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Design of Water Distribution for a Stratification Heat Accumulator in a Solar Heating System

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ABSTRACT- The calculation method for a water distributor of a constant cross section uniformly perforated along the height for a multilayer stratified thermal storage tank used in solar heating and hot water supply systems was developed.

KEYWORDS :water distribution, **heat accumulator,** solar heating system ,stratifications accumulator.

I. INTRODUCTION

Water thermal storage tanks of solar heat supply systems can function at a significant degree of temperature stratification when the top of the storage tank is hotter than its bottom [1]. The principle of the layer after-layer charging of a thermal storage tank by a solar collector, when water heated in a collector is supplied to the layer corresponding to its temperature and the mixing of layers is excluded, is widely used now in the design of solar hot water supply and heating systems [2–4]. The potential gain in the solar fraction for a solar plant with an ideally stratified tank and low specific water consumption through a solar collector in the range of 0.002–0.007 kg/(m2s) compared to a fully mixed tank and high specific water consumption through a solar collector of ~0.01–0.02 kg/(m2 s) can reach 1/3 [1] despite the fact that, under high specific consumption, the higher values of the collector heat removal factor $F_R$are provided [1]. The increase in the solar fraction of such a plant, according to some experimental data [5], is possible from 0.48 to 0.66. In practice, such a significant gain has not yet been achieved because of the complexity of implementing good temperature stratification in storage tanks [1]. Thus, the improvement of the design of stratified thermal storage tanks and their calculation methods providing stable temperature stratification is topical.

II.THE MAIN RESULTS AND FINDINGS

Let us consider water delivery by a water distributor of constant cross section with uniform perforations over the length (Fig. 1a). If we replace the perforations by a nominal slot of constant width (Fig.1b) and set up the Bernoulli equation with respect to sections x and $x + dx$, we obtain the differential equation [6]

$$\bar{W}_{\bar{x}}''\bar{W}_{\bar{x}}' + p\bar{W}_{\bar{x}}'\bar{W}_{\bar{x}} + q\bar{W}_{\bar{x}}^2 = pRi, \quad (1)$$

where

$$p = \mu^2\bar{f}^2; \;\; q = -0.5\mu^3\bar{f}^2\lambda\bar{l}; \;\; Ri = \frac{-gl}{W_b^2} \times \frac{\Delta p}{p}; \; \Delta\rho = \rho_0 - \rho \quad (2)$$

$$\bar{f} = \frac{gl}{F} = \frac{f}{F}; \;\; \delta = ma; \;\; d_e = \frac{4F}{P}; \;\; \bar{l} = \frac{l}{d_e}; \quad (3)$$

$$\bar{W}_{\bar{x}} = \frac{W_x}{W_b}; \bar{X} = \frac{x}{l}. \quad (4)$$

The boundary condition are

$$\text{for} \begin{cases} \bar{x} = 0 \; \bar{W}_0 = 0 \\ \bar{x} = 1 \; \bar{W}_b = 0 \end{cases} \quad (5)$$

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In Eqs. (1)-(5), W_b and W_x are the water velocity at the beginning of the distributor and in section $x\ (m/\text{sec})$; $l, P, d_e, and\ \delta$ are the length, perimeter, equivalent diameter, and width of the nominal slot of the distributor (m); F and f are the cross-sectional areas of distributor and slot (m^2); δ is the area of a perforation (m^2); m is the number of perforations per m of length (l/m); p_0 and ρ are the density of the surrounding and distributed water (kg/m^3); $\lambda\ and\ \mu$ are the coefficients of resistance of friction and the flow; and g is the acceleration to gravity (m/sec^2). The subscripts 0 and b indicate the cross section at the stop end of the distributor and at the beginning of the distributor.

The $\mu\bar{f}$ are called the nominal slot parameter; $\lambda\bar{l}$ are called the distributor parameter. The dimensionless complex Ri is the modified Richardson number, wich characterizes the relationship between the Archimedes forces and interial forces at the beginning of the distributor. In particular, Ri =0.5 means that these forces are equal $(-gl\Delta\rho = 0.5\rho W_b^2)$.

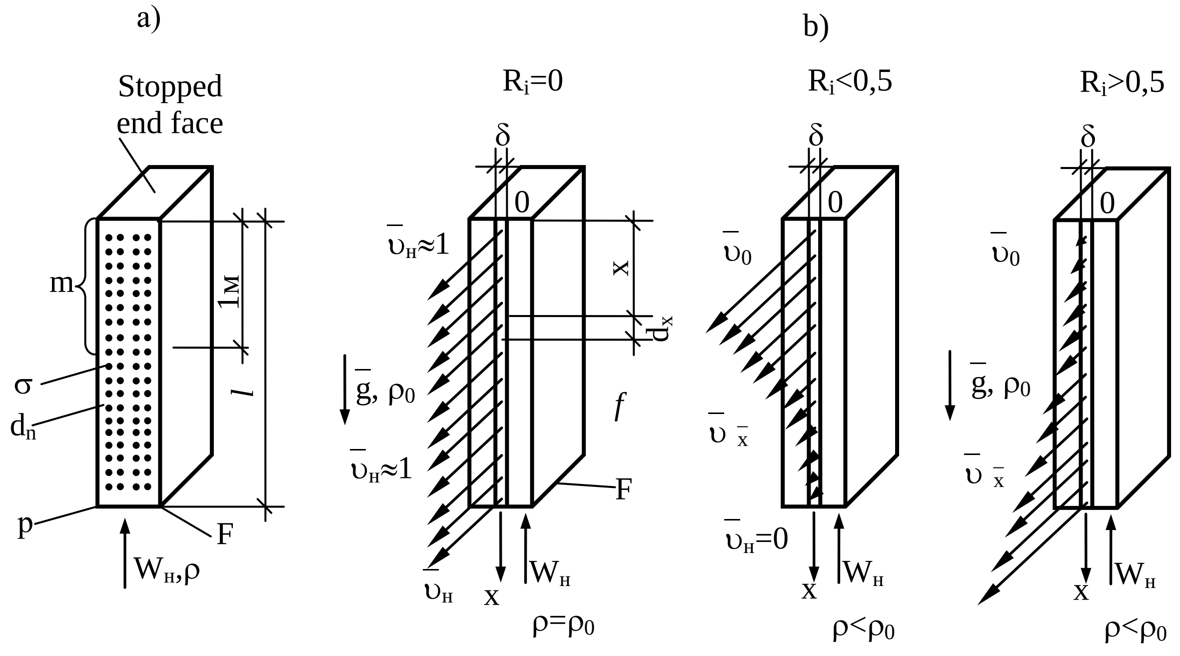

Fig.1. Diagram of water distributor of constant cross section with uniform perforation (a) and with a nominal slot of constant width (b).

If the Archimedes forces are directed upward $(\Delta\rho > 0)$, then $Ri < 0$; otherwise $(\Delta\rho < 0)$ we have $Ri > 0$.

Equation (1) and conditions (5) yield a complete mathematical formulation of the boundary value problem under consideration.

Let us assume that it has been solved, i.e., we have determined the relative water velocity inside the distributor:

$$\bar{W}_{\bar{x}} = \varphi(p, q, Ri, \bar{x}) \tag{6}$$

In this case the relative average velocity of outflow from the slot

$$\bar{V}_{\bar{x}} = \frac{V_x}{V_{av}} = \frac{FW_x'}{V_{av}gl} = \frac{FW_b}{V_{av}gl} \times \bar{W}_{\bar{x}}' = \bar{W}_{\bar{x}}', \tag{7}$$

where V_{av} is the average water velocity over the entire area of the slot.

We should note that, in the case of uniform delivery, $\bar{V}_{\bar{x}} = 1$. In a starification accumulator, the distributor provides nonunifrom delivery, as a result of the Archimedes forges, the delivery being characterized by maximum outflow velocity in one extreme section where the difference $\Delta p \approx 0$, and minimum velocity in the opposite one. Allowing for the fact that to eliminate sucking of water into the distributor $\bar{V}_{\bar{x}} \geq 0$, the conditions for which it should be designed are as follows (Fig.1b):

for $Ri = 0 \quad \bar{V}_{\bar{x}} \approx 1$; (8)

for $Ri < 0.5 \quad \bar{V}_{\bar{b}} = 0$; (9)

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$$\text{for } Ri > 0.5 \quad \bar{V}_0 = 0; \qquad (10)$$

A decisive quantity in calculations for the distributor is the nominal slot parameter $\mu\bar{f}$. According to [7], condition (8) is satisfied for $\mu\bar{f} \leq 1$. The nomimal slot parameter such that expressions (9) or (10) are satisfied will be called critical/

Let us establish how $\mu\bar{f}^{cr}$ depends on Ri; for this we simplify the problem somewhat. Let us assume that the length of the distributor is small, and that it has smooth walls, i.e.,$\lambda\bar{l} = 0$. Then Eq. (1) becomes

$$\bar{W}_{\bar{x}}''\bar{W}_{\bar{x}}' + p\bar{W}_{\bar{x}}'\bar{W}_{\bar{x}} = pRi. \qquad (11)$$

For the case $Ri = 0$ the solution of initial differential equation (11) has the following from. With allowance for (5) [7].

$$\bar{W}_{\bar{x}} = \frac{\sin\sqrt{p\bar{x}}}{\sin\sqrt{p}} = \frac{\sin\mu\bar{f}\bar{x}}{\sin\mu\bar{f}}. \qquad (12)$$

Hence the relative outflow velocity is

$$\bar{V}_{\bar{x}} = \bar{W}_{\bar{x}}' = \mu\bar{f}\frac{\cos\mu\bar{f}\bar{x}}{\sin\mu\bar{f}}. \qquad (13)$$

Substituting condition (9) into (13), we find

$$\mu\bar{f}^{cr} = \frac{\pi}{2} \approx 1.57.$$

For $Ri \neq 0$, integration of (11)

$$\bar{W}_{\bar{x}}'' + p\bar{W}_{\bar{x}}^2 = 2pRi\bar{x} + 2C_1. \qquad (14)$$

and the change of variable

$$\bar{W}_{\bar{x}} = \frac{1}{\sqrt{p}}\psi\sin y(\bar{x}) \qquad (15)$$

yields

$$y' + \frac{\psi'}{\psi}\tan y = \pm\sqrt{p}, \qquad (16)$$

where

$$\psi = \sqrt{2pRi\bar{x} + 2C_1}. \qquad (17)$$

Allowing for the that small argument values $\tan y \approx y$, *we* obtain

$$y' + \frac{\psi'}{\psi}y = \pm\sqrt{p}. \qquad (18)$$

The general solution of linear equation (18) is

$$y = \pm\frac{2}{3}\sqrt{p}\left(\bar{x} + \frac{C_1}{pRi}\right) + \frac{C_2}{\sqrt{pRi\bar{x}+C_1}}. \qquad (19)$$

from which we obtain, taking account of (17) and (15),

$$\bar{W}_{\bar{x}} = \sqrt{2Ri\bar{x} + \frac{2C_1}{p}}\sin\left[\pm\frac{2}{3}\sqrt{p}\left(\bar{x} + \frac{C_1}{pRi}\right) + \frac{C_2}{\sqrt{pRi\bar{x}+C_1}}\right]. \qquad (20)$$

Substituting (9), (10), and (5) into (14) and (20), and also allowing for the fact that $\mu\bar{f}^{cr} = 0$, we find

$$\mu\bar{f}^{cr} = \begin{cases} \frac{1.5\pi Ri}{1-(1-2Ri)^{3/2}} & for\ \ Ri \leq 0.5 \\ 1.5Arc\sin\frac{1}{\sqrt{2Ri}} & for\ Ri \geq 0.5 \end{cases} \qquad (21)$$

Formula (21) is approximate, and the error involved in using it increases with the variable $y(\bar{x})$; as follows from (15), it varies on the interval of existence of the arcsine functions, i.e., $|y| \leq 1$. To estiate it's accuracy, differential equation (11) was solved numerically the colocation method.

Experiments aimed at checking the theoretical solutions were conducted on an aerodynamic test stand (Fig.2) with heated air. The length of the air distributor was 1.5 m; the diameter was 0.2 m. A solt 0.05 m wide, equipped with a baffle, was made along it's length. Experiments were conducted for fixed baffle conditions corresponding to $\mu\bar{f}^{cr}$ from 0.3 to 1.5 with a 0.2 step, and were repeated for varying degress of roughness of the inner surface of the air distributor (for which the latter was covered with grinding-cloth).

The air distributor was carefully heat-insulated. The air velocity was measured at six points (Fig. 2) by an EA-2M semiconductor thermoanemometer, while the temperature of the heated air was measured by mercury thermometers and the ambient air temperature by an Asman psychrometer. To ensure accuracy, the air flow rate was determined twice: by a normal choke diaphragm and on the basis of the average outflow velocity, with the results being balanced. An experiment was regarded as satisfactory if the discrepancy of the balance did not exceed $\mp 10\%$. The control and measurement instruments made it possible to measure the temperature to with in ∓ 1℃, the velocity to $\mp 0.1\ m/sec$, and the pressure drop to $\mp 1\ mm\ H_2 0$.

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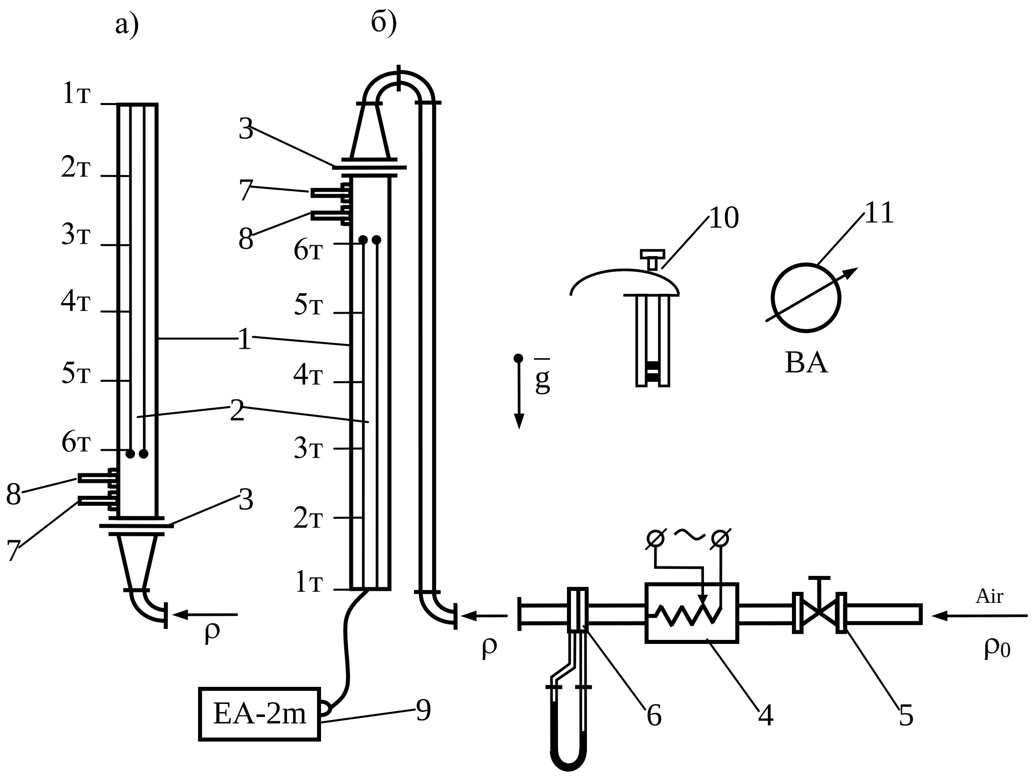

Fig.2. Basic diagram of aerodynamic test stand for investigating distribution under conditions $Ri < 0$ (a) and $Ri > 0$ (b): 1) distributor being tested; 2) longitudinal slot equipped with a baffle; 3) rectifying grid; 4) electric heater; 5) shutoff; 6) normal choke diaphragm with manometer; 7,8) dry and wet thermometers; 9) thermalanemometer; 10) psychrometers; 11) barometer.

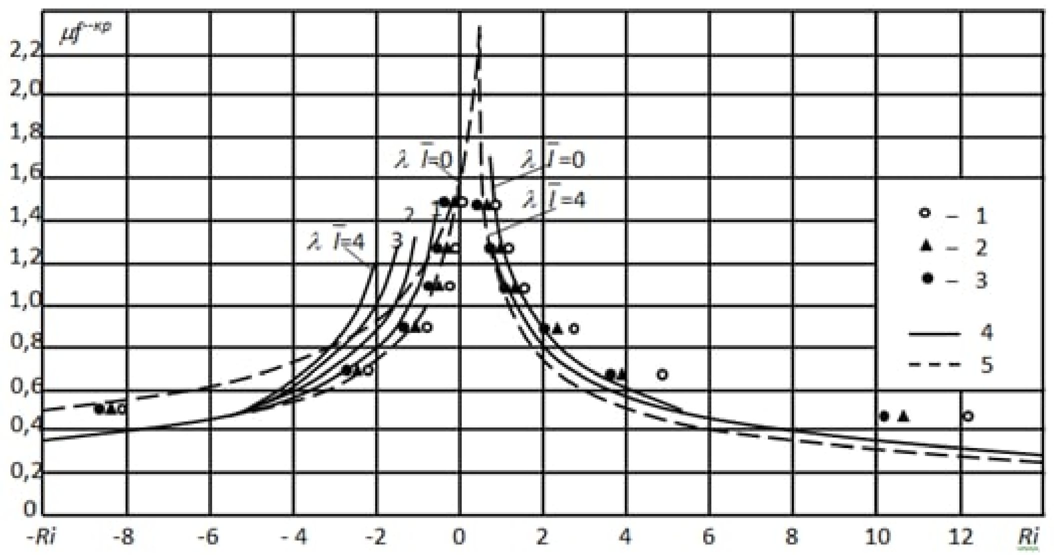

Fig.3. Critical value of nominal slot parameter $\mu\bar{f}^{cr}$ as a function of Richardson numberRi; 1,2,3) experiments for $\bar{\lambda}i = 0.28, 0.30, 0.36$; 4) calculations based on formula (21); 5) computer calculations.

The essential feature of the experiment was determination of Ri for vari ous $\mu\bar{f}^{cr}$. By varying the flowrate and temperature of the heated air, we established outflow conditions from the slot such that $\bar{V}_b = 0$ $(or\ \bar{V}_0 = 0)$, i.e., conditions corresponding to (9) or (10).

As follows from Fig.3, wish shows theoretical plotted on the basis of formula (21) and computer calculations, and also experimental date, the theoretical and experimental findings are in satisfactory agreement.

Formula (21) can be used for making calculations for water distributors for stratification accumulators. The calculations method is similar to that of [8, 9], and therefore we will confine ourselves only to making the sequence of calculations more precise: 1) we calculate d_e, F, and W_b; 2) we determine Ri; , $\mu\bar{f}^{cr}$; 3) we calculate the nominal slot area $f = l\delta = (\mu\bar{f}^{cr})F/\mu$; 4) we determine the number of perforations $m = f/\delta$; 5) we determine the resistance of the water distributor for $Ri > 0$:

$$\Delta p = \Delta p_b + \frac{\rho W_b^2}{2} = \left(\frac{V_b^2}{\mu^2 W_b^2} + 1\right)\frac{\rho W_b^2}{2},$$

and for $Ri < 0$,

$$\Delta p = \frac{\rho W_b^2}{2}.$$

In the calculations it is necessary to specify d_e in such a way that $|Ri| \geq 1.5$; otherwise the condition $\mu\bar{f}^{cr} \leq 1$ (see Fig.3), which follows from (8), will not be observed.

III. NOTATION

W_b, W_x, and W_0 are the water velocities at the beginning of the distributor, in cross section x, and at the end, respectively (m/sec); $\bar{W}_{\bar{x}}$ is the relative water velocity; V_b, V_x, V_0, and V_{av} are the outflow velocity from the slot at the beginning of the distributor, in cross section x, at the end, and as averaged over the area of the slot, respectively (m/sec); $V_{\bar{x}}$ is the relative outflow velocity of the water; x is the distance from the stop end of the distributor to the cross section under consideration; $\bar{x}$ is the relative distance; $l, P, d_e, and\ \delta$ are the length, perimeter, equivalent diameter, and width of the nominal slot of the distributor, respectively (m); $\bar{l}$ is the relative length; F and f are the cross-sectional areas of the distributor and nominal slot (m^2); $\bar{f}$ is the relative area of the slot; δ is the area of a perforation (m^2); m is the number of performations peremeter of length $(1/m)$; $\rho_0\ and\ \rho$ are the entities of the surrounding and distributed water $(kg\ /\ m^3)$; $\Delta\rho$ is the difference in densities $(kg\ /\ m^3)$; $\lambda\ and\ \mu$ are the coefficients of resistance of friction and the flowrate; g is the acceleration due to gravity (m/sec); $\mu\bar{f}\ and\ \mu\bar{f}^{cr}$ are the parameter and critical parameter of the nominal slot; $\lambda\bar{l}$ is the parameter of the water distributor; $\psi, y(\bar{x})$ are functions of $\bar{x}$; C_1, C_2 are constants of integration; p and q are the constant coefficients of the differential equation; and Ri is the modified Richardson number.

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