World Academy of Science, Engineering and Technology
International Journal of Environmental and Ecological Engineering
Vol:6, No:6, 2012

Effect of Temperature on the Performance of Multi-Stage Distillation

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***Abstract*—**The tray/multi-tray distillation process is a topic that has been investigated to great detail over the last decade by many teams such as Jubran et al. [1], Adhikari et al. [2], Mowla et al. [3], Shatat et al. [4] and Fath [5] to name a few. A significant amount of work and effort was spent focusing on modeling and/simulation of specific distillation hardware designs. In this work, we have focused our efforts on investigating and gathering experimental data on several engineering and design variables to quantify their influence on the yield of the multi-tray distillation process. Our goals are to generate experimental performance data to bridge some existing gaps in the design, engineering, optimization and theoretical modeling aspects of the multi-tray distillation process.

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

I. Introduction

OUR interest in tray distillation systems was sparked by the hard reality that the availability of clean-potable water is very limited and in short supply for entire populations in numerous parts of the world. For instance, in some areas of the Algerian Sahara and quite certainly in other areas of other countries too, clean natural spring water may be abundant but salt content is high enough to constrain its life bringing/giving properties. Whether for drinking or irrigating desert gardens, fresh water is of the essence. Due to the fact that the distillation process offers a great deal of design flexibility and versatility, the equipment design can be tailored and custom engineered to meet specific performance – cost criteria to meet specific needs of the private individual in a remote area or a population in a given community.

For the individual living in a remote area, one of the visions may be the design and fabrication of simple kits relying solely on naturally occurring or locally available sources of energy such as the sun, the wind or others and their combinations for example. These types of kits would need to meet specific criteria such as adaptable, compact, light weight, easy to assemble and dis-assemble, portable etc… for a Bedouin or Touareg family for instance. Further, the distillation unit could be used for other purposes such as storage container for instance to extend the versatility of the equipment.

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In the case of a whole population living in an Oasis, the concept of distillation coupled with the use of renewable energy sources may be used astutely to develop solutions to resolve shortages in the availability of potable or irrigation water. Indeed, one can also envision large scale systems for process/ waste water treatment that would be driven entirely by renewable, green energy sources.

At this juncture, we have designed and built a flexible and inexpensive instrumented bench scale multi-tray distillation apparatus. This type of design can be easily scaled-up and configured to run and rely solely on solar or other forms of renewable green energy sources. Part 1 of this work is an investigation of temperature effects on production rate / yield.

II. Experimental

A. 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 nth tray.

B. Data collection

The first part of this study covered the quantification of the effects of boiler and tray temperatures on the yield of the distillation apparatus. The experiments consisted of heating and then maintaining the water temperature in the boiler at a constant level. The temperature was varied to cover the range from 50 to 90°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 typically ten minutes to stabilize and reach steady state before starting to take any 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.

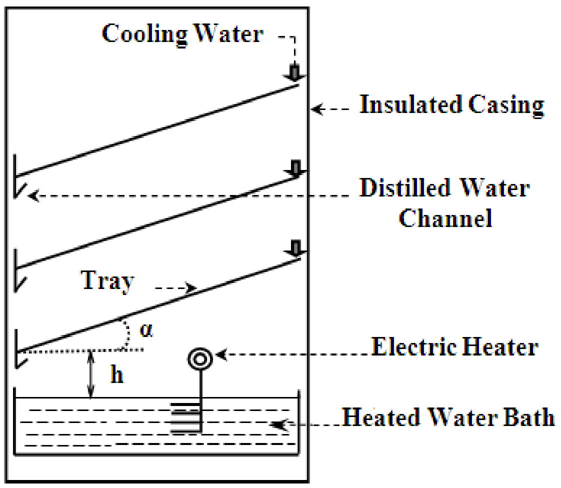

Fig. 1 Schematic Diagram of the Distillation Apparatus nonlinear

The second part of this investigation consisted of exploring the effects of the "cooling water" flow rate on yield. In this case, the water bath temperature is kept constant throughout the whole experiment while the flow rate of the "cooling water" is adjusted to a measured value. Then as mentioned above, yield is measured three times to allow calculation of an average value. Here also, a ten minute idle time is allowed between runs to allow the process to stabilize and reach steady state before taking any measurements.

In the third part of this work, we have looked at the effects of the boiler temperature on yield while the tray above the boiler is kept at a constant temperature. As the temperature of the boiler is changed to another condition, the water flow rate on the top surface of the tray is adjusted to the appropriate level so as to keep its temperature constant throughout the whole run.

The last and naturally the most crucial task in the data collection step is quality control. Since the technical viability of the process and equipment depends in the first place on how good is the quality of their outputs, electrical conductivity was selected as a measure of/ and used to monitor and assess process and equipment capabilities.

III. RESULTS AND DISCUSSION

A. Effects of water bath temperature on yield – Cooling water flow rate constant

We performed many runs under these conditions and collected a significant amount of data. Analysis of the raw data allowed us to devise and implement several improvements on the hardware and also on the data collection procedure. As a result, the first set of data summarized in Figure 2 below shows some of the findings of this part of the study.

It is worthwhile and interesting to notice that there is an exponential type of relationship between the yield of this process and the temperature of the boiler. This behavior is indeed reminiscent of the classical case of temperature effects in chemical engineering kinetics and commonly known as the Arrhenius equation, X = Xo exp (-ΔE/RT). Obviously for our case, X is the yield of distilled water and T is the absolute temperature of the boiler. The parameters in the Arrhenius equation are evaluated empirically as shown in Figure 2 below shows some of the findings of this part of the study.

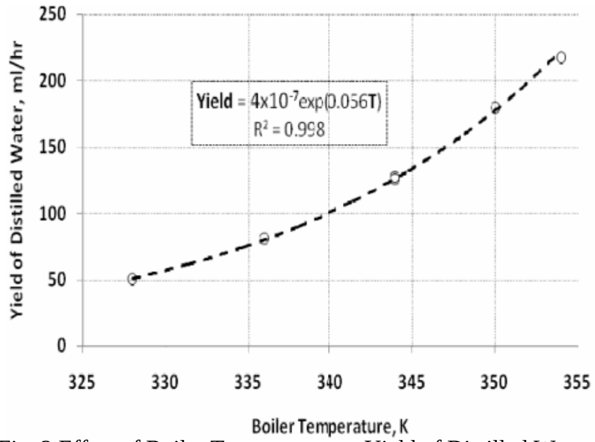

Fig. 2 Effect of Boiler Temperature on Yield of Distilled Water

It is worthwhile and interesting to notice that there is an exponential type of relationship between the yield of this process and the temperature of the boiler. This behavior is indeed reminiscent of the classical case of temperature effects in chemical engineering kinetics and commonly known as the Arrhenius equation, X = Xo exp (-ΔE/RT). Obviously for our case, X is the yield of distilled water and T is the absolute temperature of the boiler. The parameters in the Arrhenius equation are evaluated empirically as shown in Figure 3 below where the same data is plotted as ln (yield) as a function of (1/Temperature).

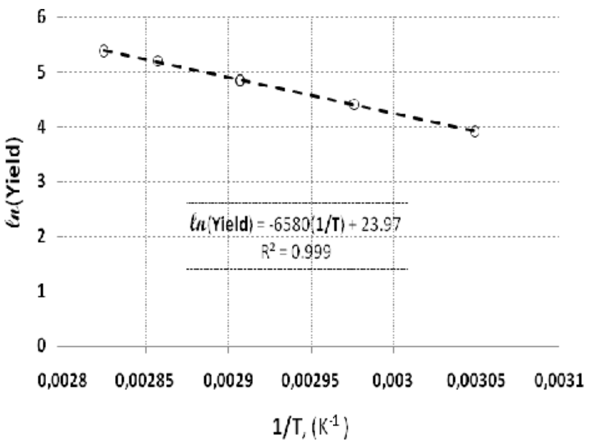

Fig. 3 Plot of natural log of yield versus (1/T)

As can be seen in Figure 3, these types of plots give a straight line. The term -ΔE/R (where R is the gas constant) is obtained from the slope of the line, while lnXo is given by the y-intercept. By analogy to chemical engineering kinetics or more generally speaking for all temperature effects on rate dependent processes/phenomena including this particular case, one can thus deduce the value of ΔE i.e. "an activation energy parameter" for the process and also the value of Xo the so-called frequency factor in chemical engineering kinetics. As an illustration for the case in study, the temperature effects on the tray distillation system can be quantified by the following equation:

$$\dot{Q} = 2.57\ x10^{10}\ ex(-6580\ /T) \quad (1)$$

Where:

$\dot{Q}$= The flow rate – output of the apparatus - of distilled water in ml/hr

T = The absolute temperature of the boiler in K

Note that the values of Xo which in this case is assimilated to $\dot{Q}$o and ΔE the activation energy term as calculated from Figure 3 are as follows:

$$\Delta E = 5.74\ x.104\ \ j/mol$$

and $X_0 = Q_0 = 2.75 \times 10^{10}\ ml/hr$

B. Effects of cooling water flow rate on yield

The results of this evaluation are shown in Figure 4 below. Typical data are shown to illustrate two cases of the investigation. The upper curve in the graph with the label 81°C represents data collected with the boiler temperature maintained constant at 81°C. Similarly, the lower curve describes the process with the boiler temperature kept constant at 71°C. The curve fittings to the data points are logarithmic. Up to this point the data quantifies and confirms one's intuitive and qualitative thinking that in order to maximize yield, one approach may be to run "a hot boiler and cool tray".

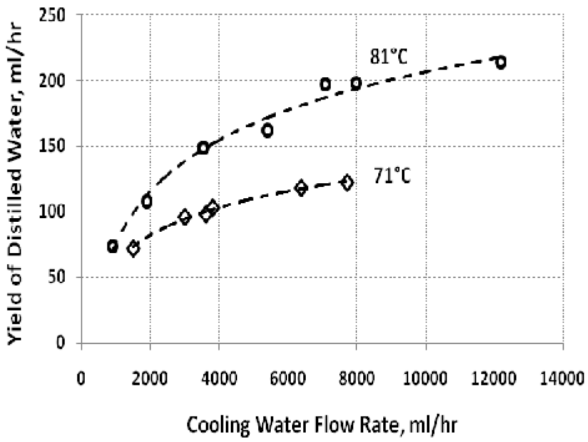

Fig. 4 Effect of Cooling Water Flow Rate on Yield

C. Effects of boiler temperature at constant tray surface temperature

The data collected so far pointed us in a direction to investigate in a little more detail the effect of boiler temperature on yield under isothermal tray conditions. Consequently, we have investigated 4 different tray isotherms, namely: 26, 35, 38 and 45°C. The raw data of this work is summarized in Figure 5. Here again, one can notice the exponential increase in the production rate of distilled water as the distillation apparatus is operated at higher and higher boiler temperatures. The data becomes quite interesting indeed when - as mentioned earlier – it is plotted in the format of ln(Yield) versus 1/(Absolute Temperature), see Figure 6 below. Notice that the isotherms are not parallel and appear to converge to a common location. We will investigate this detail in more depth in Part 2 of this work. For now, it appears from Figure 6, that the intersection point corresponds to the point of maximum throughput with a boiler temperature at 100°C, i.e. the boiling temperature of water. For the case of our bench scale model the maximum throughput is calculated from Figure 6 and is at 660 ml/hr.

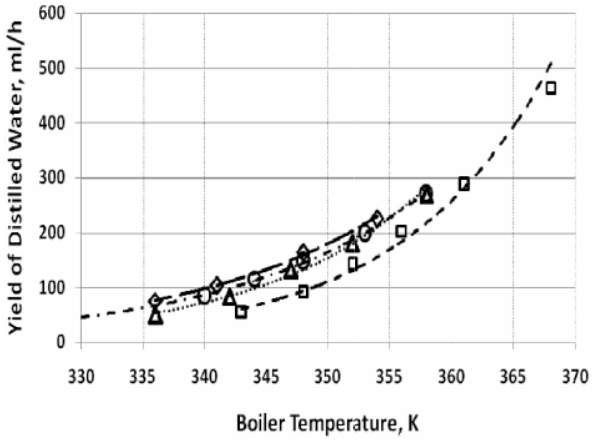

Fig. 5 Example of raw data for four different tray isotherms

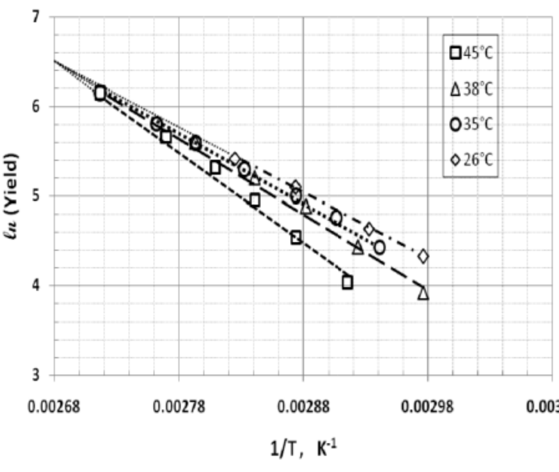

Fig. 6 Natural log of yield plot as a function of 1/(absolute temperature)

D. Quality control

It is very critical during these experiments to follow very closely the electrical conductivity σe of the distilled water. Electrical conductivity is a simple and effective means of checking and ensuring that the product quality is good and thus - most importantly - the measured yields of distilled water are correct and accurate. The σe baseline for good quality distilled water is at or below 80 μS/cm. In our case σe values are within 1.6 to 5 μS/cm. The pH was also checked occasionally and was found to be in the range of 4.62 to 5.00.

IV. Conclusion

We have completed the design and fabrication of a bench scale tray distillation apparatus. In this first part of the study we focused on temperature which is one of the most critical variables that govern production rate. Effects of temperature on yield were found to follow the exponential type of variation or the so-called Arrhenius equation. Although our bench scale system is very simple in design, the quality of its distilled water is excellent as evidenced by σe values within the range of 1.6 to 5 μS/cm.

Acknowledgements

This work is funded by The "Unité de Développement des Equipements Solaires" - UDES - Algeria. Special thanks to: Bendjebbas Hicham, Rouabhia Chemseddine, Sendjakeddine Menouar, Sid ali Guers and others who contributed to this work with their brilliant ideas and/ excellent craftsmanship. We also thank the Leader of the FTEER Division, Mr. Brahim Abbad for his insights and push forward.

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