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Engineering Study and Equipment Design: Effects of Temperature and design variables on Yield of a Multi-Stage Distillator

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***Abstract*—**The distillation process in the general sense is a relatively simple technique from the standpoints of its principles. When dedicating distillation to water treatment and specifically producing fresh water from sea, ocean and/ briny waters it is interesting to notice that distillation has no limitations or domains of applicability regarding the nature or the type of the feedstock water. This is not the case however for other techniques that are technologically quite complex, necessitate bigger capital investments and are limited in their usability. In a previous paper we have explored some of the effects of temperature on yield. In this paper, we continue building onto that knowledge base and focus on the effects of several additional engineering and design variables on productivity.

***Keywords*—**Distillation, Desalination, Multi-Stage still, Solar Energy

I. Introduction

IN the first part of this work, we have developed and fabricated an instrumented single tray distillation apparatus. We have reported some rather interesting findings on the effects of temperature on the production rate of the distillation apparatus [1]. Naturally, some of the key characteristics of this distillation instrument are that the equipment is simple, easy to operate, needs no maintenance and produces high quality distilled water.

Further and as mentioned in the first part of this research, the multiple tray distillation process has been investigated with most emphasis and focus directed to theoretical modeling aspects of the process, see for example the works of Yuan et al [2], Jubran et al. [3], A. Khedim [4], Garg et al [5], B. Bouchekima [6], and Shatat et al. [7]. It is also worthwhile pointing out that in these studies and others [8]-[11], the " pan" type tray with stagnant fluid configuration is the most widely used and studied design. We have looked at a different design and wish to generate more interest and work in this area. Our goal at this point in time is to contribute to these efforts by generating actual experimental data to quantify the effects of the engineering and design variables on the throughput of the single/multiple tray distillation apparatus. Further, our distillation apparatus for the moment is mounted with one single tray. Investigation of the twin, triple or multiple tray system will be covered separately.

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Using the same laboratory apparatus and set up as that reported in our previous work, this present work explores the effects of several design features/variables on the performance characteristics of the single tray distillation process.

II. Experimental

A. The apparatus

The experimental distillation system consists of two components: The distillation unit and an external water distribution system for the boiler and for feeding the distillation trays. Details of the distillation apparatus are shown in Figure 1.

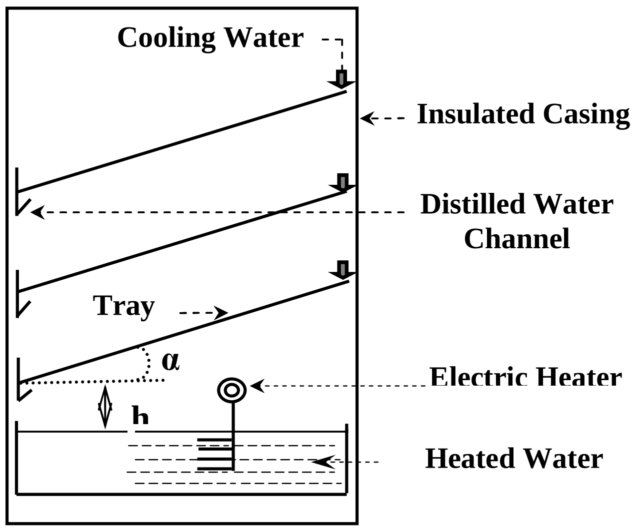

Fig. 1 Schematic Diagram of the Distillation Apparatus nonlinear

The inside dimensions of the insulated distillation casing are 630 mm in height, 350mm in width and 230 mm in depth. The first tray of the distillation apparatus is positioned at a height "h" above the water bath level and tilted at an angle "α". The width of the tray is prescribed by the depth of the distillation enclosure. The length of the tray on the other hand is determined by the tilt angle "α": The higher the tilt angle, the longer the tray and thus naturally, the larger the size of the tray. For instance, the dimensions of the first level tray in one of the evaluation set ups investigated in this work are as follows: For a tilt angle α=29°, the length of the tray is 385mm and the width is 250mm. Water vapor is produced from an electrically heated water bath – the boiler. The heat source is a 500 Watt electric heater coil which provides adequate heating power for this bench scale system. Temperature control is within 1oC of the set point and within the range of 55 to 90oC. Regulation and control of bath temperature is achieved by an ON/OFF switch. The boiler is mounted with a tubing system that serves the dual function of a water level indicator gauge and water level adjustment fixture. To monitor the thermal phenomena associated with the process, thermocouples are placed in appropriate areas in the water bath, on the tray and other points inside and outside the distillation chamber.

B. The process

In principle, the tray or multi-tray distillation process is fairly simple and can be very efficient from an energy requirements standpoint. For the sake of this investigation, for example, water in the boiler is heated to a given temperature and maintained constant. Vapors - as they rise from the boiler - come into contact with the cold bottom surface of the first tray where they condense. As the condensed water droplets grow larger in volume and thus heavier, they start making their way downwards under the pull of gravity and dripping into the collection channel at the bottom edge of the tray, see Figure 1. The latent heat released during the condensation step is transferred to the thin film of water trickling down on the top side of the tray. It is worthwhile noting at this point that, in our design, the top side of the tray is covered with a thin, loose fill cotton cloth to ensure a uniform wetting of the entire top surface of the tray to maximize productivity of the equipment. Some percentage amount of the water flowing on the top of the first tray evaporates and condenses on the bottom side of the second tray and so on up to the third or n^{th} tray.

C. Data Collection

In the first part of this study, the intent is to quantify the effects of tray size and slope or tilt angle α on the distilled water volumetric flow rate of the distillation system. The slope angle of the trays prescribes the size on the tray and vice-versa. Thus, the experiments consisted of fabricating a tray with the appropriate length so as to give a specific tilt angle α. Note that the width of the tray is determined by the inside depth of the distillation box. Then, we measured the throughput of the equipment under a number of different operation conditions. The temperature of the boiler was varied to cover the range from 70 to 95°C. For each temperature data point, yield of distilled water – expressed as volumetric flow rate - is measured thrice, and then an average value for the yield is calculated. When moving from one temperature condition to another, the equipment is allowed to run for ten minutes to stabilize and reach steady state before starting to take the next flow rate measurement. Water level in the boiler is closely monitored and kept constant by adding water when appropriate. The flow rate of the "cooling water" on the top surface of the tray is kept constant throughout the whole experiment or adjusted to the appropriate flow rate to maintain a constant tray surface temperature.

The second part of this investigation consisted of exploring the effects of surface wetting of the tray on yield. Hence we ran two series of experiments: The first one with a bare – uncovered – tray. In the second experiment, the tray was covered with a water absorbing hydrophilic cloth to ensure adequate wetting of, ideally, the whole surface of the tray.

In the third part of this work, we have looked at the effects of the tray material type on yield. For now we intend to analyze trays made of aluminum and copper. We believe that the proper choice of construction materials could have an impact on the performance/cost ratio of the distillation equipment. To simulate real life operation conditions and for comparison purposes, the output of the equipment was measured at various boiler temperatures while keeping the cooling water flow rate on top of the tray constant. Tray size and geometric configuration in the distillation system were kept identical for both the aluminum and copper trays.

The last item in this study is quality control. From our previous work we have seen and concluded that electrical conductivity checks provide a fast, simple and accurate method of monitoring the progress of the measurements and ensuring that the equipment is running properly. We have also seen that the quality of the distilled water produced with this type of instrument is excellent.

III. Results and Discussion

We pick up our study from where we left off in the first part of this work [1] as we reported some data on the yield of the distillation apparatus as a function of boiler temperature under isothermal tray conditions. As we show in Figure 2 below, we looked at the condition of using very cold water - iced water that is – as feed water flowing on top of the first tray. This data from this experiment confirms the information we have reported previously. For a given equipment and geometry, there is a maximum throughput associated with it. The maximum possible throughput of the distillation equipment could be determined using a Figure 2 type plot. The method would simply consist of running one tray isotherm and extrapolating the data to the boiling temperature of the water feedstock. For the case of our distillation model, we found the maximum throughput to be 660ml/hr as we have reported previously [1].

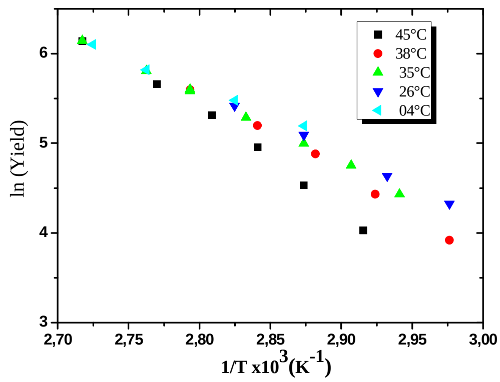

Fig. 2 Yield data under various isothermal tray conditions

A. Effects of tray size and tilt angle on Yield

The results of this study showed that the slope – or the tilt – angle of the tray has no effect on the output of the distillation equipment. This finding is indeed quite significant in that it may be counter-intuitive as one may tend to think that the higher the angle of inclination of the tray, the higher the throughput of the equipment. That is not the case as it is clearly shown in Figure 3. There is however a lower limit of the slope angle below which the yield of the equipment drops dramatically. Indeed, these experiments provided information with regards to another very useful design variable in that we observed that at slope angles $\alpha \leq 9°$, there is no throughput or only a tiny fraction of the equipment production capability. At $\alpha \leq 9°$, we have made a visual observation of distilled water droplets - forming as a result of condensation on the bottom side of the tray - dripping back into the boiler, with not much condensate flowing into the collection channel of distilled water. From a physical standpoint, the dripping back of the condensate into the boiler at $\alpha \leq 9°$, could be explained by the fact that it is a consequence of the gravity forces acting on the drops reaching the critical point of overcoming the tangential force components of the surface tension forces that cause the drops to remain "attached" to the tray and move down into the distilled water collection channel. Thus the drops of distilled water are forced by their own weight to fall back into the boiler rather than trickle down into the distilled water collection duct.

From an engineering standpoint, this finding is extremely useful in that it allows the design and building of distillation systems that are compact, with reduced size, weight and at reduced cost without sacrificing on throughput. Our experimental work showed that the optimal system configuration could be achieved by designing the trays with a tilt angle α within the narrow range of 9 to 13°.

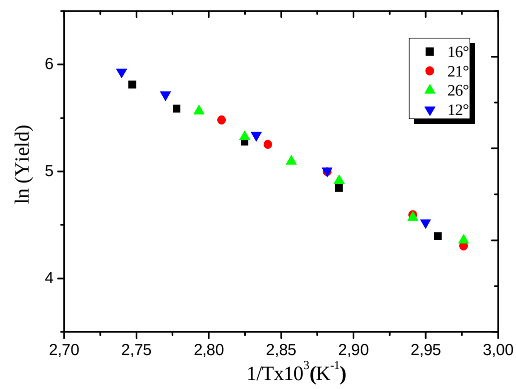

Fig. 3 Effect of slope angle α on throughput

B. Effects of tray surface wetting on Yield

As mentionned earlier in the experimental section, we have also explored the effects of surface wetting of the tray – top surface or the cooling side - on yield. Hence we ran two series of experiments: The first one was with a bare – uncovered – tray. The second series of experiments were performed while the tray was covered with a water absorbing, hydrophilic cloth to ensure adequate and uniform wetting and cooling of the whole surface of the tray.

As would be expected and as shown by the data in Figure 4, surface wetting causes a significant impact on the production rate of distilled water. The magnitude of the effect becomes larger at higher boiler temperatures as can be seen in the figure. Within the studied boiler temperature range of 85 to 90°C, and as evidenced by the data in Figure 4, we have seen a 20% improvement in the equipment throughput of distilled water when using a efficient surface wetting mechanism over a system operated and equipped with bare, unwetted tray surface. Note that in our case a cotton textile cut to the size and shape of the tray was used for tray surface wet out.

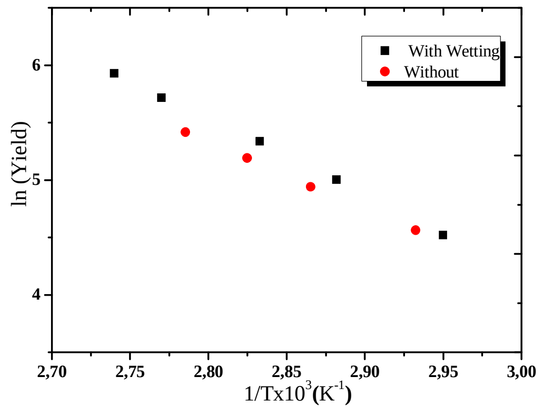

Fig. 4 Effects of tray surface wetting on Yield

C. Effects of tray materials on Yield

We have evaluated copper for benchmarking very good heat conducting property materials versus aluminum. The trays were fabricated from stock metal sheeting with a 0.5 mm thickness. The comparison data from these experiments are summarized in Figure 5.

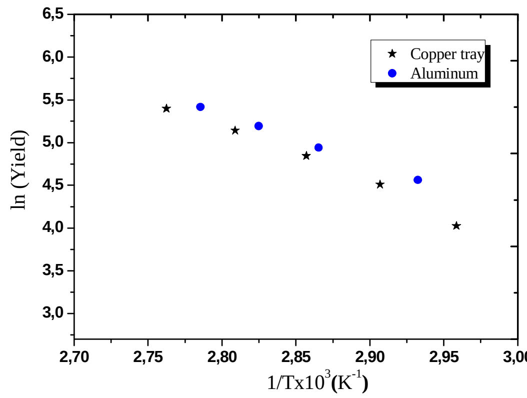

Fig. 5 Yield data of copper tray versus aluminum

For the case of a single tray distillation system set up that we investigated, the experimental data in Figure 5 above appears to indicate that the yield of distilled water produced when using an aluminum tray is similar or perhaps even slightly better (10%) than that when a copper tray is used. This observation does indeed constitute another significant finding with several design advantages to be gained when using aluminum made trays versus those made of copper: Light weight, easy machining/handling/fabricating and low EH&S (Environmental, Health and Safety) impact to name a few.

IV. CONCLUSION

This part of our investigation revealed several significant findings that would certainly greatly contribute to designing effective and optimized tray distillation systems. To summarize, our data indicates that aluminum sheet is a fine material for fabricating the trays when compared with copper. As indicated earlier, there are quite a few advantages that come along with using aluminum made trays versus copper, especially from the EH&S perspective. Second, the tray slope angle α has no impact on yield of the equipment within the range that we investigated. In fact, our data suggests the existence of an optimum slope angle α value within the narrow 9 to 13° window to achieve a highest throughput with a most compact apparatus. Third, we found that there is at least a 20% increase in throughput when using a simple surface wetting device on the tray which in our case is a piece of loose hydrophillic fabric placed on the tray. Finally and as mentionned in our previous work, this distillation device produces pure water as evidenced by the very low electrical conductivity measurements showing values within the range of 1.6 to 5 μS/cm.

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