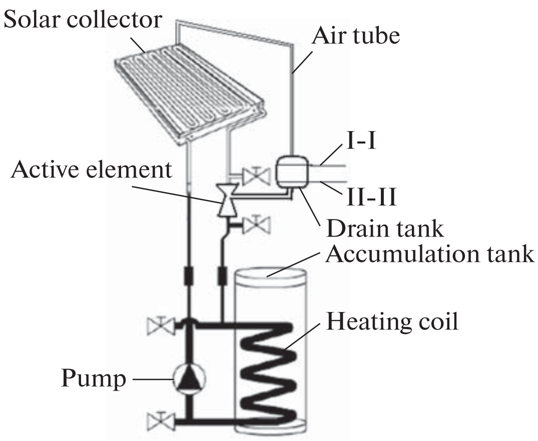

Fig. 4. Diagram of the self-draining solar plant with an active element in the form of a Venturi tube.

systems of the solar heat supply independently of the heating temperature of the heat carrier in the solar collector under atmospheric pressure.

IMPROVED DIAGRAMOF THE SELF-DRAINING SOLAR CIRCUIT

The distinctive feature of the developed self-draining solar circuit [10] is connection of the drain tank to the circulation pipeline not directly as is provided in the drainback system, but through a contracted section of the active element (AE) made in the form of a Venturi tube (Fig. 4). In this case, the role of the active element consists in automatic connection and disconnection of the drain tank to the self-draining solar circuit at the stop and start of the pump (after filling of the system with water), respectively. Thus, it operates in the hydrodynamic trigger mode. Therefore, at the stop of the pump, the solar collector is drained as usual and water is discharged to the drain tank through the holes in the contracted section of the Venturi tube, and its level in the tank rises to from the elevation *II–II* to the elevation *I–I*. In this case, the air from the drain tank is pushed to the upper part of the syphon, and interrupting the heat carrier flow provides reliable draining of the solar collector.

At the start of the pump, the water is sucked back from the drain tank through the contracted section of the active element, and the air is pushed from the solar collector to the drain tank, in which the level of water decreases from the elevation *I–I* to the elevation *II–II*. While passing through the Venturi tube, owing to the contraction of the section, the hydrostatic pressure of the water flow passes into hydrodynamic (velocity) pressure. That is why it is not discharged by gravity to the drain tank (as occurs in the drainback systems), and keeping its kinetic energy, it continues flowing, passing the side holes in the contracted section of the Venturi tube which connect it to the drain tank. Further expansion of the flow in the Venturi tube leads to recovery of the hydrostatic pressure (up to 65–80% depending on the degree of the flow contraction, flow mode, and structure and finish of the internal surface of the Venturi tube) owing to a gradual decrease in the hydrodynamic pressure.

Thus, with the operating pump, the drain tank for water discharge remains blocked by the high hydrodynamic pressure of the flow, and circulation of the heat carrier in all other points of the solar circuit is carried out under the excess hydrostatic pressure of the heat carrier, i.e., without its losses because of the jet interruption independently of the heating temperature of the heat carrier. In this case, as compared to the existing drainback systems, the power consumption for overcoming the excess hydrostatic pressure of the heat carrier lost in them at the connection point of the drain tank because of the heat carrier jet interruption in the upper part of the syphon at the temperature of more than 60°C and atmospheric pressure is excluded.

ESTIMATION OF THE ENERGY EFFICIENCY OF THE SELF-DRAINING SOLAR CIRCUIT WITH AN ACTIVE ELEMENT

The estimation of the energy efficiency of the self-draining solar circuit with an active element in the form of a Venturi tube is given in [5]. The characteristic of the flow dynamics in the self-draining solar circuit is considered in it on the basis of the generation of the Bernoulli equation. The energy consumption for the heat carrier circulation is compared upon the general connection of the drain tank to the circulation pipelines without a contracting device (i.e., through the T-joint with similar diameters D by the sides) and its connection to the pipelines through the contracted section of the Venturi tube with the diameter d.

In this case, the energy efficiency was estimated on the basis of the relative energy saving $\Delta\bar{E}_{\text{Venturi}}$ for the pump drive as compared to the existing self-draining system with the intake air valve in the upper point (Fig. 1), for the determination of which the following dependence was obtained:

$$\Delta\bar{E}_{\text{Venturi}} = \left[\left(\frac{D}{d}\right)^4\left(\frac{\alpha_1}{\alpha_2} - \frac{1}{\alpha_2}\zeta_B\right) - 1\right] \times \left[\frac{\alpha_1}{\alpha_2}\left(\frac{D}{d}\right)^4 + \frac{1}{\alpha_2}\zeta_{\text{rectilinear solar circuit}}\right]^{-1}, \quad (1)$$

where D and d are the diameter of the wide and contracted section of the Venturi tube, m; α_1 and α_2 are the Coriolis coefficients in the wide and contracted sections; and ζ_{Venturi} and $\zeta_{\text{rectilinear solar circuit}}$ are the coefficients of the local resistance of the Venturi tube and solar circuit, respectively.

In [5], a detailed physical explanation is given, as a result of which the energy saving for the heat carrier circulation appears. For this purpose, the characteristics of the pipeline networks $\Delta p_{\text{pump}} = f(G)$ are compared depending on consumption of the heat carrier G for the common solar circuit without a contracting device $\Delta p^{\text{o}}_{\text{pump}}$, when the cross section of the circulation pipelines F_2 and the T-joint at the point of connection of the drain tank F_1 are equal to each other, i.e., $F_1 = F_2$, and for the solar circuit with the Venturi tube $\Delta p^{\text{Venturi}}_{\text{pump}}$, when $F_1 < F_2$. It is shown that, after filling of the system with the heat carrier, the characteristic of the network of the common self-draining solar circuit owing to the jet interruption leading to operation of the return pipeline with the partial section, the pump performs circulation in it with lifting of the liquid to the height H, and with the increase in consumption G, the curve of the system characteristic grows monotonically according to the equation

$$\Delta p^{0}_{\text{pump}} = \rho g H + S_{\text{resistance}} G^2, \quad (2)$$

where ρ is the density of the heat carrier, kg/m^3; H is the physical height of the solar plant, m; g is the free fall acceleration, m/s^2; $S_{\text{resistance}}$ is the characteristic of resistance of the pipeline network, Pa/(kg/s)^2; and G is the heat carrier consumption, kg/s.

In the self-draining solar circuit with the Venturi tube,

$$\Delta p^{\text{Venturi}}_{\text{pump}} = \begin{cases} \rho g H - \left(\dfrac{\alpha_1}{F_1^2} - \dfrac{\alpha_2}{F_2^2}\right)\dfrac{G^2}{2\rho} + (S_{\text{resistance}} + S_{\text{Venturi}}) \;\; G^2 G \le G^* \\ (S_{\text{resistance}} + S_B) G^2 \qquad G \ge G^* \end{cases}, \quad (3)$$

where S_{Venturi} is the characteristic of resistance of the Venturi tube, Pa/(kg/s)^2; and G^* is the design consumption of the heat carrier for which the degree of flow contraction in the Venturi tube is defined, D/d, kg/s.

According to the upper equation (3), after filling of the system with the heat carrier, i.e., rise of its hydrostatic pressure to the value $\rho g H$, the curve of the characteristic of the system of the self-draining solar circuit with the Venturi tube first decreases monotonically with the growth of consumption G, and then achieving the minimum level upon the design consumption G^*, for which the degree of the flow contraction in the Venturi tube D/d is defined, it starts growing monotonically according to the lower equation (3), but already without the value of the hydrostatic pressure $\rho g H$.

Such a peculiarity of the characteristic of the solar circuit system with the Venturi tube is explained by the fact that, upon consumptions $G < G^*$, the water circulation in the circuit is carried out also with the jet interruption in the upper point. But unlike the common solar circuit, the level of filling of the return pipeline increases continuously with the growth of consumption owing to an increase of the dynamic pressure in the Venturi tube neck. In this case, the gain in the hydrostatic pressure outruns the growth of hydraulic losses specified by integrating of the Venturi tube into the circuit, owing to which the curve of the characteristic drops.

At $G = G^*$, the solar circuit is completely closed, and the increase in consumption is no longer accompanied by the gain in the hydrostatic pressure. From this moment, the curve of the characteristic rises as the hydraulic losses in the circuit increase in proportion to the consumption. The geometric (D/d) and hydrodynamic (ζ_{Venturi})characteristics of the Venturi tube affect significantly the energy efficiency $\Delta\bar{E}_{\text{Venturi}}$; the optimal place of location of the Venturi tube according to the performed analysis of distribution of the hydrostatic pressure in the solar circuit is the intake pipe of the pump.

According to the calculations performed according to formula (1), the application of an active element makes it possible to reduce the electric energy consumption for the heat carrier circulation to 65–80% owing to excluding the losses of the hydrostatic pressure connected with the jet interruption as compared to the common self-draining solar circuit having an intake air valve in the upper point of the system (Fig. 5). As compared to the common self-draining system of the drainback syphon type operating under atmospheric pressure and heating temperature of the heat carrier in the solar collector of more than 60°C, the reduction of electric energy consumption for the heat carrier circulation will be the same. To calculate the geometrical dimensions of the Venturi tube, the following formula is obtained:

$$\frac{D}{d} = \sqrt[4]{\frac{\alpha_2}{\alpha_1}\left(1 + \frac{2gH}{\alpha_2 W_2^{*2}}\right)}, \quad (4)$$

where W_2^* is the allowable water velocity in the wide section of the Venturi tube, $W_2^* = 1–1.5$ m/s.

The degree of flow contraction in the Venturi tube (D/d) depends on the solar plant height H and can vary from 2 to 5 at the height from the lowest level to the uppermost point in the system from 2 to 25 m (Fig. 6).

In the developed self-draining solar circuit, the heat carrier circulation is carried out without the jet

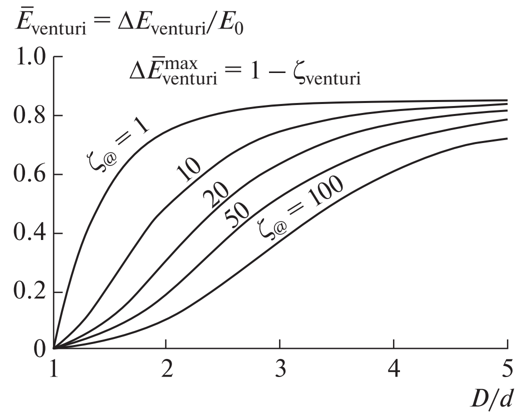

Fig. 5. Dependence of the relative energy saving $\Delta\bar{E}_{\text{Venturi}}$ on the degree of flow contraction in the Venturi tube (D/d).

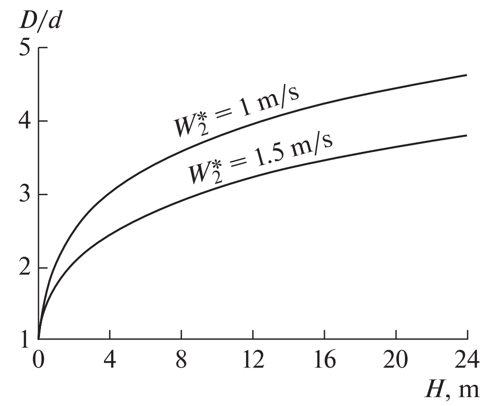

Fig. 6. Dependence of the ratio of the Venturi tube diameters (D/d) on the height of the solar plant H.

interruption and losses of the hydrostatic pressure H, which is achieved through connection of the drain tank to the contracted section of the active element—the Venturi tube. With the operating pump, the mutual conversion of the potential and kinetic energy of the heat carrier takes place at the point of connection of the drain tank equal in value to the hydrostatic pressure H. In this case, the value of the pressure recovery after the active element depends on the value of the local resistance coefficient of the Venturi tube ζ, which is defined by its geometrical and hydrodynamic parameters.

The calculation of the hydraulic resistance of the active element—the Venturi tube—with its known geometrical dimensions is a complex problem. The mechanism of action of the resistance forces is so complicated that no precise method of calculation of the resistance coefficient ζ has yet been found; in engineering calculations, it is necessary to use most often the values of the resistance coefficients given in the literature in the form of average figures or in the form of tables of experimental data for the different combinations of geometrical dimensions of the transition. The only possible method to calculate ζ for the Venturi tube in such case consists in the experimental definition of the necessary data with further summary of the results in the form of criteria [11].

In [11], as a result of processing of the experimental data, the following criterion dependences were specified to define the resistance coefficients of the Venturi tube:

—for the transitions with the curvilinear confusor,

$$\zeta_{\text{Venturi rectilinear}} = 17.639\text{Re}^{-0.464}(D/d)^{0.66}(\delta/d)^{0.09}, \tag{3}$$

—for the transitions with the rectilinear confusor

$$\zeta_{\text{Venturi rectilinear}} = 8.046\text{Re}^{-0.379}(D/d)^{0.70}(\delta/d)^{0.09}, \tag{4}$$

where $\text{Re} = \rho v d/\mu$ is the Reynolds criterion; ρ is the density, kg/m^3; v is the velocity in the contracted section (in the neck) of the Venturi tube, m/s; and δ is the diameter of the side holes in the Venturi tube neck.

Equations (3) and (4) are obtained for the Venturi tubes having a rectilinear diffusor with the angle of conicity $\alpha_{\text{diffusor}} = 7°$, the confusor of which either is outlined by the radius R_{confusor}=1.5–4d or is rectilinear with the convergence angle $\alpha_k = 30°$, and are valid at Re = (0.25–1.5) × 10^5; D/d = 2–5; δ/d = 0.2–0.6; l/d = 1.

The average deviation of the experimental data from the design data calculated according to Eq. (3) does not exceed 4.5% at the maximum deviation of 8.2%. In Eq. (4), the corresponding deviations are 4.7% and 8.1%.

CONCLUSIONS

1. The dependability and efficiency of operation of the self-draining systems of the drainback syphon type depend on the heating temperature of the heat carrier in the solar collectors and atmospheric pressure, which affect the value of the allowable atmospheric pressure drop in the highest point of the system after its filling with the heat carrier and achieving the specified heat operating mode. The decrease in the atmospheric pressure and growth of the heating temperature of the heat carrier in the solar collector lead to an increase in the energy consumption for the heat carrier circulation owing to the jet interruption in the syphon because of boiling of the heat carrier.

2. An increase in the dependability and efficiency of the self-draining water systems of solar heat supply operating under atmospheric pressure can be achieved via connection of the drain tank to the circulation pipelines through the contracted section of the active element in the form of a Venturi tube. The application

of an active element makes it possible to reduce the electric energy consumption for circulation of the heat carrier to 65–80% owing to excluding the losses of the hydrostatic pressure ρgH connected with the jet interruption because of boiling of the heat carrier as compared to the common self-draining solar circuit of the drainback syphon type operating under atmospheric pressure.

3. An increase of the efficiency of the self-draining systems of the drainback syphon type can be achieved also via creation of excess pressure (higher than atmospheric) in the solar circuit by some inert gas (for example, nitrogen). This provides favorable conditions for the syphon operation because it makes it possible to avoid boiling of the heat carriers in its upper point upon heating in the solar collector higher than 60°C. However, this engineering solution needs to be comprehensively studied, because in this case the requirements on the strength characteristics of the system and its impermeability increase, and there also appears a problem connected with emission and accumulation of the inert gas dissolved in the heat carrier in the upper point of the syphon with the pressure drop, which also can lead to the jet interruption.

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