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An Investigation into the Potential of Industrial Low Grade Heat in Membrane Distillation for Freshwater Production

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***Abstract*—**Membrane distillation is an emerging technology which has been used to produce freshwater and purify different types of aqueous mixtures. Qatar is an arid country where almost 100% of its freshwater demand is supplied through the energy-intensive thermal desalination process. The country's need for water has reached an all-time high which stipulates finding an alternative way to augment freshwater without adding any drastic affect to the environment. The objective of this paper was to investigate the potential of using the industrial low grade waste heat to produce freshwater using membrane distillation. The main part of this work was conducting a heat audit on selected Qatari chemical industries to estimate the amounts of freshwater produced if such industrial waste heat were to be recovered. By the end of this work, the main objective was met and the heat audit conducted on the Qatari chemical industries enabled us to estimate both the amounts of waste heat which can be potentially recovered in addition to the amounts of freshwater which can be produced if such waste heat were to be recovered.

By the end, the heat audit showed that around 605 Mega Watts of waste heat can be recovered from the studied Qatari chemical industries which resulted in a total daily production of 5078.7 cubic meter of freshwater.

This water can be used in a wide variety of applications such as human consumption or industry. The amount of produced freshwater may look small when compared to that produced through thermal desalination plants; however, one must bear in mind that this water comes from waste and can be used to supply water for small cities or remote areas which are not connected to the water grid. The idea of producing freshwater from the two widely-available wastes (thermal rejected brine and waste heat) seems promising as less environmental and economic impacts will be associated with freshwater production which may in the near future augment the conventional way of producing freshwater currently being thermal desalination. This work has shown that low grade waste heat in the chemical industries in Qatar and perhaps the rest of the world can contribute to additional production of freshwater using membrane distillation without significantly adding to the environmental impact.

***Keywords*—**Membrane distillation, desalination, heat recovery, environment.

I. Introduction

MEMBRANE DISTILLATION (MD) is a novel technology used to desalinate brackish water or seawater in order to produce freshwater which can be used for human consumption or industry. The most distinctive feature of MD is its driving force. The driving force for MD is the water vapor pressure difference across the membrane while the driving force for other membrane technologies is the difference in the total pressure. The membranes used for MD are hydrophobic which means they only allow water vapor to pass but not liquid water. To evaporate the water, there has to be a pressure gradient which is obtained by heating up the water and that will increase its vapor pressure. Membrane distillation does not require much energy to produce water; any low grade heat source can be utilized to heat up the feed water such as industrial, or solar. The reason why membrane distillation is taking all that attention from scientists and researchers is because it possesses some advantages over other desalination techniques which make it the prospective desalination technique. Some of these advantages are: Low energy requirement, almost 100% rejection of particles such as cells, colloids, macro-molecules, ions and other non-volatile species in the solution, low operating pressure (atmospheric) and temperature (less than 80°C); hence, cheap materials can be used to construct the system [1].

Qatar is a purely industrial country with more than 90% of its domestic income from industry especially oil and gas industry. The existence of the world's largest processing plants in different sectors has strengthened the position of Qatar to be the forthcoming capital of petrochemical industries. The price of energy is significantly cheaper than the prices elsewhere and that is the main reason behind the existence of the world's largest industries in this part of world. Unfortunately, the full utilization of the heat content in any stream is impossible; in fact, less than 50% of the energy obtained through industrial fuel combustion is lost as waste heat [2]. With the presence of the mega scale industry here in Qatar and the fact that huge amounts of heat is wasted to the environment, the possibility to recover some of the wasted heat is highly feasible and this is going to be investigated in this paper. The studied industries are: Gas To Liquid (GTL), Vinyl Chloride Monomer (VCM), Ammonia, Ethylene, and Liquefied Natural Gas (LNG). This work will enable researchers to quantify the amounts of waste heat which can be potentially recovered in addition to the amounts of freshwater which can be potentially produced if such waste heat were to be recovered using membrane distillation.

II. Background

Waste heat is a term used to describe the heat generated by fuel combustion or chemical reaction for the purpose of heating a process stream or reactor and now become useless

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and must be dumped to the environment (atmosphere or sea). On average, more than 50% of the energy obtained through industrial fuel combustion is lost as waste heat [3]. The temperature range of the waste heat is not fixed; waste heat temperatures depend on the industry itself. For instance, the waste heat of metals and glass industry is in the range of 300-400°C while that of petrochemical and refining industry have temperatures below 150 C and that of food and beverages industry is 80°C [2]. In order for any waste heat stream to be called low grade waste heat, it has to have a specific temperature range. For the membrane distillation application, low grade waste heat streams are waste heat streams with temperature range below 200°C and above 70°C. Huge amounts of heat energy can be utilized from emission sources such as process streams or flue gases. Normally, furnaces, ovens, kilns and boilers are used to generate hot flue gases which are used to heat up process streams; however, these gases are emitted through stacks before utilizing a considerable amount of its energy content. The utilization of waste heat has a dual benefit on the industry and environment as it reduces the amount of fuel burnt so it has an economical aspect; also by doing that the industrial emissions to the environment are reduced. In this study, the two sources of waste heat recovery are: process streams and flue gas.

Using any sort of heat exchanging equipment, the recovered waste heat will be used to heat up the incoming seawater before being introduced into a membrane distillation module which will be used to produce freshwater and reject the salts. In membrane distillation, the distillate flux is a function of the temperature difference between the hot and cold sides. Hence, the higher the temperature of the waste heat stream is the higher the produced flux is. Elevating the temperature of the seawater will result in increasing the vapor pressure of the water; hence, increasing the vapor pressure difference between the hot and cold side. The ultimate result would be increasing the produced flux.

III. Methodology

In order to estimate the amounts of freshwater produced from the studied industries, several steps must be performed which start by fully understanding the process under consideration and determining the stream's flow rates, temperatures and compositions. The next step is to get and estimate all the required physical properties of the process streams (such as the specific heat capacity, density, enthalpy of evaporation, etc.) either through simulation (using HYSYS) or predictive equations (using semi-empirical correlations). Having obtained the flow rates, specific heat capacity, enthalpy of evaporation and inlet and outlet temperatures, the heat duty which has been gained or lost from any process or utility stream (such as flue gas) can be calculated using the following equations:

$$Q = m\ Cp\ (T_{out} - T_{in}) \tag{1}$$

$$Q = m\ \Delta H_{phase\ change} \tag{2}$$

where Q_{stream} is the heat gained/lost from any process stream, m is the mass flow rate, C_p is the specific heat capacity of the stream, Tout and Tin are the outlet and inlet temperatures, and $\Delta H_{phase\ change}$ is the enthalpy change corresponding to phase change in the stream.

If the stream is experiencing a change in the temperature without a change in the phase (only sensible heat transfer); then (1) must be used. On the other hand, if the stream experienced a phase change (from liquid to vapor or vice versa), then latent heat are being transferred and hence (2) must be used. In this study, the selection of the optimum waste heat sources must avoid waste heat streams at high temperatures (above 200°C) because such streams are not low grade waste heat streams and still have precious calorific value. These streams are most probably utilized in the plant to generate steam or preheat the inlet streams to any boiler. Waste heat streams at low temperatures (below 80°C) are also avoided as they cannot heat the feed water up to the target temperature (80°C) due to thermodynamic infeasibility. By conducting literature review on the optimum feed temperature, it has been found that the optimum feed temperature which corresponds to the highest flux is the highest temperature possible which is 70°C. Heating the feed stream above 70°C will turn the MD system into conventional thermal desalination which is not economically feasible; hence, during this study, the temperature of any waste heat stream must not be below 70°C assuming a temperature difference of 10°C between the hot (waste heat stream) and cold stream (feed seawater). After shortlisting the plant's process streams into couple of streams, a couple of visits to the processing plants were arranged to discuss and double-check with the plant's engineers regarding the availability and correctness of the selected streams. Finally, the modified heat flow can now be used to estimate the amounts of freshwater which can be produced. Using the GOR correlation, the amounts of freshwater can now be figured out by relating it to the amounts of heat available as discussed below.

A. Freshwater Production Using GOR

The translation of the possibly-recovered waste heat (in Joules) into amounts of freshwater (in cubic meters) can be done through the concept of Gain Output Ratio (GOR). Traditionally, the original relationship which used to relate the amounts of freshwater produced to the heat transferred in desalination was the Performance Ratio. This performance ratio (η) can be defined as:

$$\eta = \frac{m_d}{m_s}\frac{\Delta H_{ref}}{\Delta H_{h.i.}} \tag{3}$$

where, md and ms are the mass flow of distillate and steam, respectively, $\Delta H_{h,i}$ refers to the enthalpy difference between the inlet and outlet of steam and ΔH_{ref} stands for the enthalpy of steam at 100°C and 1 atm which has a value of 2326 kJ/kg [4].

The performance ratio has been replaced by GOR which is a simpler way to relate the freshwater output to the heat input.

GOR is a measure of how much thermal energy is consumed in desalination process. It is defined as how many kilograms of distilled water are produced per kilogram of steam consumed [5]; mathematically:

$$GOR = \frac{m_d}{m_s} \quad (4)$$

where, m_d and m_s refer to mass flow of distillate and steam, respectively.

Different desalination technologies have different GOR value. Not only the desalination technology determines the GOR value but also the temperature and salinity level of the feed water as well. The lower the salinity level and the higher the number of stages is, the lower the GOR value is [6].

According to Summers et al [7], the optimum GOR value of a single stage system employing membrane distillation as a desalination technology and the Arabian Gulf as a source to its feed water is 0.9. This value will be used in carrying out the calculations required to estimate the amounts of freshwater produced using the available industrial waste heat.

In membrane distillation, there will be no steam used to heat up the feed water as the feed water needs to be heated up to a mild temperature (maximum of 70°C). However, the same equation (GOR) can still be used but with a minor change. The amounts of steam produced (md) can still be used but the mass of steam consumed (m_{steam}) needs to be calculated. In order to calculate m_{steam}, the amount of energy recovered from the waste heat stream must be converted to equivalent mass of steam using the enthalpy of steam. This can be figured out from:

$$\text{Amount of steam} = m_{steam} = \frac{Q}{\Delta H_{vap}} \quad (5)$$

where Q is the recovered waste heat and ΔH_{vap} is the latent heat of steam at required pressure. The most common source of heating in desalination plants is saturated steam at 1 bar and 100°C; hence, in calculating the equivalent amount of steam (m_{steam}), saturated steam at the same conditions is going to be taken as a reference (by convention). The enthalpy value of this saturated steam at 100 and 1 bar is:

$$\Delta H_{vap} = 2326 \frac{kJ}{kg}$$

By the end of this section, the main steps followed in this research to conduct a heat audit on the Qatari industries and predict the amounts of freshwater produced are depicted in Fig. 1.

IV. Results and Discussion

After conducting the waste heat recovery on all the studied plants, the amounts of freshwater which can be potentially produced vary depending on the amounts and scale of waste heat which can be recovered. The obtained results are listed and discussed in this section. Out of the available waste heat from the studied industries (605 MW), a daily production of 5078.7 cubic meter of freshwater was estimated which can be considered as an extra pure freshwater source which can be potentially used for industry or human consumption. In this study, the ammonia process was the largest producer of freshwater (58.1%) due to the presence of huge amounts of recoverable waste heat in the ammonia production process (via steam reforming). The majority of the recoverable waste heat from the ammonia process was attributed to the process streams followed by the flue gas. Fig. 2 depicts the individual freshwater production from the studied processing industries in Qatar while Fig. 3 depicts the percentage of the produced water from both sources: process streams and flue gas. Since most of the processing industries in Qatar are modern, the possibility of recovering waste heat from the flue gas is lower when compared to the process streams. However, there is still some waste heat to be recovered from the flue gas (20.3%). The majority of the low grade waste heat from the Qatari processing industries can be found in the hot process streams (79.7%) which need to be cooled down by cooling water or air.

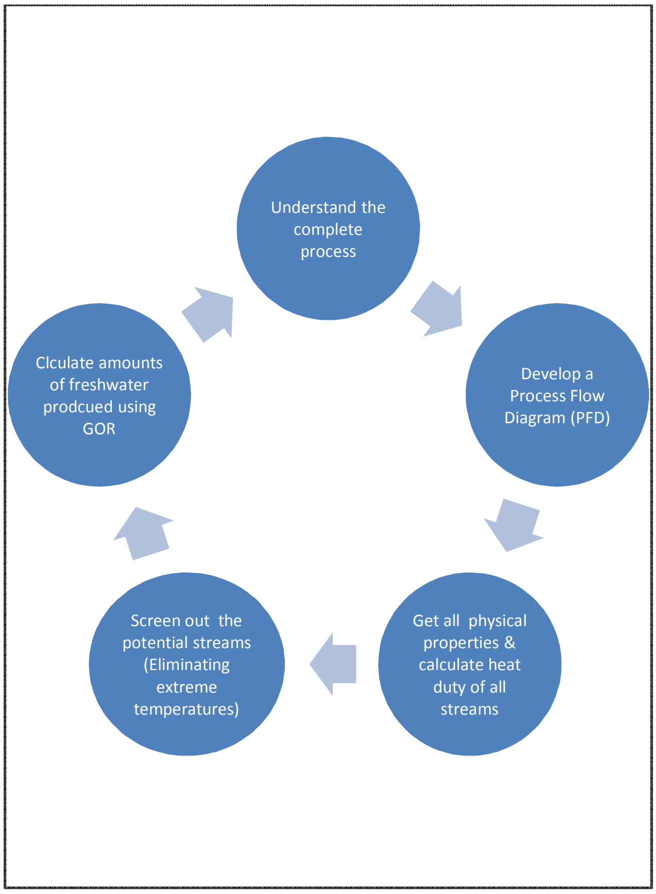

Fig. 1 Simple flow diagram showing the steps followed to predict the amounts of freshwater produced

To significance to the amounts of freshwater which can be potentially produced, the freshwater production from the selected Qatari industries was compared to the production

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from RAF B2 plant which is a moderate desalination plant (113,562 m3/day) when compared to other huge plants such as Q Power (227,124 m3/day). Fig. 4 depicts the daily production from the two sources along with the percentage from the Qatari industries.

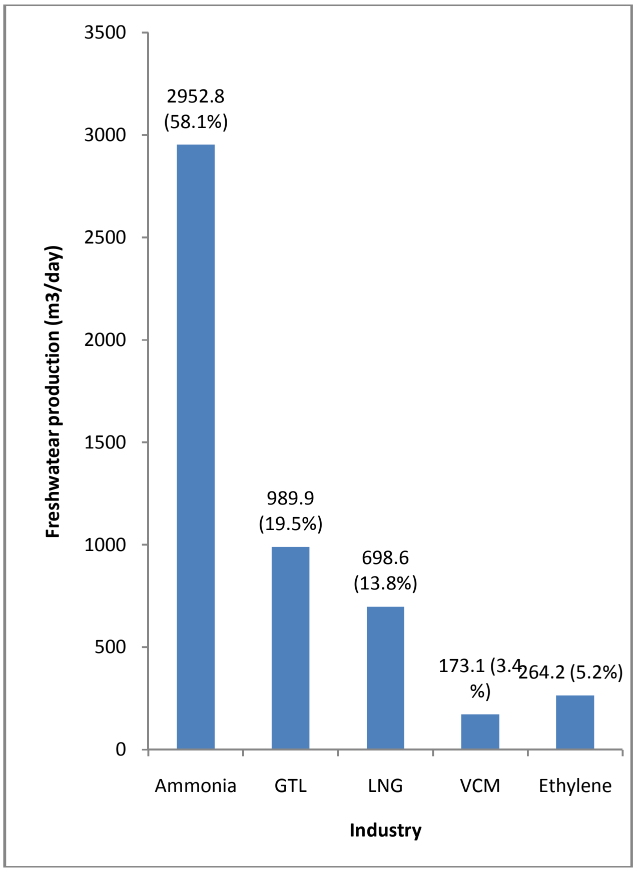

Fig. 2 Freshwater production from different Qatari industries

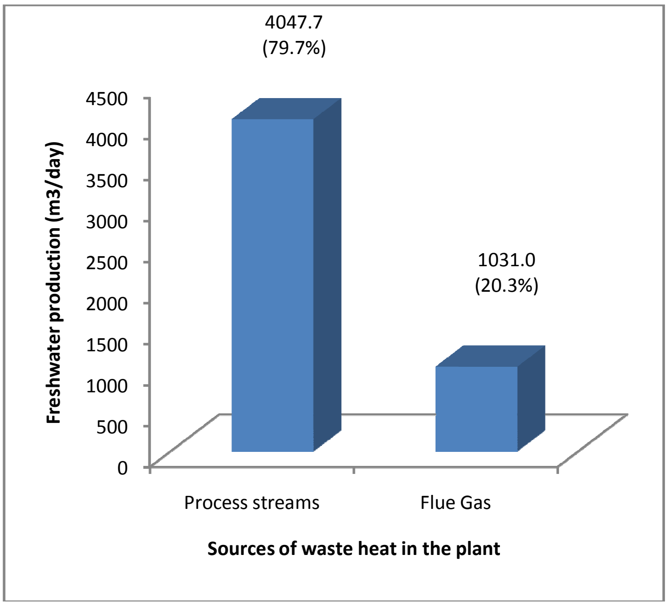

Fig. 3 Freshwater production from different sources of waste heat in Qatari industries

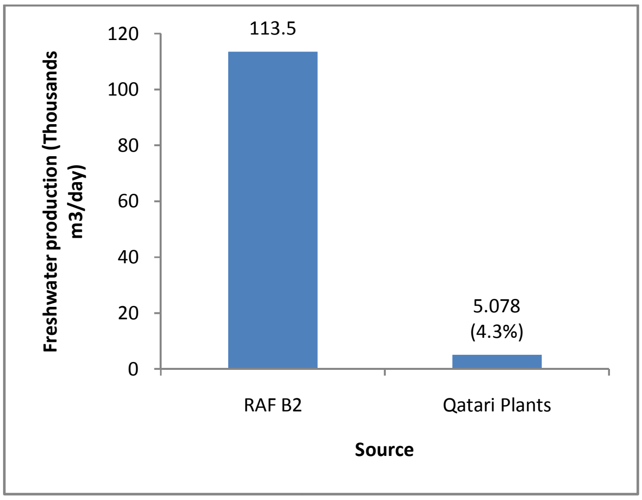

Fig. 4 Freshwater production from this study compared to RAF B2 production

V. Conclusion

The heat audit conducted on the Qatari industries and power generation and water desalination plants show that there are huge amounts of heat which can be utilized to produce freshwater using the membrane distillation technology. The most important feature of the freshwater produced here is that it is almost free of energy charge and free from any environmental footprint. The energy used to produce the freshwater was going to be dumped if it was not recovered as it cannot be used in the process. This energy would have been released to the environment which would warm up the globe and drastically affect the environment. If this technology has not been used, the production of freshwater will have to come through the energy intensive process (thermal desalination) which consumes a lot of fossil fuels and pollute the environment.

The amounts of freshwater produced from this study cannot be compared to the freshwater production from the major desalination plants in Qatar as they are one of the world's largest plants. Rather, the daily production of freshwater using MD was compared to the daily production of water from a moderately-sized desalination plant in Qatar (RAF B2). A percentage of 4.3% of the total production of freshwater from RAF B2 may seem low at first glance, but one must keep in mind that the aim of RAF B2 plant is to produce freshwater by burning huge amounts of fossil fuels and employing specialized technologies to achieve the highest production rate possible; however, the freshwater production through the study of this paper utilizes low grade waste heat which is completely useless to the industry. In other words, this freshwater produced was originated from wastes as it comes from waste energy to produce valuable product out of it. According to Adham et al. [8], the quality of the distillate water from the membrane distillation technology is remarkable and is even better than the water produced from thermal desalination plants (more than 99.999% rejection of salts). Hence, this very pure freshwater can be used in a wide variety of applications such as human or industrial

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consumption. The produced water can be used to supply freshwater to small industrial cities where a daily production of 5,741 cubic meters is sufficient to meet all their needs. This water can also be used to supply freshwater to small cities or villages in remote areas where there is no connection to the water grid. Hence, apart from the energy aspect of this produced water, the water produced from this study is more advantageous when compared to conventional desalination technologies as almost no environmental impacts will be associated with the process of freshwater production. All of the energy required to produce this water will be supplied through industrial waste heat which reduces the amount of fuel which would have been burnt if thermal desalination was to be used as the main source of freshwater production.

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