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Article

Main Problems of Hydrodynamics of a Flat-Plane Solar Collector

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Abstract: In this paper, the relevant hydrodynamic aspects occurring in the implementation of flat-plate solar collectors are reviewed. It studies causes for non-uniform coolant flow distribution, which plays a role in heat transfer and system losses. Particular attention is paid to the formation of air lock, increase of hydraulic resistance and effect of flow situation on overall collector efficiency. It underlines the importance of enhance design of distribution systems, optimal coolant flow and fouling prevents for better performance in solar collector. The reduction or elimination of hydrodynamic problems leads to enhanced reliability and longevity of solar thermal systems.

Keywords: Solar Collector, Hydrodynamic, Efficiency, Optimization, Flow, Circulation.

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1. Introduction

Nonuniform distribution of the coolant flow at a flat plate solar collector. An important hydrodynamic shortcoming of flat-plate solar collectors is the nonuniform distribution of flow among the coolant channels for absorber. This has the disadvantage of serious degradation in system efficiency due to unequal heating of the collector surface and unequal heat transfer between the coolant and absorber plate. Cause of nonuniform distribution are: (i) Inhomogeneities of the hydraulic resistance of the channels due to variations in length, shape [1] or roughness. Improperly designed distribution and collector systems whereby the fluid mostly flows in the nearest channels, with disregard for more distant ones [1]. Variations in the viscosity of the coolant as it heats and impacts flow. The existence of air or vapor locks preventing continuous flow of the fluid. Unequal slope of the collector, stagnation or accelerated flow in some regions. When the surface is not flat, hot and cold spots are produced which detrimental to the overall efficacy of the system. Thermal expansion and material wearing can be accelerated locally in overheated places [2]. The potential for cavitation and production of steam microbubbles also is enhanced. Methods of elimination:

-Optimization of distribution pipeline design (bore increase in supply manifolds, differentiated openings).

The employment of equalizing throttles or hydraulic compensators.

Properly assembly of the collector, and the field slopes for air removal.

The best coolant flow rate is selected for a stable transition in Re (Re ≈ 2000–4000). The use of balancing valves in multi-section systems References [3].

2. Materials and Methods

High flow resistance in flat-plate solar heat exchanger is an obvious disadvantage. The high pressure drops in the absorber channels through which the coolant flows are two of significant hydrodynamic problems in flat-plate solar collector. These losses have a negative impact on the energy efficiency of the system, because higher pump force is required to keep fluid flowing.

Reasons for pressure loss:

Small channel diameter. Hydraulic resistance of small bore tubes It is well known that small bore tubing have significantly higher hydraulic resistance especially at high flow rates.

Long channel lengths. The more run is carried in this cooling channel, the greater is the friction at the end - and therefore also flow resistance pressure drop.

High coolant flow velocity. At higher flow rates, losses increase with the square of the velocity.

Wall surface roughness and wall surface contamination. The smoothness of the surface is prevented by salt formations, corrosion or scale and also resistance will be higher.

Suboptimal pipeline configuration. There are also twists, turns and constrictions that cause local resistance.

Such significant pressure losses may result in: excess energy usage for coolant flow, reduced real coolant flow capacity, resulting in poor heat transfer and lower manifold efficiency; overloading pumps with shortened operating life expectancy, as well as heating certain areas of the manifold due to a decreased coolant supply.

Methods for reducing pressure include: optimizing pipeline design—selecting the ideal diameter and shortest possible pipe length, using smooth materials with low internal surface roughness, employing an efficient manifold connection system (e.g., diagonal—"crossover"), regularly cleaning the system to remove deposits and contaminants, and monitoring coolant velocity and flow patterns to avoid excessive turbulent losses.

3. Results

Turbulent and laminar flow in a flat-plate solar collector . The flow regime of the coolant was one of the dominant parameters that governs the heat transfer and hydraulic behaviors in flat-plate solar collector. The flow may be laminar or turbulent depending on the flow velocity and fluid characteristics. The laminar behaviour is experienced at low coolant flow rates and a description for a regular the motion of layers of liquid that slide over each other without mixing is defined [4].

Mathematical determination of the turbulent regime in a flat solar collector mathematical calculation of hydrodynamics and heat transfer on turbulent flow inside an absorber channel, step-by-step example with explanation of results [5].

1. What are we quantifying and how do we quantify it?

Reynolds number: $R_e=\frac{\rho\mu D_h}{\mu}$

Prandtl number: $P_r=\frac{C_p\mu}{k}$

Friction factor (Haaland, explicit approx .): $\frac{1}{\sqrt{f}}= -1.8\ log_{10}(\frac{\varepsilon/D_h}{3.7}+\frac{6.9}{R_e})$

(Pressure drop (over length L) using Darcy-Weisboch equation: $\Delta_p=f\frac{L}{D_h}\frac{p\mu^2}{2}$

Nusselt number (Dittus-Boelter equation) for turbulent inner-tube flow: $N_\mu= 0.023\ R_e^{0.8}P_r^{0.4}$(for liquid heating)

Heat exchange coefficient: $h = \frac{N_\mu k}{D_h}$

Power required by the pump to compensate losses: $P_{p\mu mp} = \Delta_p \cdot Q$, where Q is the volumetric flow rate .

2. Initial suppositions (example); typical values of 40 ~ Z for water are used; channel in a circle equivalent)

Density of water : p = 992 kg /m^3

Dynamic viscosity: μ=$6.5 \cdot 10^{-4}$Pa · s

Thermal conductivity: k = 0.632 W /(m · K)

Specific heat capacity: C_p=4182 J / (kg · K)

Hydraulic channel diameter: D_h=0.01 m (10 mm)

Average flow velocity: μ=0.5 m / s

Channel length: L = 2.0 m

Wall roughness (copper/smooth surface): ε=$1.5 \cdot 10^{-6}$m

(The volumetric flow rate in such a channel is $Q = \mu \cdot A$, here $A = \pi D_h^2 /4$) . For our values$Q \approx 3.927 \cdot 10^{-5} m^3/s$

3. Step-by-step calculation (numbers – according to the example)

1. Reynolds number: $R_e = \frac{992 \cdot 0.5 \cdot 0.01}{6.5 \cdot 10^{-4}} \approx 7{,}630$ is the turbulent regime (transition/weak turbulence), $R_e > 4000$

2. Prandtl number:$P_r = \frac{4182 \cdot 6.5 \cdot 10^{-4}}{0.632} \approx 4.30$

3. Coefficient of friction (Haaland): $\frac{1}{\sqrt{f}} = -1.8 \log_{10}(\frac{1.5 \cdot 10^{-6}/0.01}{3.7} + \frac{6.9}{7630})$

$\Rightarrow f \approx 0.0337.$

4. Nusselt number (Dittus - Boelter) : $N_\mu = 0.023 \cdot R_e^{0.8} \cdot P_r^{0.4} \approx 52.6$

5. Heat exchange coefficient: $H = \frac{N_\mu \cdot k}{D_h} = \frac{52.6 \cdot 0.632}{0.01} \approx 3.326 W/(m^2 \cdot K)$

(high value - typical for small diameters and moderately turbulent conditions).

6. Pressure loss over a length of L = 2 m : $\Delta_p = f \frac{L}{D_h} \frac{p\mu^2}{2} \approx 836.7 Pa$

7. Volumetric flow rate Q≈ $3.927 \cdot 10^{-5} m^3/s (\approx 0.0393$ L / s ≈ 141.3 L / h).

Pump power to overcome losses (per channel): $P_{p\mu mp} = \Delta_p \cdot Q \approx 0.033W$ (per one narrow channel is very small; in a real system we sum across all channels (sections)

4. Interpretation of results and recommendations

We $R_e \approx 7{,}6 \cdot 10^3$ have weak turbulence, which is much prefered - good heat exchange with not to large pressure losses. Heat transfer coefficient h In the example provides: -The high flow rate mentioned is supported by small diameter bringing a significant effective mean to remove heat from absorber. The pressure losses (≈ 837 Pa for 2m)are moderate and they rise sharply at high flow velocities or small diameters ($\Delta_p \sim \mu^2$ и $\Delta_p \sim 1/D_h$). The pump power per channel is less, but in a multi-channel plate the total power needed (the sum of all channels) can become large [6].

Optimization: - decrease pressure losses (◎ increase dh,decrease pathlength, Decrease speed only if you can do it. Hence, to maximise heat exchange without raising blowing losses: add fins/ turbulators (will increase h and f - tradeoff), or work within the design domain $R_e \approx 3000 - 5000$. Use exact correlations "N_μ and f " for a given cross-section (a flat channel ≠ round pipe; in case of rectangular thin channels certain correction are accounted and the equivalent Dh) Take into account that viscosity depends on temperature_- when water is heated up, μ f drops → R_e is growing, , thermal efficiency/heat losses varies with time as well [7].

1. Reynolds number (Re) for laminar flow: Re < 2300 Re < 2300 Re <2300

2. Advantages: Low pressure loss. Lower energy requirements to pump liquid.
3. Drawbacks: Low degree of turbulence results in poor heat exchange between the absorber and the coolant. Dead zones and over-heating of some portions of the collector are undesireable. Turbulent regime is obtained at high Re and in this case, intense mixing of fluid particles ensures efficient heat transfer [8].
4. Reynolds number (Re) for turbulent bounday flow:Re > 4000 Re > 4000 Re > 4000
5. Advantages: Increased heat transfer coefficient. Uniform temperature distribution across the collector surface.

Cons: Very high pressure drop. Can be used to stimulate pump load and energy consumption of system.

There's a region of transition between laminar and turbulent flow, around Re = 2300–4000, Re = 2300–4000, Re = 2300–4000, the flow goes unstable and is partially even turbulent. [9] stated that the low-turbulence mode is believed to be the optimum mode of operation for flat-plate solar collectors, in which an optimal ratio of heat transfer-to-pressure losses could be reached.

Discussion

The hydrodynamic phenomena occurring in a flat-plate solar collector play an important role on both the thermal performance as well as the reliability during operation. The coolant flow behavior in collector channels is mainly affected by the flow velocity, channel geometry, flow pattern and turbulence intensity [10].

The calculation results indicated that higher flow rate contributed to raising the Reynolds number enabling a transition to turbulent. The turbulent flow allows a more efficient transfer of heat between the absorber and the coolant, but causes higher pressure losses. As a result, it demands more energy for fluid transportation and forceful pumping needs to be provided [11].

In effect, small hydraulic diameter channels feature high heat transfer coefficients but also substantially enhanced hydraulic resistance. For this reason, the most appropriate diameter and length of the channel is a trade-off between thermal resistance and pressure drop [12].

The profile of the channels cross section is important. For flat plate and rectangular channel solar collectors, temperature and velocity distribution varies non-uniformly across the cross-section height. As a consequence, heat transfer coefficient is lower than that of round tubes under the same conditions. To describe the processes properly, corrections have to be introduced which consider the hydraulic diameters and aspect ratios of the channels [13].

Other hydrodynamic phenomena such as air locks, sediment layering in the channel walls and uneven flow distribution in parallel branches of the system appear during collector operation. These factors also decrease the efficiency of this system in general, and remedies in terms of design and operation are needed [14].

Overall, the results of the study show that uniform distribution of coolant flow, optimum channel geometry and identifying the flow regime is crucial to enhance efficiency and reliability of a FPS collectors [15].

4. Conclusion

In this work, we focus on some relevant hydrodynamic problems that arise in the performance of FPCs. The following are the major causes of heat transfer and the general efficiency of the system are as follows:

Wrong distribution of coolant flow, which overheats some parts and impairs collector performance.

Large pressure losses in pipelines result in excessive energy consumption for pumping the liquid and overload of the pump.

-Heat transfer efficiency and hydraulic losses depend on the nature of coolant flow (laminar, transitional or turbulence).

Channels of various shapes and sizes, in particular flat ones with a rectangular cross-section, necessitate the use hydraulic diameter and empirical adjustments for the calculation of heat transfer coefficients and resistance.

The mathematical analysis has shown that an optimal flow velocity, diameter and pipe length can be found where the efficiency of heat transfer and the reduction of pressure loss are significant to a similar extent. Using corrections for rectangular cross-sections and empirical correlations (Dittus-Bölter, Gnelinskiy, Sider-Tate) provides more accurate values of the hy-drodynamic and thermal resistance of reservoir.

To increase the efficiency and reliability of flat plate solar collectors, in general it is recommended:

provide for more uniform flow of coolant within the channels;

keep the process in a state of turbulence as much as possible;

correctly take into account the pipe geometry and the hydraulic diameter in calculations.

If these guidelines are followed, collector performance is enhanced and service life extended, a fact that is of great importance in solar thermal system design.

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