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Experimental study on the vacuum load of low-temperature thermal desalination plant

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ABSTRACT

The objective of this paper is to present a methodology to predict vacuum load theoretically and to compare those results with the experimental values for validation especially the non-condensable gas load and escape water vapour load. The primary objective of this paper is to find out the accumulated effect of non-condensable gases on the vacuum load of low-temperature thermal desalination (LTTD) plant. Suggestions to control the NC gas and escape vapour load on the LTTD process were also discussed in this paper. Determination of an exact amount of vacuum load for the plant is significant, since vacuum system alone shares about 31% of total energy demand of the LTTD plant. Load contribution given by the gas mixtures such as escape water vapour, non-condensable gas and air leak in to the system was experimentally measured by conducting suitable experiments in a running plant of 100 m^3/d capacity located in the Island of Agatti, UT Lakshadweep group of Islands, India. Study at Kavaratti plant of same capacity showed that the escape vapour rate was equivalent to 0.3% of the freshwater generation rate of the plant, which was used as an input value for Agatti vacuum load calculation for escape vapour rate. On comparison of the experimental results of non-condensable gas release rate of Agatti plant with the published data and predicted values using methodology, an agreement up to 16 and 7.7% was obtained, respectively, under the same operating conditions. Also, an agreement up to 15% was obtained between the experimental results of Agatti plant with that of observed results of Kavaratti for water vapour escape rate from the main process condenser. It was reported in the literature that for MED desalination system, the extraction of vapour from the evaporator unit linked with a removal of 10–20 units of vapour corresponded to every unit mass of NC gases. But in the present study, for the LTTD process, it was measured that the accumulated effect of NC gases for every unit mass resulted in extraction of 1.6 unit mass of vapour (approx) from the process condenser. This low value could be due to low operating temperature range of LTTD process and use of low-temperature deep-sea cooling water from the ocean in the condenser tubes. From calculation, it was noticed that decrease in molecular weight of gas increased the volumetric vacuum load for the same operating

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conditions and gas mass flow rates. Also, it was observed that the parameters such as operating pressure, duct loss, mass flow rate of feed water influence the total vacuum load of LTTD plant.

Keywords: NC gases; Escape water vapour; Air leak rate; Pumping speed; Vacuum load; LTTD

1. Introduction

Demand for potable water is alarmingly increasing all over the world. Many sophisticated desalination technologies have been developed in the last few decades to produce cost-effective potable water for satisfying the needs of the world population. Presently, technologies such as reverse osmosis, multi-effect desalination and multi-stage desalination are widely used in most of the developed and underdeveloping countries. But these technologies possess certain drawbacks like complicated process design, huge capital investment, scaling, chemical treatment and threat to the ecosystem of the earth. On the other hand, the technology such as low-temperature thermal desalination (LTTD) implemented by National Institute of Ocean Technology (NIOT) proved to be a simple and eco-friendly technology, which uses naturally available ocean temperature gradient between surface and deep-sea water for producing potable water. In LTTD process, the surface sea water at 28–30˚C is vaporized inside an evaporator, where pressure is maintained at 27 mbar (abs) and the flashed vapour is condensed in the shell-and-tube condenser using deep-sea cooling water at 12–13˚C drawn from a depth of around 350–400 m through a long HDPE cooling water pipe of around 1,000 m. The schematic diagram of LTTD process is shown in Fig. 1. So far, three LTTD plants have been commissioned by NIOT at Kavaratti, Agatti and Minicoy. All these plants are land-based plants of each 100 m^3/d freshwater production capacity, which are presently under operational in Lakshadweep group of Islands. LTTD plant possess merits such as low maintenance, no addition of chemicals or additives, low operating temperature range and no scaling.

In LTTD process, vacuum system plays an important role in maintaining the process condition of the plant. The determination of an exact amount of vacuum load for the plant is eminent for sustaining the process condition. It is estimated that the vacuum system alone consumes around 31% of total energy demand of the LTTD plant as indicated in pie-chart in Fig. 2. Vacuum load to the LTTD plant is mainly contributed by escape water vapour from process main condenser, non-condensable gases from sea water and air leak in to the system through flanges, gaskets and instruments. Water vapour escapes from main condenser are getting condensed in the intermediate condenser provided in the vacuum system. The amount of vapour escapes depends on the performance of condenser, which in turn depends on the cooling water temperature, mass flow rate and mainly the amount of non-condensable gases present inside the condenser. The decrease in cooling water temperature actually helps in reducing the size of vacuum pump by way of

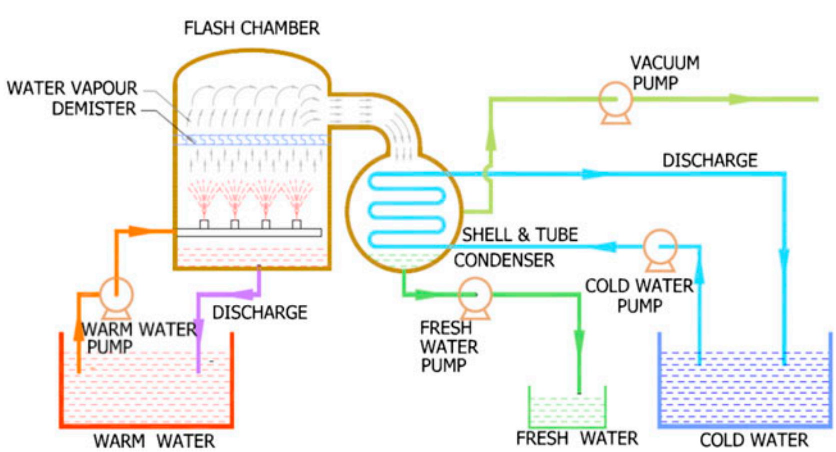

Fig. 1. Schematic diagram of low-temperature thermal desalination process (LTTD).

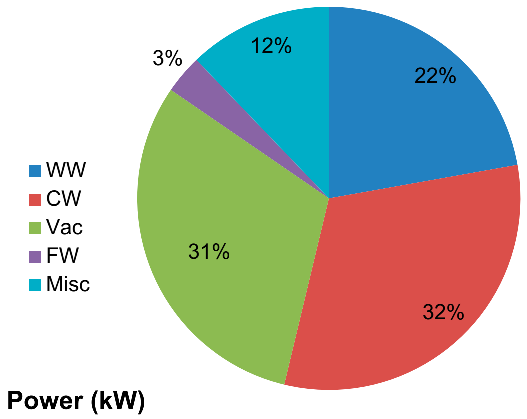

Fig. 2. Percentage of power consumption of individual equipment of the LTTD plant.

cooling the non-condensable gases and minimizing the vapour escape rate. The air leak rate into system could be controlled by ensuring proper leak proof tightness at all connecting flanges and fittings. The non-condensable gases quantity depends on the mass flow rate of surface sea water enters into the process equipment as most of these gases available in atmosphere are found in sea water. Gases such as nitrogen and oxygen are available in abundant in sea water [1]. Argon, nitrogen, oxygen are molecularly dissolved and chemically non-reactive in sea water, whereas carbon-di-oxide is chemically reactive in sea water [1]. Solubility of dissolved CO_2 in sea water for 35 g/kg salinity and 25˚C atmospheric temperature is reported as 0.4 ppm [1]. Apart from that, the rare gases such as ammonia, argon, helium, neon and hydrogen are present in sea water in minute quantities [2]. Greater part of carbon-di-oxide present in sea water is in the form of carbonates and bicarbonates compared to free CO_2 [2]. The factors such as temperature of sea water, salinity of sea water, biological processes, ocean currents and mixing processes affected the quantity of gases dissolved in sea water [3].

Ferroa et al. [4] introduced a technique called as flashing and stripping phenomena for sea water desalination. In this paper, the deaeration efficiency is studied and discussed with regard to a sea water desalination plant under construction in Riwas. Parametric studies have been carried out for analyzing the effects of sea water and stripping steam flow rates, as well as those of temperature, pressure and packing height and other operating conditions or geometrical characteristics on the non-condensable gas removal. In this paper, new solutions are proposed to reduce the costs of the deaerator installation and management. In this study, it is found that even when the packing is completely removed, the liberation of oxygen from the sea water reached an acceptable level. In addition, it is observed from the simulation result that operating the deaerator without the stripping steam feeding considerably reduces the operating costs. Glade et al. [5] have investigated the release of CO_2 in multi-effect distillers. This paper aimed at gaining the in-depth understanding of the physical and chemical processes involved in non-condensable gas such as CO_2 release in MED plants. Oldfield et al. [6] specified that deaerator normally be used to provide a non-condensable gas such as dissolved oxygen concentration in the make-up flow leaving the deaerator lower than 20 ppb. Genthner et al. [7] explained that non-condensable gases such as O_2, N_2 and Ar content entering the distiller with the feed water are considered to be almost completely released in the first three stages, actually more than 95% in stage-1 and rest in the stages 2 and 3. Darwish et al. [8] indicated that deaerator is essential for both acid- and additive-treated plants. Deaerator has to be located after the decarborator in acid-treated plants. The deaerator consists of a packed column with stainless-steel nozzle for water spraying at the top of the tower. The packing materials are provided to complete the job of exposing the water to a maximum contact area with strip stream flowing upwards. He recommended the permissible limit of concentration of oxygen and CO_2 after deaeration is 10 and 3 ppb, respectively, in the sea water for controlling the corrosion. He also suggested that deaeration should be done in separate tower. Sharma et al. [9] experimentally investigated the influence of various parameters on oxygen stripping using a two-stage spray- and tray-type deaerator. In this experiment, it is observed that mass flow rate of water leads to an increase in heat and mass transfer coefficient in both stages. There is no significant influence of deaerator pressure and length of the second stage on the heat transfer coefficient in the range tested. Increase in deaerator pressure enhances mass transfer coefficient, whereas increase in length of second stage has no significant influence. Abdulrazaq Jassim [10] explained the capability of improving the rate of dissolved gas removal using professional types of packings (pall rings) in separation towers. Results of his experiment showed that the rate of dissolved gas removal could be improved when the area of contact between the gas and liquid streams is increased. Said et al. [11] studied that increase in non-condensable gases concentration decreases the overall heat transfer coefficient. Also, he suggested that the presence of 0.015 wt.% concentration of NC gases in MSF plants results in increase in steam flow rate due to variation in heat transfer coefficient value and increase in the product water flow with decreased GOR. Mojonnier et al. [12] obtained a patent for "Reflux De-aeration System". In this system, the carbonating gas under relatively high pressure is conducted from a beverage carbonating mechanism to a water conduit for mixing with the water. In accordance with the qualitative principles of Dalton's Law, the introduced carbonating gas drives out air dissolved in the water. Costa et al. [13] specified that injecting antifoaming agent into sea water inside deaerator prevents foam formation. He also suggested that foam formation would badly affect the release of non-condensable gas. He also stated that in early MSF plants, deaerator is kept as separate equipment but nowadays the usual design is a chamber connected directly to the last evaporator stage.

The objective of current paper is to find out how close the developed methodology predicted the vacuum load towards the experimental values of Agatti and also to discuss about the influence of non-condensable gases on the LTTD plant vacuum load. The experimental non-condensable gas vacuum load of Agatti plant is validated with published data of Kavaratti plant [14] under the same operating conditions. The amount of non-condensable gas released in LTTD process plant is estimated theoretically using the methodology Eq. (2) and compared with Agatti experimental data for validation whose data are validated with published data. The amount of non-condensable gases released into the evaporator may affect the thermal performance of the desalination process. Because these non-condensable gases would wrap the outside surface of heat transfer tubes after reaching condenser and act as a thermal barrier between water vapour and condensate film on the tube surface that lead to decreased condensation rate. This resulted in increased escape water vapour rate and hence the vacuum load. Therefore, the amount of non-condensable gas present in the condenser considered to be the most influential parameter that decides the amount of vapour escape rate from the condenser. In order to determine the release rate of these non-condensable gases, a suitable experiment is conducted at Agatti LTTD plant located at UT Lakshadweep group of Islands, India, and results are analyzed and discussed in this paper.

In the present study, it is theoretically estimated that non-condensable gas release rate is around 7.44 kg/h (O_2 and N_2) for corresponding warm feed sea water flow rate of around 378 tons/h (105 kg/s) for the temperature of surface sea water at 29℃. Also, it is estimated from the experimental study that at least 60.4% of total vacuum load is contributed by escape water vapour rate alone followed by non-condensable gas (37.9%) and air leak rate (1.59%). In conventional thermal desalination plants, the sea water would be sprayed from the top on the packing columns and hot steam would be fed from the bottom, the sprayed sea water would be heated to the required temperature corresponding to the saturation pressure maintained inside degassing equipment by the counter flow steam and non-condensable gases would be stripped from sea water by increasing its surface area and residence time using packed columns. But, in LTTD process, the same feed water at ambient temperature is fed into deaeration chamber operating at 160–180 mbar and then the process equipment where the operating pressure would be maintained at 24–27 mbar and no steam is used for heating the feed water. Non-condensable gas release rate is measured experimentally using the raise in pressure method for the given time [14].

Apart from the non-condensable gases, the vacuum load of the LTTD plant is also influenced by the pressure drop that is taking place inside the plant equipment when the gas mixtures flows across the mist-eliminator, vapour duct, shell side baffles and heat transfer tubes. This drop in pressure proportionately increases the specific volume of the same amount of gases flowing in the process equipment which in turn increases the volumetric vacuum load of the process plant. During the experiment, a pressure drop of around 2–3 mbar (maximum) is observed between evaporator and condenser. Apart from the pressure drop, the molecular weight of the individual gas components and warm feed sea water flow rate (non-condensable gas) also influenced the vacuum load of the LTTD process. The effect of these factors on vacuum load is discussed in this paper. Also, the accumulated effect of the non-condensable gases in the LTTD desalination process is discussed in this paper.

2. Methodology to determine (volumetric) vacuum load of LTTD plant

Based on the vacuum load offered by each gas component such as escape water vapour, NC gases and air leakages in the system, the volumetric vacuum load [i.e. pumping speed] required for proper sizing of the vacuum system (m^3/h) for the given suction pressure can be determined using following Eq. (1) and methodology for determining the volumetric vacuum load is shown in Fig. 3.

$$V = \left[\frac{R.T}{P}\right]\left[\frac{m_{\text{vap}}}{M_{\text{vap}}} + \frac{m_{\text{NC}}}{M_{\text{NC}}} + \frac{m_{\text{air}}}{M_{\text{air}}}\right] \quad (1)$$

Air leak rate into the system can be estimated using HEI charts with respect to volume of equipment and

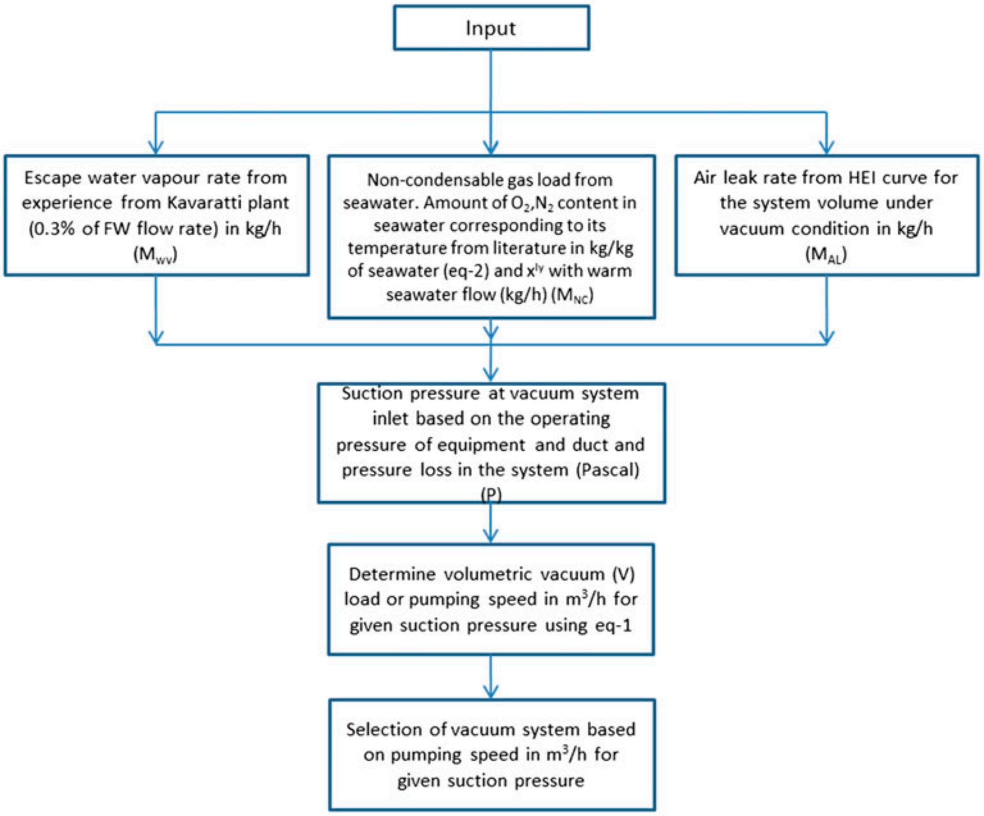

Fig. 3. Methodology for determining the volumetric vacuum load for selection of vacuum system pumping speed.

pipelines, which are under vacuum. NC gas release rate from the sea water is estimated as shown in Eq. (2).

$$m_{NC} = m_{ww} . m_{nc} \quad (2)$$

where m_{nc} = load of non-condensable gases (oxygen, nitrogen) present per kilogram of warm surface sea water [15,16] and m_{ww} is the mass flow rate of feed surface sea water (kg/h).

3. Effect of pressure drop in process equipment on vacuum load—an experimental and theoretical study

During the experiment, a pressure drop of around 2–3 mbar (maximum) is observed between evaporator and condenser. As the pressure drop between the equipment increases, the operating pressure in the condenser decreases, which resulted in increase in volumetric vacuum load of pump as a result of increased specific volume of gases as depicted in the Fig. 4. Timely variation of operating pressure and vacuum load due to tidal level variations is indicated in Figs. 5 and 6, respectively. Volumetric vacuum load for the

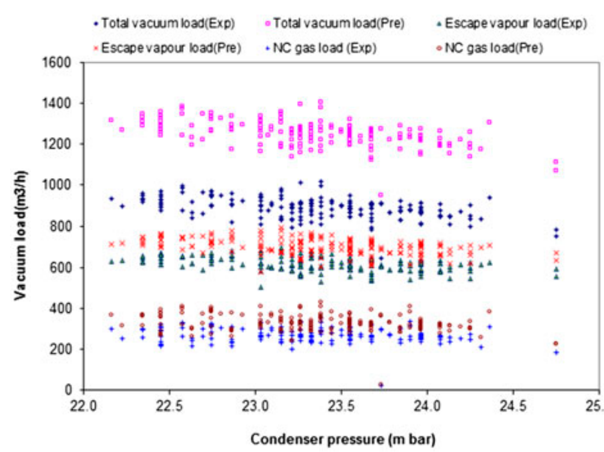

Fig. 4. Condenser pressure vs. vacuum load.

vacuum system mainly depends on the pressure at which it sucks the gas mixtures from the equipment. Drop in the suction pressure of the vacuum system mainly happens because of the restriction to the flow of gas mixtures locally caused by mist-eliminator inside the evaporator and friction loss in the vapour duct. That ultimately develops differential pressure

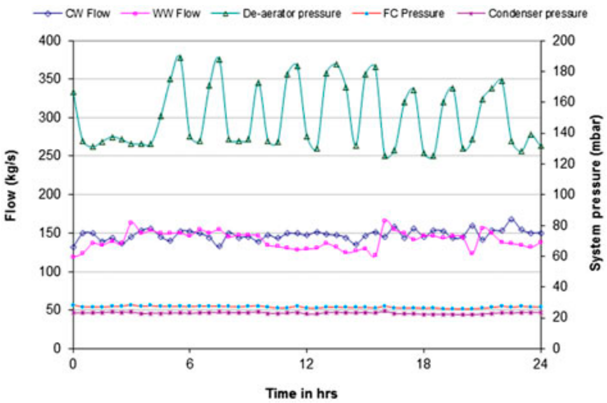

Fig. 5. Time vs. operating parameters.

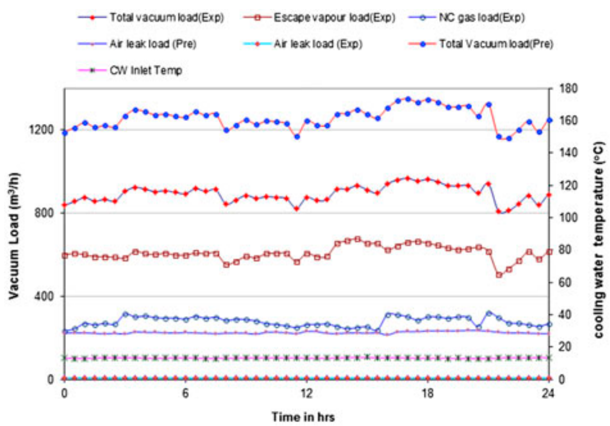

Fig. 6. Time vs. vacuum load.

between the evaporator and condenser even though they are interconnected as a single unit. This event leads to drop in pressure at the inlet suction of the vacuum system. Fig. 7 depicted the increment of total vacuum load as the suction side pressure of vacuum system decreased and Fig. 8 depicted the development of an additional load to vacuum system when condenser pressure dropped below 27 mbar (designed pressure) as a result of duct and mister-eliminator losses. If the load to the vacuum system is designed without considering the drop in operating pressure due to the internal friction losses, then the plant performance would be greatly affected. A situation would occur in which the required saturation pressure in the evaporator could not be maintained that ultimately ended up with reduced plant production.

4. Effect of molecular weight of gas mixtures on vacuum load—a theoretical study

Molecular weight of components of gas mixtures plays an important role in the determination of volumetric load to the vacuum system. Even though the mass flow rate of all the gas components remains same, still the volumetric vacuum load of each of the gas differs from other. This could be due to the difference in their molecular weight. Calculation showed that gas with high molecular weight has given minimum load rather than the gas with low molecular weight for the same mass flow rate, pressure and temperature (Fig. 9). This could be due to the fact that a gas with lower molecular weight for the given mass flow increases the number of moles which in turn increased the volumetric vacuum load (Fig. 10). For

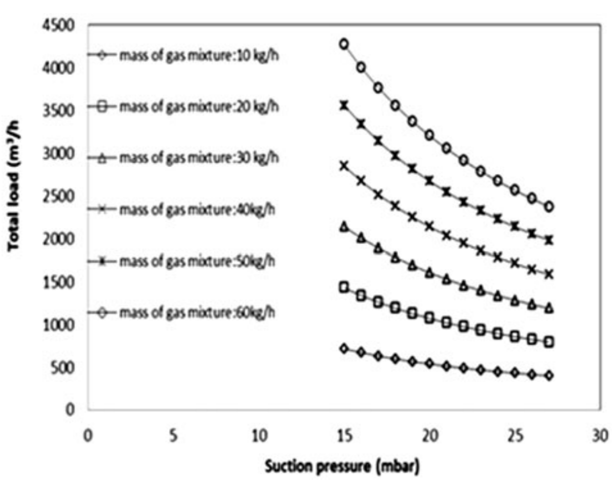

Fig. 7. Suction pressure vs. total vacuum load.

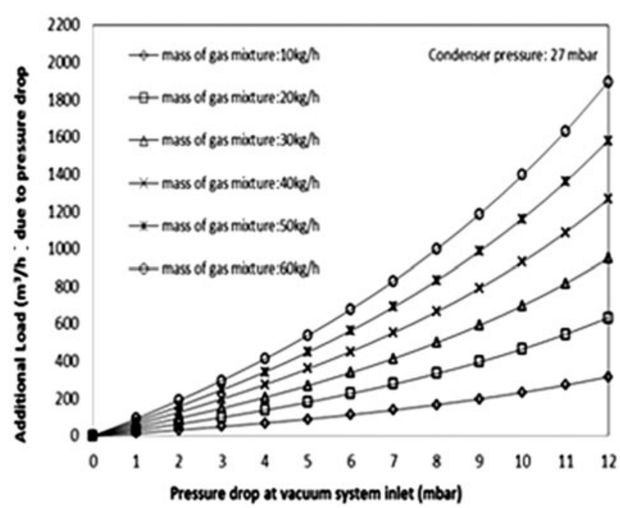

Fig. 8. Vacuum load vs. drop in pressure.

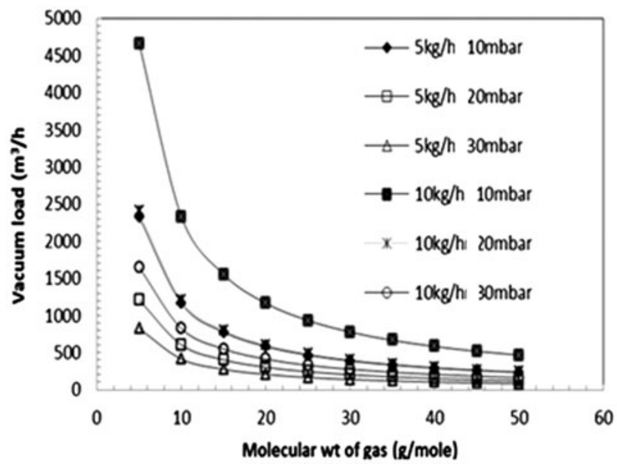

Fig. 9. Molecular weight vs. vacuum load.

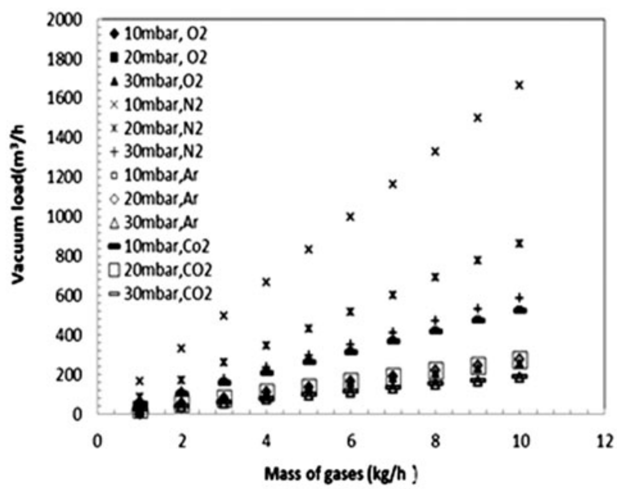

Fig. 10. Mass flow of gases vs. vacuum load.

example, one mole of O_2 gas contains 32 g weight of molecules, whereas one mole of CO_2 possesses 44 g of molecules. For the same mass flow rate and pressure of gas, the number of moles for O_2 is found to be greater than CO_2. As shown in Table 1, an increase in mole counting lead to an increase in the volumetric vacuum load for the same mass flow rate of gas compound. It is also shown in the Table 1 that the gas with low molar mass gives high vacuum load as a result of increased mole counting under the same operating conditions and mass flow rate. The variation in vacuum load for different mass flow rate of gas mixtures under different suction pressure is shown in the Figs. 11–13. Increase in mass flow rate or decrease in the system pressure lead to an increase in the vacuum load. Reduction in system pressure leads to increase in the specific volume of the gas molecules due to increase in the intermolecular distance between the molecules that in turn increases the load to the vacuum system. Vacuum pump spent most of its energy in decreasing the gap between the adjacent molecules during the evacuation.

5. Experimental set-up and measurement procedure

Vacuum system of Agatti consists of equipment such as roots pump, intermediate condenser and the base vacuum pump with total power consumption of around 13.5 kW. Schematic diagram of Agatti is shown in Fig. 14 and picture of Kavaratti and Agatti vacuum system is shown in Figs. 15 and 16, respectively. The suction line from the main condenser connected to the roots pump through main butterfly valve, which controls the load to the vacuum system. Water vapour escape rate from the main condenser is measured using intermediate condenser inbuilt within the vacuum system. Air leak rate into the system is measured using vacuum transmitters provided in the process equipment such as evaporator and the condenser. Similarly, to measure NC gases, warm water flow rate is very essential. This flow rate is measured using insertion-type flow meter. The objective of the experiment is to compare the theoretically predicted vacuum load with the measured vacuum load and to find out how close the developed methodology predicted the vacuum load towards the experimental results. Observed water vapour escape rate of Kavaratti is used as an input for theoretical vacuum load estimation for Agatti plant. HEI chart is used for air

Table 1
Change in vacuum load with respect to mole counting under the same operating condition and flow of gas

Compound	Mass flow (m) (kg/h)	Suction pressure (m bar)	Temperature (K)	Molar mass of gas (M) (kg/k mole)	Number of moles (n = m/M)	Vacuum load (m^3/h)
N_2	10	20	291.15	28.01	0.35	424
O_2	10	20	291.15	32.00	0.31	375
CO_2	10	20	291.15	44.01	0.22	266

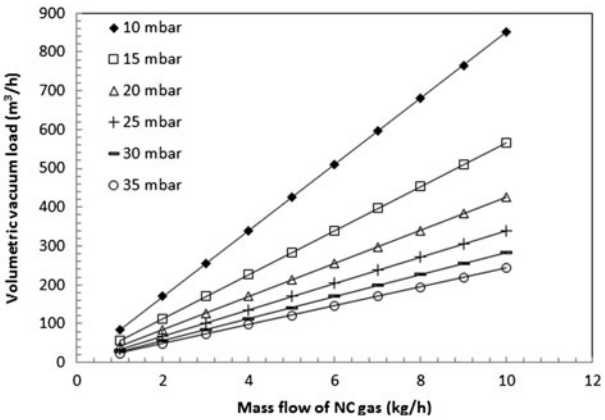

Fig. 11. Mass flow of NC vs. vacuum load.

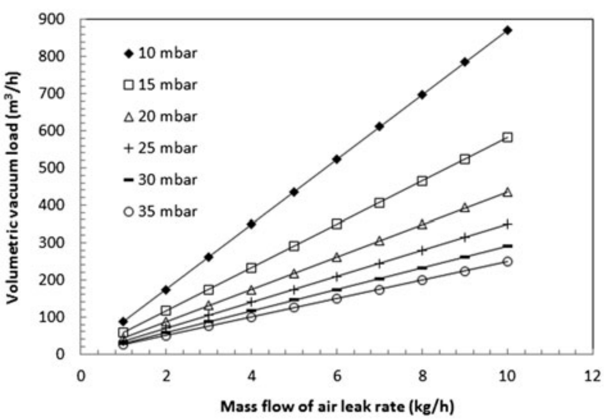

Fig. 12. Mass flow of air vs. vacuum load.

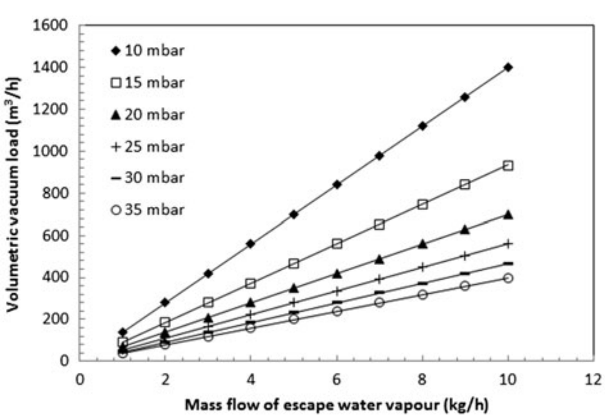

Fig. 13. Mass flow of escape vapour vs. vacuum load.

leak rate estimation and NC gas quantity present in sea water is obtained from the literature [15,16]. Air leak test is conducted for 24 h with a system volume of 33.33 m^3 and raise in system pressure is observed to be around 40.2 mbar 22.25–58.75 mbar. Similarly, non-condensable gas release test is conducted for 10 min in which the warm water flow rate is maintained constant at 105 kg/s with vacuum system to evaporator completely isolated by closing the main valve and increase in system pressure is observed. The pressure increased from 22.71 to 69.18 m bar (Fig. 17).

6. Results and discussions

6.1. Accumulated effect of non-condensable (NC) gases on vacuum load of LTTD process

Amount of non-condensable gas presence depends on the temperature of sea water (29˚C) at which it is supplied to the plant. Amount of these gases released inside the process equipment depends upon the mass flow rate of feed sea water as shown in Figs. 18 and 19. It is reported in the literature that even 1% wt. by volume of NC gas has the ability to reduce the heat transfer coefficient by 50% [11]. It is observed from the experiment that the increase in non-condensable gas flow rate increased the water vapour escape rate which is equivalent to 60.4% of the total vacuum load. It is estimated that non-condensable gas content in the sea water would be in the range of 14–16 mg/l and it goes maximum up to 19.2 mg/l [15,16]. The percentage of the NC gases to the generated vapour flow rate is in the range of 0.19–0.27% maximum corresponding to the maximum feed water flow rate (648 tons/h) that enters the evaporator. Even though its contribution on the vacuum load is found to be less compared to escape water vapour, still it played a major role in increasing the escape rate of the water vapour. This is due to the fact that the non-condensable gases give resistance to heat transfer that takes place between the water vapour and condensate film formed on the outer surface of the cooling tube as discussed earlier which may increase the chances of more quantity of water vapour to escape to the vacuum system. A decay in equipment efficiency in thermal desalination plants due to non-condensable gas interference is wrongly attributed to fouling formation on tubes [17], but in LTTD plants, the fouling on condenser tubes seems to be having insignificant effect. The difference in partial pressure between the water vapour with respect to its temperature and the saturation pressure of the condensed liquid film formed on tube outer surface with respect to its temperature decides the heat transfer rate between the two fluid streams [18]. If the saturation temperature of the water vapour reaches sub-cooled temperature, then most of this

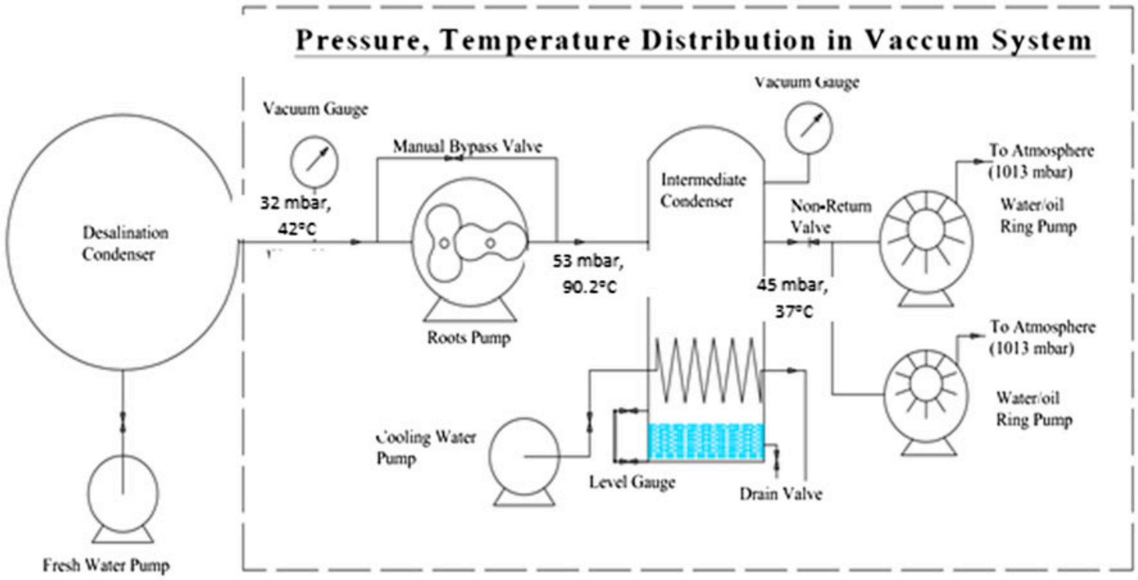

Fig. 14. Schematic diagram of Agatti LTTD vacuum system.

Fig. 15. Vacuum system in Kavaratti.

water vapour would be sucked by the air removal vacuum pump due to poor condensation rate that resulted in increased load of water vapour compared to non-condensable gases. If the partial pressure of the water vapour is greater than the saturation pressure of the liquid film on the tube surface with respect to its temperature, then condensation takes place even though the percentage of NC gas presence near the tube surface is greater [18] as a result of mass diffusion. This event would lead to reduced escape vapour rate from the process condenser and hence the vapour escape load.

In the present study, the water vapour entered the condenser tube bundle on the top in a super-heated state. As it passes across the tube bundle, it loses its sensible heat and finally condensed to form potable water on the cooling tube surface at saturation temperature. Partial pressure of water vapour gradually decreases as it moved downwards across the tube bundle due to partial condensation of vapour that finally resulted in reduced vapour concentration and decreased temperature driving force available between the cooling tube surface and vapour. This happens especially when the vapour reaches the bottom

Fig. 16. Vacuum system in Agatti.

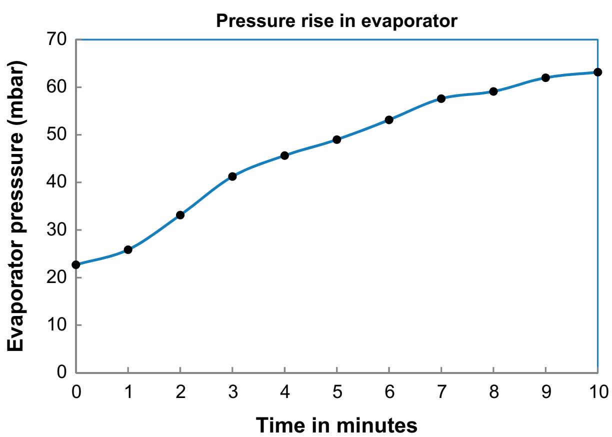

Fig. 17. Pressure rise in evaporator for a period of 10 min.

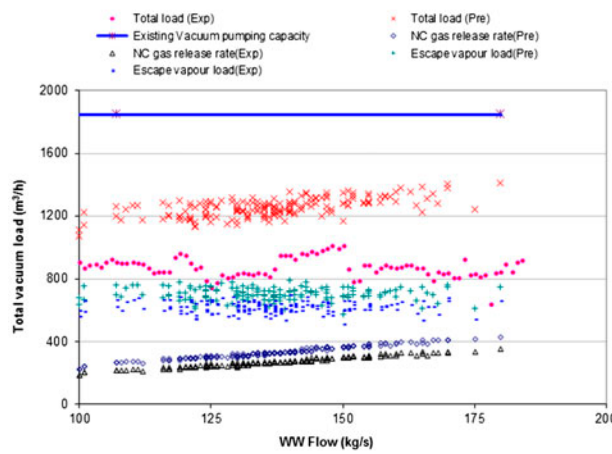

Fig. 19. WW flow vs. vacuum load.

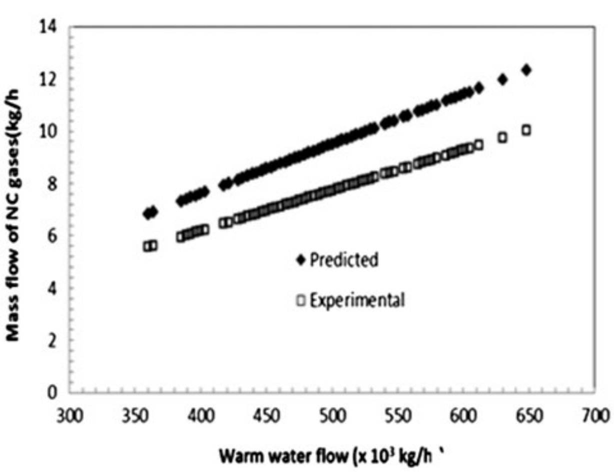

Fig. 18. WW flow vs. mass of NC gas.

portion of the tube bundle, where the vacuum suction port is located. On the other hand, the partial pressure of the non-condensable gas increases gradually from top to bottom of the tube bundle that resulted in decreased condensation rate, increased inert concentration, increased escape vapour rate and hence the vacuum load. However, supplying low cooling water temperature inside the tube decreases the escape vapour load to a certain extent. This could be due to increase in convective heat transfer rate as a result of increase in the temperature difference between water vapour and inlet cooling water temperature circulated in the first tube pass. The U_o value of the condenser would be greater on the top of tube bundle due to the higher concentration of water vapour compared to non-condensable gases where the vapour is initially at its dew point temperature and film coefficient would be almost closer to the pure condensing coefficient for water vapour. As the water vapour progressed into the tube bundle, its concentration gradually decreased that resulted in decreased potential for diffusion of vapour into the gas mixture with NC gas towards the condensate film on the tube surface. This lead to reduced vapour condensation coefficient that would certainly affect the U_o value of condenser and it finally resulted in increased vapour escape load. It is reported that 100 times variation is possible in U_c value for condensation of vapour in the presence of non-condensable gas between the inlet and outlet of the condenser [18].

The suggestions to control the effect of non-condensable gas on the LTTD process performance are as follows:

(1) Introduction of deaeration chamber before the process equipment can help in removing a portion of dissolved gases.
(2) Increase the residence time of sea water inside the deaeration chamber may improve the removal rate of dissolved gases.
(3) Release rate of dissolved gases present in the sea water can be enhanced by creating some kind of disturbances in the flow passage of water entering into the deaeration chamber such as tube bundles, packed beds, dimple tubes and rods. However, this may increase the power consumption of the feed water pump due to flow obstruction. Tube bundles or rods may be a better choice since it would give less pressure drop compared to other configurations.
(4) Splashing of sea water increases the surface area which in turn increases the possibility of the release rate of the dissolved gases in the deaeration chamber.
(5) Improvement in the flashing efficiency may be possible to a certain extent when the water is deaerated before splashed into the evaporator.
(6) Removal of a portion of dissolved gases in the deaeration chamber may reduce the vacuum pumping size and hence the power consumption. This is due to the fact that, the operating pressure of the chamber is in the range of 160–180 mbar, so its specific volume would be 3.5 times lesser (approx) when compared to the same gases evacuated from the condenser where the operating pressure is in the range of 18–22 mbar. This would marginally reduce the load on the air removal vacuum pump.
(7) Removal of NC gases prior to the process equipment can improve the performance of the condenser.

6.2. Degassing of non-condensable gases in LTTD process—an experimental study

The removal of non-condensable gas from sea water and air leakage into the system through flange connections and gaskets are the two factors that decide the vacuum pumping power and hence the total power. During the plant shutdown conditions, the air leak rate is observed for a period of 24 h and the vacuum pressure is increased from 22.27 to 58.75 mbar which comes to around 0.29 kg/h for a system volume of 33.33 m^3. While the plant is running, a test is conducted to estimate the degassing by isolating the vacuum system suction line from the plant equipment at 22.71 mbar (8:32:02 am) and feed warm water flow rate is maintained at 105 kg/s and after 10 min gap, the vacuum level is raised to 63.18 mbar (8:42:15 am) as shown in Fig. 17.

This raise in pressure is due to vapour generation, degassing and air leakage. The water vapour generated in the evaporator is condensed in the shell-and-tube condenser using deep-sea cooling water that is still flowing inside tubes. The water vapour escaped from process condenser is collected at intermediate condenser of the vacuum system and is measured as 11 kg/h. Therefore, above vacuum raise is due to non-condensable gas released from the warm feed surface sea water and ambient air leak in to the system. Comparison of experimental results with published data for validation is shown in Table 2. It is reported that, in the ME system, the extraction of vapour from the evaporator unit linked with a removal of 10–20 units of vapour corresponded to every unit mass of NC gases [17]. But in the present study, for the LTTD process, it is measured that 1.6 unit of vapour (approx) is extracted corresponding to every unit mass of NC gases released in warm feed sea water that flows into the evaporator, this could be due to low operating temperature range of LTTD process and use of low-temperature deep-sea cooling water from the ocean in the condenser.

6.3. Escape water vapour rate in the LTTD process—an experimental study

By conducting suitable experiment in pioneer plant of similar capacity located at Kavaratti, the vapour escape rate for given warm water flow rate is obtained. Measured escape vapour rate is found to be around 0.3% of the vapour condensed in the process

Table 2
Comparison of demonstration desalination working conditions and corresponding non-condensable gas and air leak loads

Description	Measured values: Kavaratti [10] (Published data)	Measured values: Agatti % diff.	Estimated values Agatti
Non-condensable gas load	8.21 kg/h	6.90 kg/h 16	7.44 kg/h
Air leak rate	1.10 kg/h	0.29 kg/h	4 kg/h[a]
Warm water flow rate	105 kg/s	105 kg/s	105 kg/s
System volume	42 m^3	33.33 m^3	33.33 m^3
System pressure rise in 10 min	31.2 mbar	40.47 mbar	–
Warm water inlet temperature (avg)	29˚C	29˚C	29˚C

[a]Estimated using HEI air leakage curve.

Table 3
Comparison of vacuum load of Agatti LTTD plant

Components of vacuum load	Estimated vacuum load (kg/h)	Measured vacuum load (kg/h)	% Diff.
Item description			
Escape vapour (WV)	13[a]	11[b]	15
NC gas release (NC) Total load (NC + WV)	7.44 20.44	6.90 17.90	7.7 14.1
Air leak rate	4[c]	0.29	92.75
Total load	24.44	18.19	25.57
In terms of volumetric vacuum load-total	1,405 m^3/h @ 20 mbar	1,017 m^3/h @ 20 mbar	
Operating conditions			
WW flow rate (kg/s)		105	
CW flow rate (kg/s)		165	
Saturation pressure (mbar)		20	
CW inlet temperature (˚C)		12.25	
Warm water inlet temperature (avg)		29˚C	
Freshwater flow (kg/s)		1.18	

[a]Measured data from experiment conducted at Kavaratti from intermediate condenser collection tank after installing the after-condenser.
[b]Measured from intermediate condenser collection tank at Agatti.
[c]Estimated using HEI air leakage curve.

condenser. These data are given as an input for theoretical calculation for Agatti plant and calculated values are validated with the measured values of Agatti plant as shown in the Table 3. From the comparison, it is observed that the least percentage difference between experiment and predicted escape water vapour rate is found to be around 15% average. Air leak rate into the system is experimentally measured by conducting leak test for 24 h and leak rate is determined as 0.29 kg/h which is far less than the predicted air leak rate of 4 kg/h obtained from HEI charts for corresponding system volume and operating pressure. This could be due to the fact that all air leak flange joints are ensured with maximum leak proof tightness. For this, the difference in percentage comes to 92.75% average between measured and predicted which is indicated in Table 3. Percentage of difference between predicted and measured total vacuum load is found to be around 25.5% (average). In the year 2008, a modification is performed in the Kavaratti plant in which a small shell-and-tube after-condenser is introduced in between the main process condenser and the suction side of the vacuum system (Fig. 20). This is done to reduce the escape water vapour load from main condenser to the vacuum pump. Before the installation of the after-condenser, the vapour escape rate is measured to be in the range of 30–34 kg/h and after installation, the water vapour rate escaped to vacuum pump is reduced to 13–18 kg/h, whereas in the Agatti plant, the vapour escape rate is measured

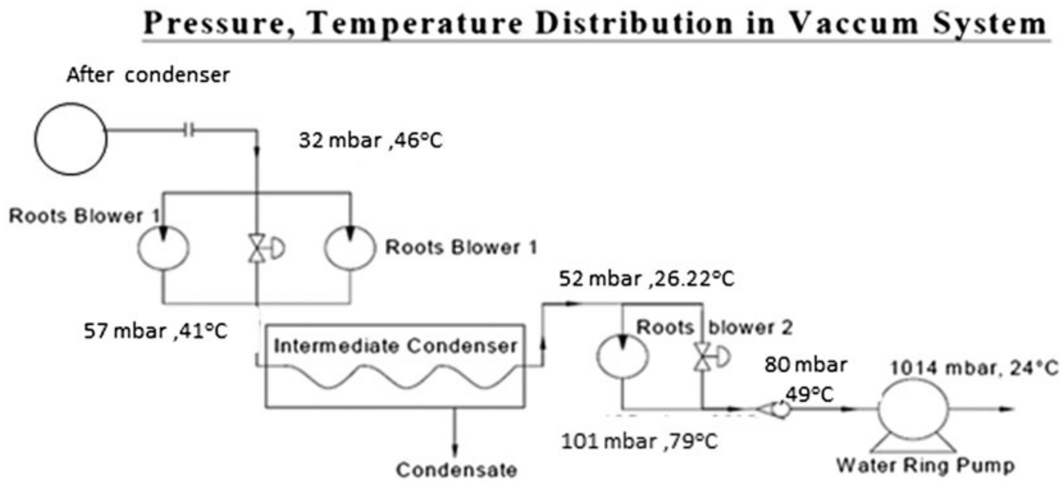

Fig. 20. Schematic diagram of Kavaratti LTTD vacuum system with after-condenser.

to be around 11–14 kg/h for the corresponding feed water flow rate that varied between 105 and 180 kg/s, which could be due to optimized condenser design done using HTRI software for Agatti plant.

Some of the factors that would increase the water vapour escape rate at site and suggestions to control are as follows:

(1) Selection of higher capacity vacuum pump for the given vacuum load may lead to quick evacuation of uncondensed water vapour from main condenser before they condensed to form liquid. Hence, determination of vacuum load closer to true value is essential which can be obtained to certain extent using the methodology presented in Fig. 3.
(2) Amount of dissolved gases and their presence in certain areas of the condenser tubes would increase the chances of more amount of vapour to escape the condenser. This could be averted if deaeration of sea water is done effectively.
(3) Temperature of the cooling water circulated inside the condenser tubes also plays an important role in controlling the escape vapour rate. If there is a raise in cooling water temperature due to local leak in cooling sea water pipeline, then there would be a possibility for increase in water vapour escape rate. This could be due to reduced heat carrying capacity of the cooling water in process condenser. Pipeline should be inspected periodically for any leak.
(4) Maldistribution of water vapour all along the condenser length and across the tube bundle in the shell side also influences the escape rate of water vapour. Some portions of the tubes may be idle with no water vapour flow in that region resulted in more escape rate of water vapour from the process condenser. Proper design of baffle placement and arrangement of distributor plate may avert this problem.
(5) Inadequate mass flow rate of cooling water resulted in increased escape vapour rate from the process condenser. Trapped dissolved gases inside the cooling water tubes may restrict the free flow of cooling water in some of the tubes especially at the top portion of condenser. This event lead to increased water vapour escape rate due to reduced condenser performance as a result of reduction in the heat transfer area of the tubes. However, this could be avoided by doing periodic venting of the trapped gases from the tube-side water box.
(6) Formation of fouling on the tubes as generally observed in thermal desalination plants and thermal power plants due to high operating temperature would greatly reduce the heat transfer rate of the condenser, this would certainly lead to poor condensation of vapour which in turn resulted in increased vapour escape rate. However, in the present study, the physical observation on the condenser tubes did not show any significant formation of bio-fouling on the tubes [19]. Also, the scale formation on the tubes due to salt content of sea water is not observed which could be due to low operating temperature range of process liquid.
(7) Poor design of process condenser may also lead to increase in the escape vapour rate.

7. Conclusion

Experience from the operation of vacuum system in Island LTTD plants helps in predicting vacuum load close to the measured values for plants of similar capacity. Hence, the power requirement can be optimized to a great extent. Experiment conducted at Kavaratti showed that escape water vapour rate was around 0.3% of the freshwater generation rate of the LTTD plant. On comparing the experimental results of non-condensable gas release rate of Agatti plant with the published data and predicted values using methodology, an agreement up to 16 and 7.7% was obtained, respectively, for the same operating conditions. Also, an agreement up to 15% was obtained between the experimental results of Agatti plant with that of predicted value for water vapour escape rate and also with the data of Kavaratti. Also, it was estimated from the experimental study carried out at Agatti plant that at least 60.4% of total vacuum load was contributed by escape water vapour rate alone followed by non-condensable gas (37.9%) and air leak rate (1.5%). It was reported in the literature that, for ME desalination system, the extraction of vapour from the evaporator unit linked with a removal of 10–20 units of vapour corresponded to every unit mass of NC gases [17]. But in the present study, for the LTTD process, it was measured that 1.6 unit of vapour (approx) was extracted corresponding to every unit mass of NC gases released in warm feed sea water that flows in to the evaporator, this could be due to low operating temperature range of LTTD process and use of low-temperature deep-sea cooling water from the ocean in the condenser.

Nomenclature

V	—	volumetric vacuum load ($m^3\ h^{-1}$)
R	—	universal gas constant (Jk $mole^{-1}\ K^{-1}$)
T	—	temperature of gases (K)
P	—	pressure of the gases (Pa)
m_{vap}	—	vacuum load of escape water vapour ($kg\ h^{-1}$)
M_{vap}	—	molar mass of water vapour ($kg\ mole^{-1}$)
m_{NC}	—	vacuum load of NC gases ($kg\ h^{-1}$)
M_{NC}	—	molar mass of NC gases ($kg\ mole^{-1}$)
M_{AL}	—	vacuum load of air leak into system ($kg\ h^{-1}$)
M_{AL}	—	molar mass of atmosphere air ($kg\ mole^{-1}$)
m_{ww}	—	mass flow rate of warm sea water ($kg\ s^{-1}$)
m_{nc}	—	mass of NC gas in /kg of sea water ($kg\ s^{-1}$)

Abbreviation

LTTD	—	low-temperature thermal desalination
NC gases	—	non-condensable gases
UT	—	union Territories
HEI	—	heat exchanger institute
WW	—	warm sea water
CW	—	cooling sea water
FW	—	fresh water flow
Vac	—	vacuum system
Mis	—	miscellaneous

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