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INTERNATIONAL

Theoretical and Experimental Validation of Evacuated Tubes Directly Coupled with Solar Still[1]

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Abstract– Experimental study of evacuated tubes coupled solar still in the climatic conditions of Mehsana, a region of North Gujarat, India during summer and winter climate conditions has been made. Experimental setup was made by authors. Fourteen double-walled hard borosilicate glass tubes have been used. Evacuated tubes were inclined at angle of 45° from horizontal. Outer tubes of evacuated tubes were transparent, inner tubes were coated with a selective coating of Al-Ni/Al compound for better solar radiation absorption and minimum emittance. It has been shown that evacuated tube attachments to the solar still increased the water temperature inside the solar still for increment in the generation of distillate output. Evacuated tubes coupled solar still is not only produce distilled water during sunshine hours, but also off-sunshine hours due to heat storage effect. For the validation of the experimental results, a theoretical model is proposed based on the fundamentals of heat and mass transfer equations for solar still glass cover, water in basin and basin bottom. Two main statistical parameters—root mean square error and mean bias error—were calculated to compare the results of experiments and theoretical analysis. Closed matching of the experimental and theoretical results has been found.

Keywords: solar still, theoretical analysis, evacuated tubes, distillate output
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Only one percent of the Earth water is potable water, hence there is a strong need to work on a solar distillation, for the conversion of saline or brackish water into the drinkable water. Sampathkumar et al. [1] had designed and fabricated passive solar still with evacuated tube collector and tested in climate conditions of Coimbatore, India. They took various readings from June 2009 to March 2010. They found that, the distillate output of a solar still with vacuum tubes. They concluded that, distillate output of a solar still integrated with evacuated tube collector found always more than conventional solar still. Panchal and Shah [2] used single basin solar still and compared with various depths of water and found optimum water depth of 0.03 m. Panchal and Shah [3] tested three different solar stills with different glass cover thicknesses and found lower glass cove thickness is more productive. Shobha et al. [4] conducted several experiments with various depths of brine on solar still. They also carried out a theoretical analysis of passive solar still with vacuum tubes with experimental results and received a good agreement. Xiong et al. [5] fabricated multi-effect solar still with enhanced condensation surface in climate conditions of China. They took corrugated shape stacked trays for reducing condensation resistance and increasing distillate output. They also conducted a numerical analysis of the present still and compared with experimental results and received a good agreement with numerical results and experimental results. They found average 5.5 kg distillate output.

Omara and Eltawil [6] had integrated passive solar still with solar tracking system installed parabolic dish collector and boiler. They tested such system during six months in climate conditions of Egypt and found 244% and 347% increment in distillate output with and without the use of solar tracking system with parabolic dish collector. Kargar Sharif Abad et al. [7] had carried out several experiments with pulsating heat pipe integrated with a solar still. Pulsating heat pipe had benefit like flexible and higher performance thermal conducting device, etc. They concluded that, distillate output of the present still is increased by 40% by use of pulsating heat pipe compared with conventional solar still. Many research works done in Gujarat for increment in distillate output on solar still [2, 3, 8–22].

The main problem of the solar still is a lower distillate output. Because, the water and glass cover temperature difference is found lower in case of conventional solar still. It can be increased by supplying hot water through solar flat plate collector. But the effi-

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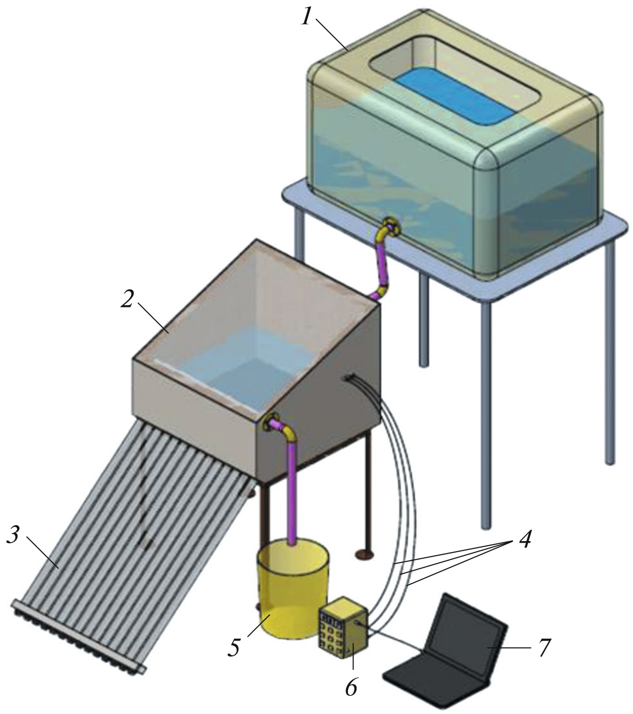

Fig. 1. Schematic diagram of evacuated tubes coupled solar still. *1*—Feeder tank; *2*—solar still; *3*—vacuum tubes; *4*—thermocouples; *5*—measuring jar; *6*—data logger; *7*—computer.

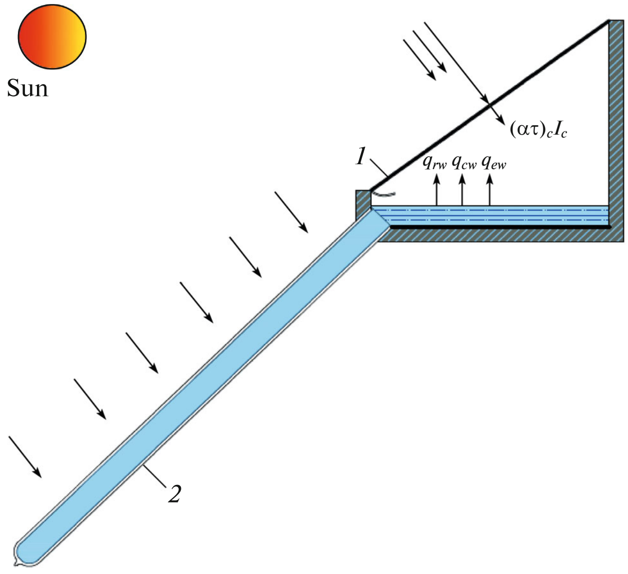

Fig. 2. Schematic diagram of energy flows in the installation. *1*—Glass cover; *2*—vacuum tubes.

ciency of flat plate collector is lower, hence evacuated tubes are used in the present experiment. Hence, fabrication of the evacuated tubes coupled solar distillation system by locally available materials and tested in actual climate conditions to see its performance. A series of experiments were conducted during the month of April 2012 and considered these days whose climate conditions are moreover similar and compared with the theoretical analysis to see the validation.

EXPERIMENTAL

A schematic diagram of the experimental setup of passive solar still with vacuum tubes is shown in Fig. 1. The system consists of an evacuated tube coupled solar still. The solar still with an effective basin area of 1 m^2 used in this study and mounted on an iron base. It consists of an airtight basin, usually made of polyurethane foam (PUF). The PUF thickness is about 0.05 m and thermal conductivity is about 0.221 W/(m K) has been considered in the present analysis. The basin liner is painted black to increase absorptivity to radiation. Transparent glass cover (thermal conductivity of 0.76 W/(m K) with thickness of 0.004 m with an inclination of 23° (latitude of Mehsana) to the horizontal fixed to the top and sealed with Silicon rubber to make it airtight to prevent vapor leakage. Fourteen numbers of double-walled hard borosilicate glass tubes with 1.6 mm thickness, inner diameter of 0.047 m, outer diameter of 0.058 m, and a length of 1.5 m used for present experiment. The outer tubes of evacuated tubes are transparent and allowing light rays to fall through it. The inner tubes are coated with a selective coating of aluminum nickel alloy compound (Al-Ni/Al) for better solar radiation absorption (>93%) and minimum emittance (<6%). An evacuated tube or vacuum tubes consist of a number of concentric borosilicate tubes inclined at angle of 45° from horizontal.

Fourteen numbers of tubes coupled with lower curved portion of solar still with help of rubber bush. To prevent breakage of glass tubes at bottom, capital is provided therefore, direct contact of floor and tubes is minimized. These tubes transfer the heat to water filled inside through its contact peripheral surface. The hot water rises up due to low density, whereas; the cold water gets its position due to gravitation and high density of solar still as shown in Fig. 2. The circulation flow rate within the collector loop is determined by the instantaneous solar energy input, fluid temperature and the collector configuration. The orientation of the complex system is assumed to be kept south in order to receive maximum solar radiation throughout the year. This setup requires three thermocouples for measurement of water, inner glass cover and ambient temperature. Here, vacuum tubes are attached with passive solar still; hence solar intensity falling on vacuum tubes is also needed along with radiation falling on solar still. Temperatures and solar radiations falling on solar still and evacuated tubes are recorded by the data logger.

THEORETICAL ANALYSIS OF EVACUATED TUBES COUPLED SOLAR STILL

Theoretical analysis is based on the energy balance equations. Hence, the energy balance for each component of the present system in thermo-syphon mode has been carried out with the following assumptions:

(a) the solar still unit is vapour leakage proof;

(b) heat capacities of glass and basin material are negligible;

(c) temperature dependent heat transfer coefficients have been studied in the present experiment;

(d) side heat loss from the solar still is ignored;

(e) there is no thermal stratification across the water depth;

(f) attenuation of solar radiation within the water mass is considered;

(g) initial values of water and inner glass cover temperatures have been used to determine internal heat transfer coefficients;

(h) the system operates in a quasi-steady state regime during day time;

(i) water level in the drainage area of a solar still kept constant;

(j) process is quasi steady-state.

Energy balance of glass cover in evacuated tubes coupled solar still. The sum of the radiation absorbed by the inner glass cover surface and heat transferred from the water to glass surface is equal to the rate of conductive heat transfer from the inner glass cover surface to the outer glass screen surface.

$$\alpha_g I_s + h_1 (t_w - t_{ci}) = \frac{K_g}{L_g}(t_{ci} - t_{co}), \tag{1}$$

where α_g is the absorptivity of glass cover; I_s—insolation on solar still with coupling of vacuum tubes, W/m^2; h_1—total heat transfer coefficient, W/(m^2 K); t_w—Temperature of water inside passive solar still; t_{ci}, t_{co}—temperatures of inner and outer sides of glass cover, °C; K_g—thermal conductivity of glass cover, W/(m K); L_g—thickness of glass cover, m.

Energy balance of water mass in evacuated tubes coupled solar still. The amount of radiation absorbed by water mass and heat stored from basin liner to water equals to the amount of heat stored in water and high temperature transfer from water surface to glass surface:

$$\alpha_w (1 - \alpha_g) I_s + h_2 (t_b - t_w) + Q_u = (MC)_w \frac{dt_w}{d\tau} + h_1 (t_w - t_{ci}), \tag{2}$$

where α_w—the absorptivity of water; h_2—heat transfer coefficient from glass cover to water, W/(m^2 K); t_b—temperature of basin, °C; $(MC)_w$—heat stored by the water, kJ/kg; τ—time, s;

$$Q_u = F_R \left[(\alpha\tau)_c I_c - U_{LC} \frac{A_s}{A_{ET}} (t_w - t_a) \right], \tag{3}$$

—heat gained by vacuum tubes when coupled with passive solar still, kJ; F_R—collector heat removal factor; $(\alpha\tau)_c$—effective transmittance-absorptance product of vacuum tube collector (supposed 0.87 in calculations); I_c—insolation on vacuum tube collector, W/m^2; U_{LC}—total heat transfer loss coefficient for vacuum collector, W/(m^2 K); A_s, A_{ET}—area of solar still and vacuum tube collector, m^2; t_a—ambient temperature, °C.

Energy balance of basin in evacuated tubes couple solar still. Solar radiation absorbed by the basin liner is equal to the amount of heat transfer to the water by convection and high temperature transfer from basin side surface to the ambient. Here, side loss is low, therefore; it is not taken into thoughtfulness.

$$\alpha_b (1 - \alpha_g)(1 - \alpha_w) I = h_2 (t_b - t_w) + U_b (t_b - t_a), \tag{4}$$

where α_b—absorptivity of basin; I—insolation on passive solar still, W/m^2; U_b—bottom loss coefficient for passive solar still, W/(m^2 K).

Convective heat transfer rate, convective heat transfer coefficient, evaporative heat transfer rate, evaporative heat transfer coefficient, radiative heat transfer rate and radiative heat transfer coefficient [3] can be calculated by

$$q_{cw} = h_{cw}(t_w - t_{ci}); \tag{5}$$

$$h_{cw} = 0.884 \left[(t_w - t_{ci}) + \frac{t_w (p_w - p_{ci})}{268.9 \times 10^2 - p_w} \right]^{\frac{1}{3}}; \tag{6}$$

$$q_{ew} = h_{ew}(t_w - t_{ci}); \tag{7}$$

$$h_{ew} = 0.016273\ h_{cw} \left(\frac{p_w - p_{ci}}{t_w - t_{ci}} \right); \tag{8}$$

$$h_1 = h_{rw} + h_{cw} + h_{ew}; \tag{9}$$

$$q_{rw} = \varepsilon_{eff} F_{12} \sigma \left(t_w^4 - t_{ci}^4 \right); \tag{10}$$

$$h_{rw} = \varepsilon_{eff} \sigma \left(t_w^2 - t_{ci}^2 \right)(t_w + t_{ci} + 546), \tag{11}$$

where p_w, p_{ci}—water pressure and partial pressure of steam near glass cover; ε_{eff}—emissivity of glass cover;

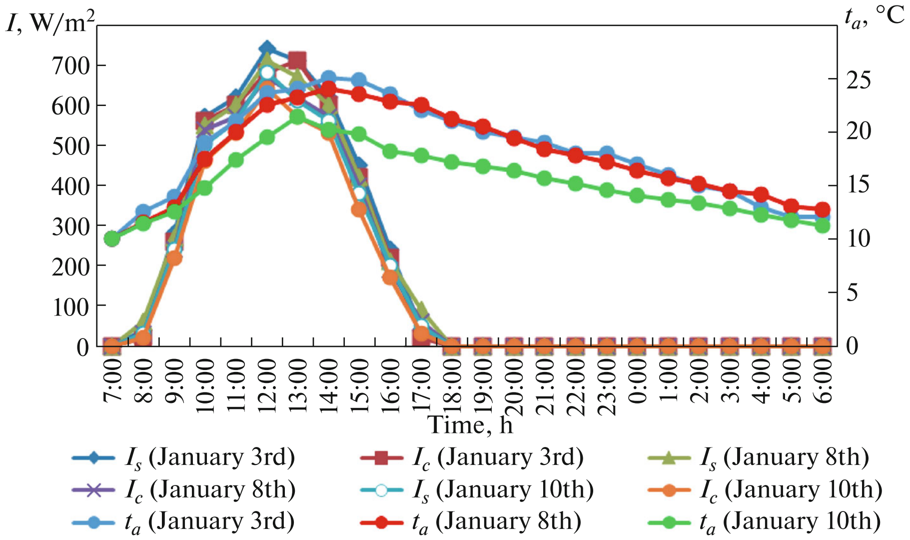

Fig. 3. Hourly variation of solar intensity and ambient temperature for evacuated tube coupled solar still during winter experimental days (January 3rd, 8rd and 10rd 2012).

F_{12}—form factor; σ—Stefan-Boltzmann constant, W/(m^2 K^4).

Hourly distillate output of the present still is [11]

$$m = \frac{h_{ew}(t_w - t_{ci})}{L}3600A_s. \tag{12}$$

The daily distillate output is [11]

$$M_{ew} = \sum_{j=1}^{24} m_j, \tag{13}$$

where j—hours of day.

STATISTICAL TOOLS

There are mainly two statistical tools like Root mean square error (RMSE) and Mean bias error (MBE) used to compare the experimental and theoretical analysis.

$$\mathrm{RMSE}=\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{X_i - Y_i}{Y_i}\right)^2}; \tag{14}$$

$$\mathrm{MBE} = \frac{1}{N}\sum_{i=1}^{N}\frac{X_i - Y_i}{Y_i}, \tag{15}$$

where N is the number of readings, X_i is the theoretical readings obtained from the thermal analysis and Y_i is the experimental readings obtained from the experimental works.

Coefficient of correlation is given by [11]

$$r = \frac{N\sum(X_iY_i) - \left(\sum X_i\right)\left(\sum Y_i\right)}{\sqrt{N\sum X_i^2 - \left(\sum X_i^2\right)}\sqrt{N\sum Y_i^2 - \left(\sum Y_i^2\right)}}. \tag{16}$$

RESULTS AND DISCUSSION

In this present work, many trials were carried out continuously for 24 hours. Figures 3 and 4 demonstrate the solar insolation and ambient temperatures versus time measured on January 3rd, 8th and 10th and May 5th, 7th (winter series) and 9th, 2012 (summer series). These days are chosen for the study, the intellect is the solar insolation and ambient temperatures of such days are found quite similar. It is distinctly indicated that the ambient temperatures and solar insolations are the main parameters for the prediction of clear idea around the public presentation of a solar still. Upper limit temperature and maximum insolation both found between 1 and 3 p.m. due to the winter climate and summer climate conditions. And after passing the maximum values, both starts decreasing.

Water temperature is a main parameter for the increment in performance of some solar still. The higher water temperature inside the solar still, leads to the increment in air temperature inside the cavity between the basin and glass cover area. Likewise, lower glass cover temperature inside the still also leads to the increase in distillate output. But it can be maintained by various processes [11]. Hence, the performance of any solar still depends on the water temperature inside the basin. Figure 5 shows the water temperature of evacuated tube coupled solar still during summer and winter days.

Figure 6 shows the comparison between the theoretical distillate output and experimental distillate output obtained from the evacuated tube coupled solar still during summer and winter climate conditions. It can be seen that, there is a good similarity between the results obtained during the theoretical and experimental results. And it can be clearly found from the values

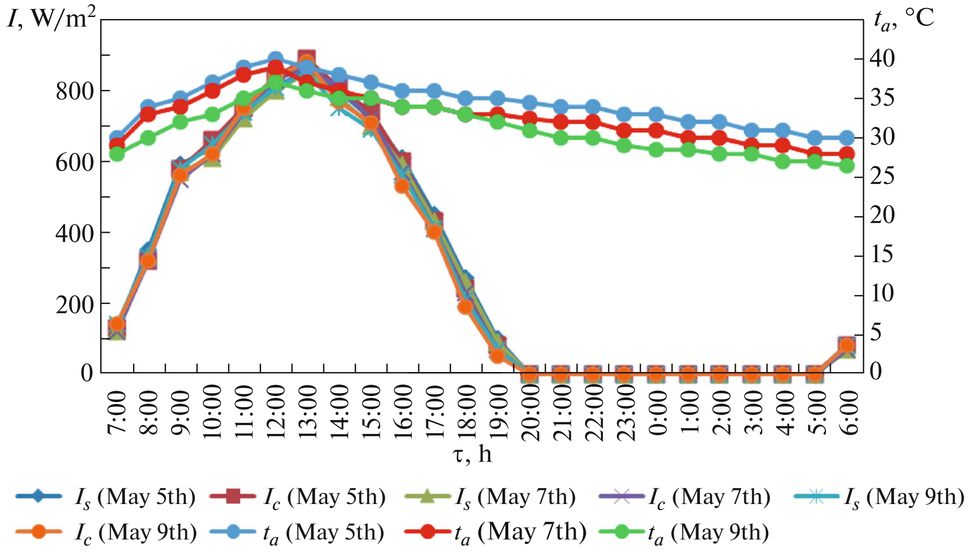

Fig. 4. Hourly variation of solar intensity and ambient temperature for evacuated tube coupled solar still during summer experimental days (May 5th, 7th and 9th 2012).

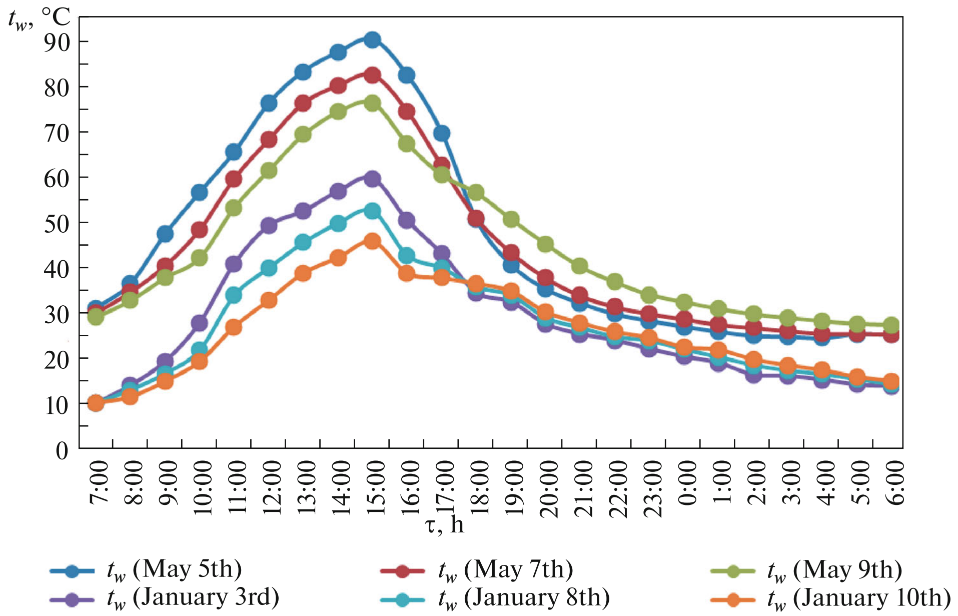

Fig. 5. Hourly variations of water temperature on varying depth of water for evacuated tube coupled solar still during summer and winter experimental days (May 5th, 7th, 9th and Jan 3rd, 8th, 10th 2012).

obtained by root mean square error (RMSE), mean bias error (MBE), coefficient of correlation (r):

	Summer	Winter
RMSE, %	13.97	15.3
MBE, %	3.73	4.07
Coefficient of correlation r	0.997	0.983

CONCLUSION

(1) There is a good similarity of experimental and theoretical results of evacuated tube coupled solar still during summer and winter climate conditions.

(2) Evacuated tube attachments to the solar still increased the water temperature inside the solar still for increment in the generation of distillate output.

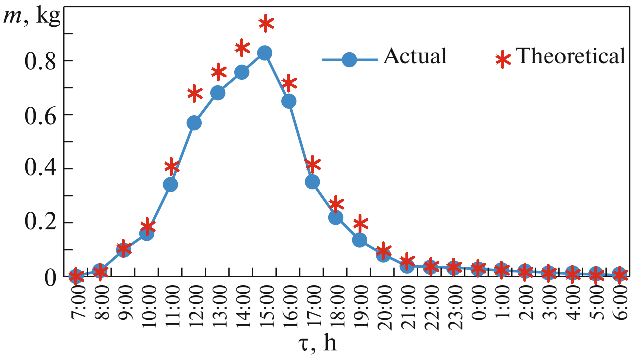

Fig. 6. Hourly variations of theoretical and experimental distillate output for 0.04 m depth of water inside the evacuated tube coupled solar still during summer experimental day (May 7th, 2012).

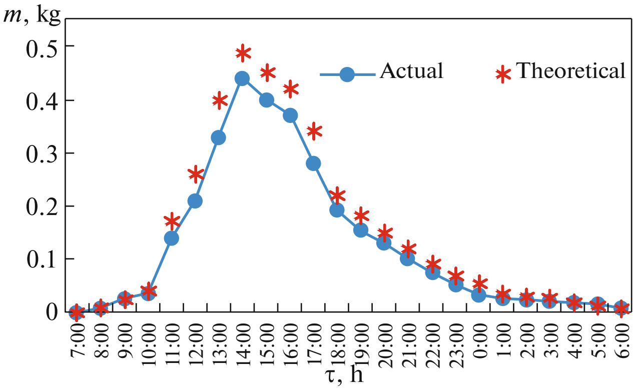

Fig. 7. Hourly variations of theoretical and experimental distillate output for 0.03 m depth of water inside the evacuated tube coupled solar still during winter experimental day. (January 3rd, 2012).

(3) Polyurethane foam type insulation (5 cm) gives better heat resistant in the solar still for the generation of distillate water. Evacuated tubes coupled solar still is not only produce distilled water during sunshine hours, but also off-sunshine hours due to heat storage effect.

(4) Evacuated tubes reduce the heat loss, hence maximum solar energy is utilized for increment in water temperature and hence, the distillate output. Evacuated tubes can be used for other geometrical shapes like circular, square, semi-circle for increment in distillate output.

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