SELF-ACTING AND SELF-REGULATING CIRCULATING PUMP POWERED BY LOCAL HEAT INSTEAD OF ELECTRICITY FOR SOLAR INSTALLATIONS

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1. Abstract

A new technology for heat-transfer agent circulation in the flow circuit of a solar installation is proposed in this article. Devices that are built according to this technology can be called "two-phase reverse thermosyphons with two work-agents". A new innovation is the use of two substances for doing two different actions. Liquid water or its solutions are used for heat transfer and the vapour of a low-boiling substance (such as pentane or butane) is used to force circulation of the heat-transfer agent in the loop. In comparison with other known reverse thermosyphons, a very small quantity of a low-boiling substance (about 10-40 g per 1 kW of heat transfer power) is needed to create the vapour and force circulation. Thanks to this new technology, solar installations do not need electrical circulating pumps with control systems and they can be independent from any power grid. Full-sized experimental examples of the devices have been successfully tested under laboratory conditions and in combination with an experimental solar installation. Such devices have good perspectives for practical use.

2. Introduction

Solar collectors are usually situated above tank-accumulators at solar installations. A fluid circuit and an electrical circulating pump are needed for downward heat transfer. Electrical components are the most accident-sensitive elements and solar installations are liable to be damaged when an electrical supply is lost or the solar radiation is excessive. Moreover, electrical pumps and their control systems account for around 20% of the cost of solar installations for a detached house. Therefore, designing circulating pumps which are fail-safe, cheap and independent of external energy sources is an important task to improve solar installations. Many attempts have been made to create passive circulating loops for solar installations, which have been described previously (Dobriansky 2011). Saturated pressure vapour is used in most of the proposals for passive downward heat transfer. Such devices are called "two-phase reverse thermosyphons".

Reverse two-phase thermosyphons (which transfer heat downward) and ordinary two-phase thermosyphons, (which transfer heat upward) share some similar features; namely, that two kinds of heat-transfer agent (liquid or vapour) can be used in both kinds of devices.

Vapour is preferred for use in ordinary thermosyphons because it contains a great amount of latent heat. This means that small amounts of vapour are needed with lower hydraulic resistance during vapour flow, there is a lower difference in saturated vapour pressure and less than 1 K difference in temperature is necessary for forcing the vapour flow from evaporating aria to the condensation area. The condensate is simply returned via gravity.

A much greater difference in temperature is needed for reverse thermosyphons because the difference in saturated vapour pressures should be great enough (about 50-100 kPa) to overcome the weight of a column of a condensate with a height of 5-10 m. Nevertheless, a requisite difference in temperature of about 5 – 20°C is acceptable and such solar installations have been built and successfully operated for several years (De Beni and Friesen 1993). The main shortcoming of the installation is the great quantity (about 20 dm^3 of refrigerant) which is needed to fill installation. If water is used instead of refrigerant, pressures below atmosphere pressure should be kept in the installation. Such an experimental installation had a vertical distance of heat transfer downward in the range of 1–2 m and it operated at a collector temperature of 70–90°C (Roonprosag et al. 2008). It unlikely that both of the above-mentioned construction options will be widely applied in practice.

Much less difference in pressure is needed to force reverse circulation when liquid water is used as a heat-transfer agent. This difference is similar to the pressure which causes natural convection and the requisite difference of temperature can be less then 1 K. An additional certain difference in temperature between the hot and cold branches of a loop is needed for containing and carrying heat. Comparison of the heat flow in the technical pipes with water heated by 5 K water and with water vapour with atmospheric pressure has shown that their values are similar (Dobriansky and Yohanis 2011). Therefore, two-phase reverse thermosyphons with liquid water or with its solutions can have acceptable effectiveness. Such a reverse thermosyphon has been built and tested with water as a work-agent (Dobriański J. et al., 2004).

3. Principles of operation of a two-phase reverse thermosyphon with a single work-agent and a liquid heat-transfer agent

If liquid is used as a heat-transfer agent, a great difference in pressure is not needed to force the liquid motion because the difference between the weight of the hot and cold liquid columns is small when both branches are filled with liquid. For example, within the temperature range of 20ºC to 100ºC, the working pressure which is caused by the difference between the specific densities of the liquid water is only 0.1–0.4 kPa (12–38 mm H_2O) when the temperature difference is 5 K and the height of the loop is 10 m. In contrast, the difference in the pressure of saturated water vapour ranges from 0.85-20 kPa for the same conditions. Therefore, the difference in saturated vapour pressure between the hot and cold branches can overcome the natural convection forces and can move the hot liquid in a direction opposite to the direction of natural convection (Fig. 1).

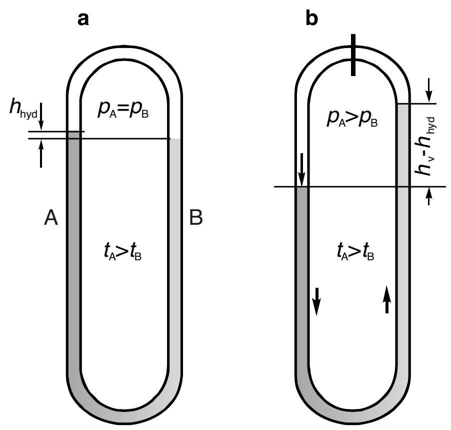

Fig. 1: Liquid levels in a loop partly filled by liquid:
(a) Action of liquid density difference when the upper part of the loop is open;
(b) Action of saturated-vapour-pressure and liquid-density difference when the upper part of loop is blocked

When the level of liquid in the cold branch increased, the excess cold liquid has the possibility to flow down from the top of the cold branch to the top of the hot branch through an additional intermediate channel which must be located between the cold and hot branches and the upper part of the circulation loop (Fig. 2). This phenomenon takes place when the control valve is unblocked for the vapour pressure balance in both branches.

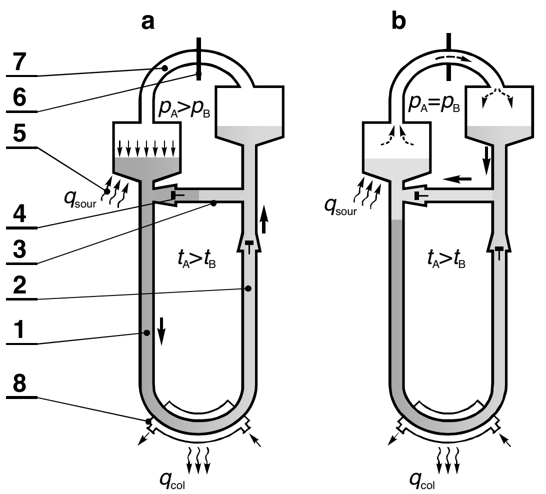

Fig. 2: Scheme and stages of action of the device:
1 – hot lowering branch, 2 –cold rising branch, 3 – intermediate canal, 4 – non-return valve, 5 – heat source, 6 –control valve (liquid seal), 7 – upper part of the loop, 8 – cooler, a – pumping stage (hot liquid flows downward), b – drainage stage (cold liquid flows to hot branch)

Therefore, the device operates in a two-stage cycle:

- heating the upper part of the hot branch and pushing the hot liquid downward results in a rise in the liquid level in the cold branch (see Fig. 2a),
- opening the upper part of the circulation loop results in an equilibrium of vapour pressure between both branches and a pouring off an excess of cold liquid through the intermediate canal to the upper part of the hot branch via gravity (see Fig. 2b).

The upper parts of each branch are widened to allow a greater portion of liquid to be pumped during each cycle, i.e., to allow them to act as reservoirs. The directions of liquid flows in the main part of the loop and in the intermediate canal are maintained by the placement of non-return valves. A liquid seal is used as a special control valve for the periodic opening and closing of the upper part of the circulation loop (Fig. 3). When the liquid level reaches the upper bend of the siphon (3), the dosing vessel of liquid seal is filled with liquid by siphon action (3) and the vapour flow is blocked. The passage between the hot (1) and cold (2) branches opens through the passage pipe (5) when the pressure in the hot vessel becomes sufficient to force liquid out from the passage pipe (5).

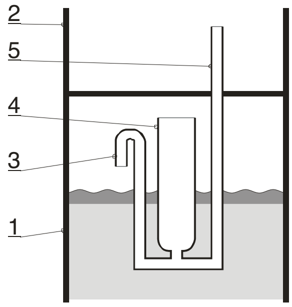

Fig. 3: Scheme and stages of action of the device:
1 – hot vessel, 2 – cold vessel, 3 – filling siphon, 4 – dosing vessel, 5 – passage pipe

The maximum vertical distance for downward heat transfer by this system was calculated for different working fluids, falls in the range of 70-600 m and is shown in Fig. 4.

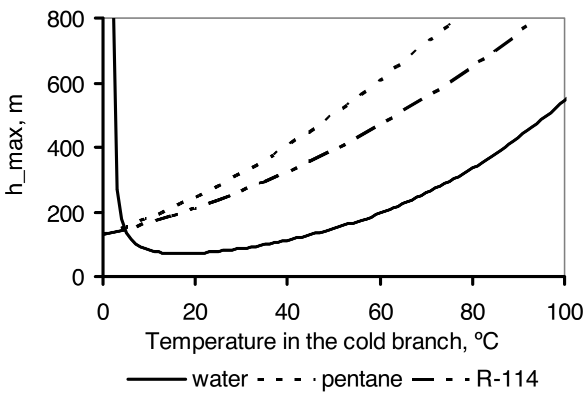

Fig. 4: Maximum vertical distance for heat transfer calculated at a temperature difference of 5 K for different working fluids

An analysis of the characteristics of the proposed device showed that heat transfer capacity is 1-4 kW, when the portion of pumped water is ΔV = 1 liter, cycle duration is τ_c = 20 s and the temperature difference between the branches is Δt = 5 K

Other estimated physical characteristics of the device were: the pressure needed to overcome inertial forces, p_{acc} = 200 Pa = 2 cm H_2O; the pressure needed to overcome the hydraulic resistance of a 15-metre loop is

Δp_{hydr} = 1,320 Pa = 13 cm H_2O; and the work necessary for liquid lifting W_{lift} = 0.1 W.

Experimental testing was done with working models, both under laboratory conditions and when adapted to a solar thermal installation. The first model was made with water as a working fluid. The aim of the first model was to confirm the operability of the device and identify any major shortcomings of the design. The operability of the device was successfully confirmed, with heat transferred downward at rates of 80-280 W [Dobriański J. et al., 2004].

Air leakages are the main shortcoming which caused noticeable increases in temperature differences between the branches. If the working temperature is in the range of 0-100°C, the pressure of saturated water vapour is below atmospheric pressure, thus air appears from leaks due to construction imperfections and also as the result of extraction of dissolved air from the water heat-transfer agent. Air gradually accumulates in the cooler part of the installation, blocking access of the vapour to cold surfaces and retarding the process of condensation.

4. Two-phase reverse thermosyphon with two work-agents and a liquid heat-transfer agent

An additional low-boiling substance was introduced in the device to increase the pressure to above the atmospheric pressure inside the device. The amount of the pumping substance should be not less than that which is necessary to fill the remaining volume of the circulating loop which is unoccupied by the liquid heat-transfer agent with vapour of the pumping substance and to fill the drainage pathway of the condensate which leads from the condensation area to the evaporation area. The density of the pumping substance should preferably be less than the density of the heat-transfer agent.

Hydrocarbons (such as pentane or butane) can be used as the low-boiling substance. The two-phase reverse thermosyphon with two work-agents must have means for evaporation and condensation of the low-boiling substance as well as means for returning the condensate to the evaporation area. The evaporation and condensation can be done at the site of direct contact of the low-boiling substance with the hot and cold heat-transfer agent. A moveable inlet to an intermediate channel, which is being supported just below the liquid surface in a cold fluid vessel with help of floats, or collecting funnel can be used as a means for transportation of condensate from the condensation area to the evaporation area. A scheme of the device is shown in fig. 5.

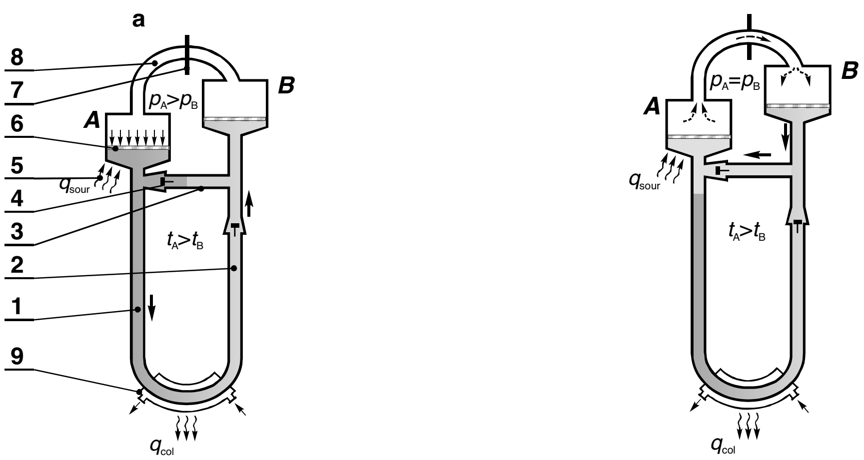

Fig. 5: Scheme and stages of action of the device:
1 – hot lowering branch, 2 – cold rising branch, 3 – intermediate canal, 4 – non-return valve, 5 – source of heat, 6 – layer of low-boiling liquid, 7 – control valve (liquid seal), 8 – passage pipe in the upper part of the loop, 9 – cooler, A – hot fluid vessel, B – cold fluid vessel, a – push stage (hot liquid flows downward), b – drainage stage (cold liquid flows to the hot branch

Figure 5 is a photograph of the laboratory installation; and figure 6 shows the system of operating temperatures when the heating power is 700 W and the maximum temperature is limited to 65°C.

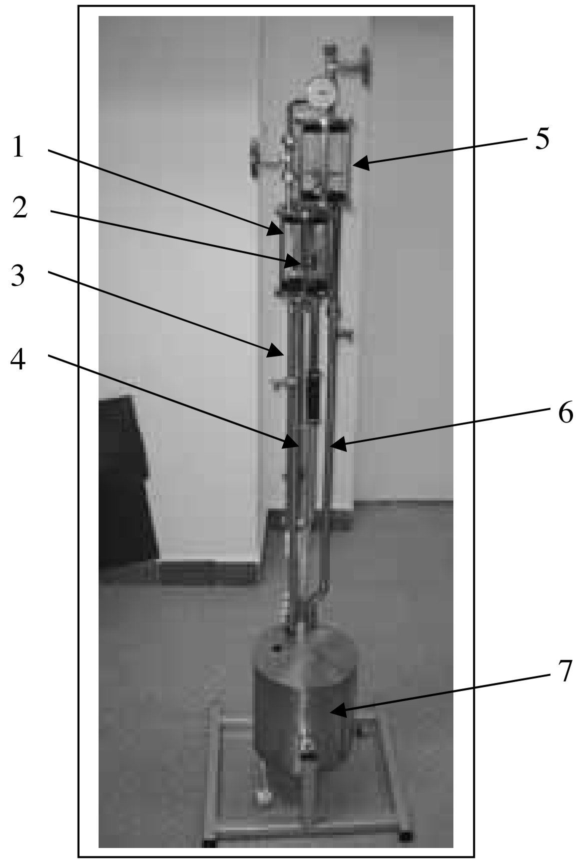

Fig. 1. Photograph of laboratory installation:
1 – hot fluid vessel, 2 – control valve and intermediate canal, 3 –1500 W heater with temperature controller, 4 – hot down-flow pipe, 5 – cold fluid vessel, 6 –cold up-flow pipe, 7 – cooler (accumulator tank)

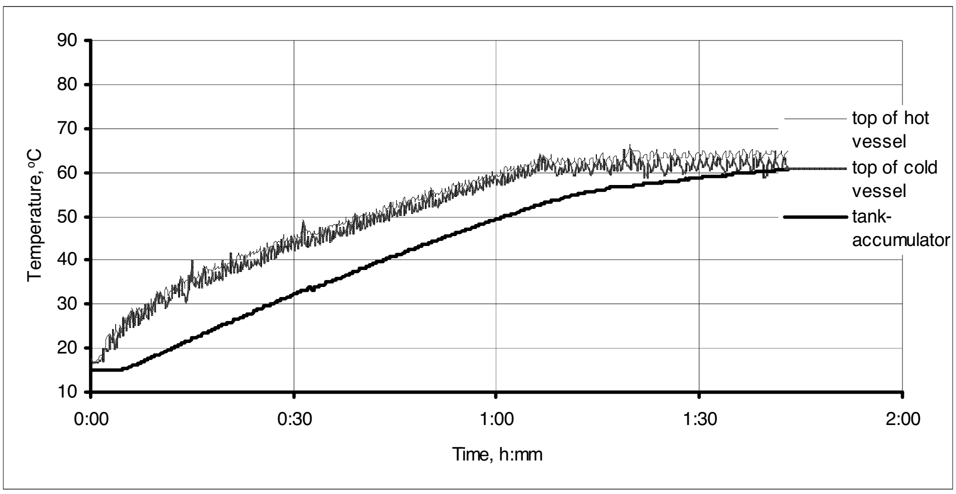

Fig. 6. Operating temperatures at the tops of hot and cold vessels and in accumulator tank at a heater power of 700 W with a solution of propylene glycol as the heat-transfer agent

The changing temperatures at the tops of the hot and cold vessels are evidence of the cyclical character of the device in operation. Water and a water solution of propylene glycol were used as heat-transfer agents.

Figure 7 shows the hot and cold vessels which were integrated into a solar thermal installation.

Fig. 7. Photo of the upper part of self-acting circulating pump integrated into a solar installation

Figure 8 shows the operating temperatures at the tops of the hot and cold vessels and in the accumulator tank (300-L capacity) situated 15 meters below the collectors as well as the magnitudes of solar irradiance (W/cm^2).

Fig. 8. Operating temperatures of the tops of hot and cold vessels and accumulator tank of the proposed device, and the magnitudes of solar irradiance

5. Conclusions

The innovative aspect of this two-phase reverse thermosyphon is the addition of a small quantity (a few dozen grams) of the second low-boiling work-agent that gives the possibility of using water and water solutions as heat-transfer agents without the risk of retarding the process of condensation due to air leakage into the system. Thanks to this new technology, solar installations do not need electrical circulating pumps with control systems and they can be independent from the power grid. Full-sized experimental examples of the devices have been successfully tested under laboratory conditions and in combination with an experimental solar installation. Such devices have good perspectives for practical use.

6. References

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