Influence of non-condensable gases on performance of the low temperature thermal desalination plants

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This article addresses the effect of non-condensable (NC) gases on the thermal performance of condensers used in Low Temperature Thermal Desalination (LTTD) plants utilizing natural ocean temperature gradient as well as waste heat recovery from process plants. The NC gases that flow along with the water vapour cause local reduction of heat transfer in the condenser and leading to high operating power and cost escalation. A computational investigation was performed and results showed that with increase in NC gases concentration, there was a decrement in overall heat transfer coefficient, increment in uncondensed water vapour and thus reduction in yield.

Keywords: Condenser, desalination, low temperature thermal desalination, non-condensable gases.

Introduction

SEAWATER desalination technology has become a viable solution to meet the demand for potable water in many areas of the world. A cost effective desalination technology that utilizes temperature difference between the warm and cold water bodies named as Low Temperature Thermal Desalination (LTTD) has been developed at the National Institute of Ocean Technology (NIOT), MoES, India. LTTD works on the principle of utilizing temperature gradient between two water bodies, i.e. one at higher temperature than the other[1,2]. In this process, a fraction of the warmer water gets evaporated at low pressures known as flashing and the resultant vapour condenses on the surface of the colder water to produce pure water. Natural thermal gradient between different layers of the ocean water column provides huge reservoirs of warm water (surface seawater) and cold water (deep seawater) that can effectively be utilized. The temperature gradient available at process plants, where large quantities of waste seawater as warm water and surface seawater as cold water, have also been utilized.

Land-based LTTD plants were established at Kavaratti, Agatti and Minicoy islands in Lakshadweep, India[1–4]. Each has a capacity of 100 m³/day and are under continuous operation. A 1000 m³/day barge mounted LTTD plant at 40 km off Chennai coast and a 150 m³/day coastal thermal power station based LTTD plant working with waste heat available from the power plant condenser discharge water have been demonstrated[3].

The advantages of LTTD plants include non-requirement of pre-treatment of feed water, low operational and maintenance costs, environmental friendly, availability of an assured quality of the product water (TDS according to the BIS/WHO standards), low risk of scaling, corrosion and thermal pollution[1–5]. LTTD technology has been shown to be highly competitive among the other desalination technologies by considering the economic, environmental and ecological costs[6].

The condenser among the mechanical components required to operate the LTTD plants contributes major portion of the capital and operational costs. The condensation mode of heat transfer is used in engineering because of the high heat transfer coefficients achieved. The condensation heat transfer is degraded significantly due to the presence of any non-condensable (NC) gases with the condensing water vapour. Moreover, reduction in heat transfer due to the NC gases plays a vital role at low pressures and low Reynolds numbers of the mixture[7]. Nitrogen, oxygen and argon represent approximately 99% of the total dissolved gases by volume in seawater. The influence of the NC gases on the heat transfer coefficient (HTC) and yield is significant when the initial mass fraction is over 0.1%. As this parameter increases to 1%, the HTC is decreased up to 10% (ref. 8). The rise in partial pressure of the NC gases near the film reduces the vapour pressure and correspondingly the saturation/condensation temperature. Depression of saturation temperature causes reduction in thermal performance of condenser by about 10–20% predominantly at low temperatures[9]. A typical design assumption for Multi Stage Flash (MSF) distillers is an average sub-cooling of about 1 K, which results in 10–20 kg of steam extraction with each kg of NC gases[10]. Low HTC, reduction of saturation temperature and carryover of water vapour with NC gases lead to increase in heat transfer area, inlet mass of water vapour, cold stream flow rate of the condenser and volumetric gas load of the vacuum system. The former two effects result in increase in the capital cost up to 3.5%, since more heat transfer

area is required compared to pure water vapour condensation for this application, leading to more number of tubes in the condenser and the latter two effects result in increase in the operating cost up to 2.5% of the system, due to the requirement of higher cold water pumping power. This implies that even though the amount of non condensable gases is small, its impact on the heat transfer coefficient is high. The heat transfer coefficient drops significantly, thus resulting in reduction in freshwater production up to 1%. Hence the study of NC gases has vital role in the design of thermal desalination condensers, especially at low operating pressures. This article addresses the quantification of dissolved NC gases liberated during the flashing of seawater and validated with the experimental data available in the literature. A computational investigation was performed using Heat Transfer Research Institute (HTRI) Xchanger Suite® (Xist module V 7.2.1) software, which was found to be better for this type of applications compared to other similar softwares[11]. The condenser performance was compared with and without the presence of NC gases during the water vapour condensation. The influence of the inlet temperature of cold stream (cold seawater) was also presented. This analysis was carried out for two cases, i.e. LTTD based on natural ocean temperature gradient and waste heat recovery from thermal power plant.

Quantification of NC gases

Estimation of mass of NC gases liberated from seawater

Major gases such as N_2, O_2, Ar and CO_2 are dissolved gases in feed seawater, apart from trace gases. According to Henry's law, solubility of a gas in a liquid is directly proportional to the partial pressure of the gas above the liquid. Henry's law is given in eq. (1).

$$p = K_H \times C, \tag{1}$$

where p is the partial pressure of the gas above the sea water (atm), K_H the Henry's constant and C is the concentration of the gas in seawater (mol/l).

When the temperature of a liquid increases, the solubility of gas in a liquid decreases. Hence the Henry's constant will also change. Van't Hoff gives the effect of temperature on Henry's constant according to eq. (2).

$$K_H(T) = K_H(T^\theta) \times \exp\left\{-C_v \times \left[\frac{1}{T} - \frac{1}{T^\theta}\right]\right\}, \tag{2}$$

where $K_H(T)$ is the Henry's constant for any given temperature, $K_H(T^\theta)$ the Henry's constant for the standard temperature, C_v the Van't Hoff Constant of a gas, T

the temperature (K) and T^θ is the standard temperature (298.15 K).

At the given pressure and temperature of feed seawater, concentration of individual gases has been calculated using eqs (3)–(6).

Sea water flow rate in l/sec

$$Q_{sw} = m_{sw} \times \rho_{sw}, \tag{3}$$

where Q_{sw} is the sea water flow rate (l/s), m_{sw} the mass flow rate of seawater (kg/s) and ρ_{sw} is the density of seawater (kg/m³).

Partial pressure of respective constituents in atm

$$p = \frac{\% \text{ of constituent by volume}}{100} \times p_{atm}, \tag{4}$$

where p_{atm} is the atmospheric pressure (atm).

Concentration of gas in solution in mol/l

$$C = \frac{p}{K_H(T)}. \tag{5}$$

Mass of each constituent of NC gases per kg of seawater in ppm

$$m_{nc} = C \times M \times 1000. \tag{6}$$

where m_{nc} is the mass flow rate of NC gases (kg/s) and M is the molar mass of gas (g/mol).

By using above equations, the dissolved capacity of NC gases in seawater at various temperatures and pressures was estimated. Hence the difference in dissolved capacity gives the maximum possible amount of NC gases liberated from the seawater when it is exposed to low pressure with respect to ambient pressure. Figure 1 shows the combined effect of temperature and pressure on dissolved capacity of NC gases per kg of seawater. Hence
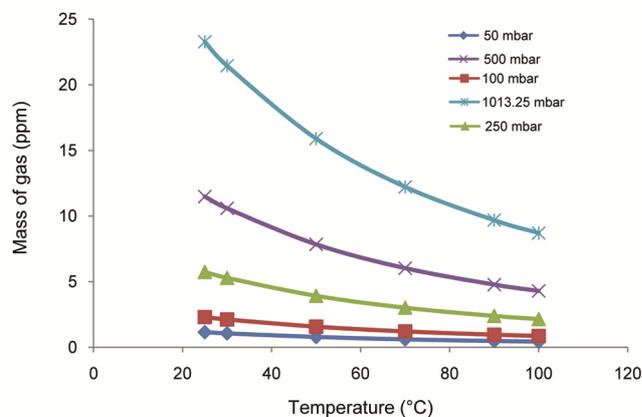

Figure 1. Effect of temperature and pressure on dissolved capacity of NC gases per kg of seawater.

Table 1. Amount of NC gases liberated during flashing in the case of LTTD based on natural ocean temperature gradient

Gas component	Mass of NC gases dissolved per kg of seawater		
	Temperature: 28°C Pressure: 1013.25 mbar (ppm) (a)	Temperature: 28°C Pressure: 25 mbar (ppm) (b)	Amount of NC gases liberated per kg of seawater (ppm) (a–b)
N_2	12.9	0.3	12.6
O_2	8.3	0.2	8.1
Ar	0.4	Insignificant	0.4
CO_2	0.5	Insignificant	0.5
Ne, He, H_2, CO		Insignificant	

Table 2. Amount of NC gases liberated during flashing in the case of LTTD based on waste heat recovery from thermal power plant

Gas component	Mass of NC gases dissolved in 1 kg of seawater		
	Temperature: 39°C Pressure: 1013.25 mbar (ppm) (a)	Temperature: 39°C Pressure: 56.5 mbar (ppm) (b)	Amount of NC gases liberated per kg of seawater (ppm) (a–b)
N_2	11.1	0.6	10.5
O_2	6.8	0.4	6.5
Ar	0.3	Insignificant	0.3
CO_2	0.4	Insignificant	0.3
Ne He, H_2, CO		Insignificant	

with known input conditions (pressure and temperature) of the feed seawater and vacuum pressure maintained in the flash chamber, it is possible to estimate the dissolved capacity of NC gases in seawater before and after flashing.

Validation of procedure developed for estimation of NC gases

The theoretically used methodology and equations for estimating the mass of NC gases liberated during flashing were validated using an experimental study[12] reported for similar application in the literature. The operational parameters considered in the literature are surface seawater temperature from 28°C to 30°C, pressure is 33.1 mbar and mass flow rate of seawater is 105 kg/s. NC gases are found to be 8.21 kg/h (21.7 ppm) experimentally. According to the above mentioned methodology and equations for the same conditions, the calculated value of NC gases is 21.4 ppm and 20.7 ppm for seawater temperature of 28°C and 30°C respectively. Variations observed between experimental and analytical value were about 1.24% and 4.42% less for both temperature cases. This may be due to the difference in salinity of seawater and experimental uncertainty in measurement.

Mass of NC gases for the selected process parameters

For the selected process parameters, amount of NC gases liberated during the flashing process was estimated

according to methodology mentioned above. Tables 1 and 2 show the mass of individual gas components and the total gas per kg of seawater for the selected two LTTD applications. As gas dissolving capacity of seawater is inversely proportional to temperature and directly proportional to pressure, the net amount of NC gases liberated per kg of seawater is lower in case of waste heat recovery-based LTTD plant compared to natural ocean temperature gradient-based LTTD plant.

Estimation of air leakage rate

The other source of NC gases in this process is simple penetration of air through small holes and pores in the component flanges, connections, pipes, etc. This is significant as process components are operated under vacuum. Hence air leakage (w) was calculated using eq. (7)[13].

$$w = 5 + (0.0298 + 0.03080 * \ln(p') - 0.0005733 * \ln(p')^2) * V^{0.66}. \quad (7)$$

It is a function of operating pressure (p') and total volume (V) of the components. Volume of the components depends on the production rate and quality of potable water.

Design parameters

LTTD plants at Lakshadweep Islands operate with temperatures of around 28°C and 12°C for warm and cold

Table 3. Design parameters of LTTD plant

Parameter	Unit	LTTD – natural ocean temperature gradient	LTTD – waste heat recovery from thermal power plant
Warm seawater temperature	°C	28	39
Cold seawater temperature	°C	12	30
Condenser pressure	mbar	25	56.5
Fresh water production capacity	MLD	1	
Condenser TEMA type		AXL shell and tube condenser	
Tube outer diameter	mm	25.4	
Tube length	m	12	
Tube material		Cu–Ni 90/10	
Air leakage rate (approx.)	kg/hr	25	
Mass of NC gases liberated during flashing	kg/hr	101.7	147.8

Table 4. List of cases considered in the analysis

Name	Details
Case I(a)	Pure water vapour condensation – LTTD based on natural ocean temperature gradient
Case I(b)	Water vapour and NC gases mixture condensation – LTTD based on natural ocean temperature gradient
Case II(a)	Pure water vapour condensation – LTTD based on waste heat recovery from thermal power plant
Case II(b)	Water vapour and NC gases mixture condensation – LTTD based on waste heat recovery from thermal power plant

Table 5. Condenser parameters for all cases

Parameter	Case I(a)	Case I(b)	Case II(a)	Case II(b)
Overall heat transfer coefficient (W/m^2 K)	1682	1548	2055	1854
Drop in saturation temperature of hot stream (°C)	1.75	8.53	0.38	4.39
Uncondensed water vapour (%)	0	0.33	0	1.04
Mass flow rate of cold water (kg/s)	1390	1425	1983	2004
Heat transfer area (m^2)	3823	3956	5451	5553
Fresh water generation (MLD)	1	0.9967	1	0.9896

water respectively[1–4]. Venkatesan *et al.*[14] have conducted various experiments by using power plant condenser reject seawater and reported that the temperature difference between warm and cold seawater is about 9°C in any season. Thoothukodi Thermal Power Station (TTPS) in Tamil Nadu discharges thermal effluent at the rate of 115×10^6 litres/day into the adjacent water body with temperature ranging between 40 and 44°C (ref. 15). The process parameters that are most suitable for design of the LTTD plant for the respective applications are shown in Table 3. Theoretically, the leakage rate of air through small openings, if they can be regarded as orifices or short nozzles, is constant at vessel pressures below 53% of atmospheric pressure[16]. Shell and tube condenser was designed considering the parameters mentioned in Table 3 for both the selected cases. Sum of air leakage rate and NC gases liberated during the flashing process is considered as total NC gases present in the condensation process, as composition of both are same.

Results and discussions

Effect of NC gases on the condenser performance for the two LTTD applications is discussed below and Table 4 shows the list of cases. Under the considered process parameters and limits, condenser performance parameters are shown in Table 5 for all cases.

Comparing case I(b) with case I(a), overall HTC was reduced by 7.96%, heat transfer area and flow rate of cold seawater was increased by 3.47% and 2.52% respectively. The same trend was observed for case II(b) with case II(a) as 9.78%, 1.87% and 1.05% correspondingly.

The variation of overall HTC on the plane for all cases is shown in Figure 2 *a*, *b*. Significant degradation in overall HTC can be observed in case of water vapour condensation in presence of NC gases compared to pure water vapour condensation. As water vapour condensation begins at the top and progresses towards the bottom, HTC also reduces proportionally. This is due to the decrease in mass ratio of water vapour to NC gases with condensation process and increase in partial pressure of NC gases. Minor variation is observed from front to rear head, since the selected shell type 'X' causes even distribution of hot stream at inlet of the shell. Pure water vapour condensation also shows minor variation in reduction of HTC, due to frictional pressure drop on the shell side.

The variation of hot and cold stream temperatures on the same plane for all cases is shown in Figure 3 *a–d*. In case of water vapour condensation in presence of NC gases, condenser was provided with additional heat
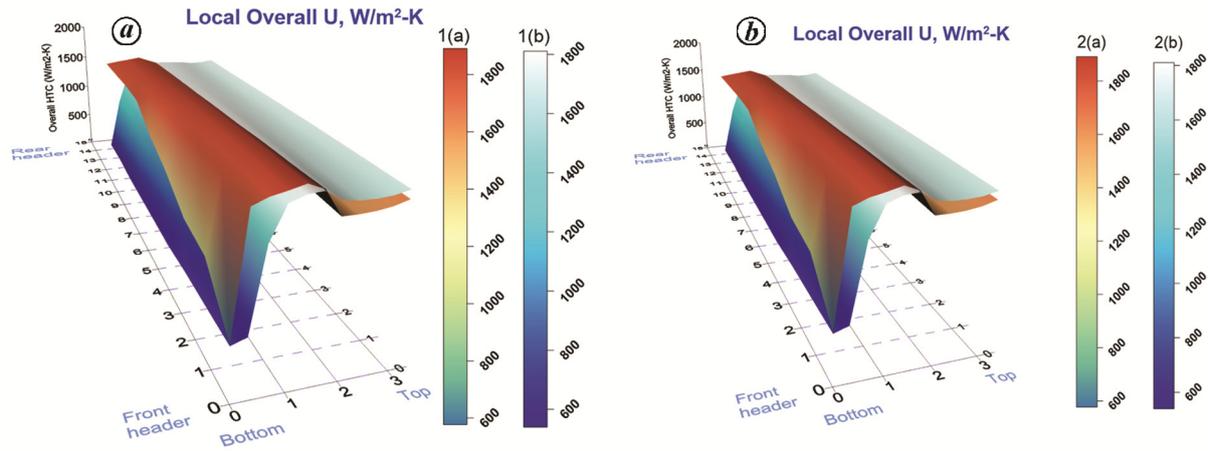
Figure 2. Overall HTC variation in condenser for: *a*, cases I(a) and I(b); *b*, cases II(a) and II(b).
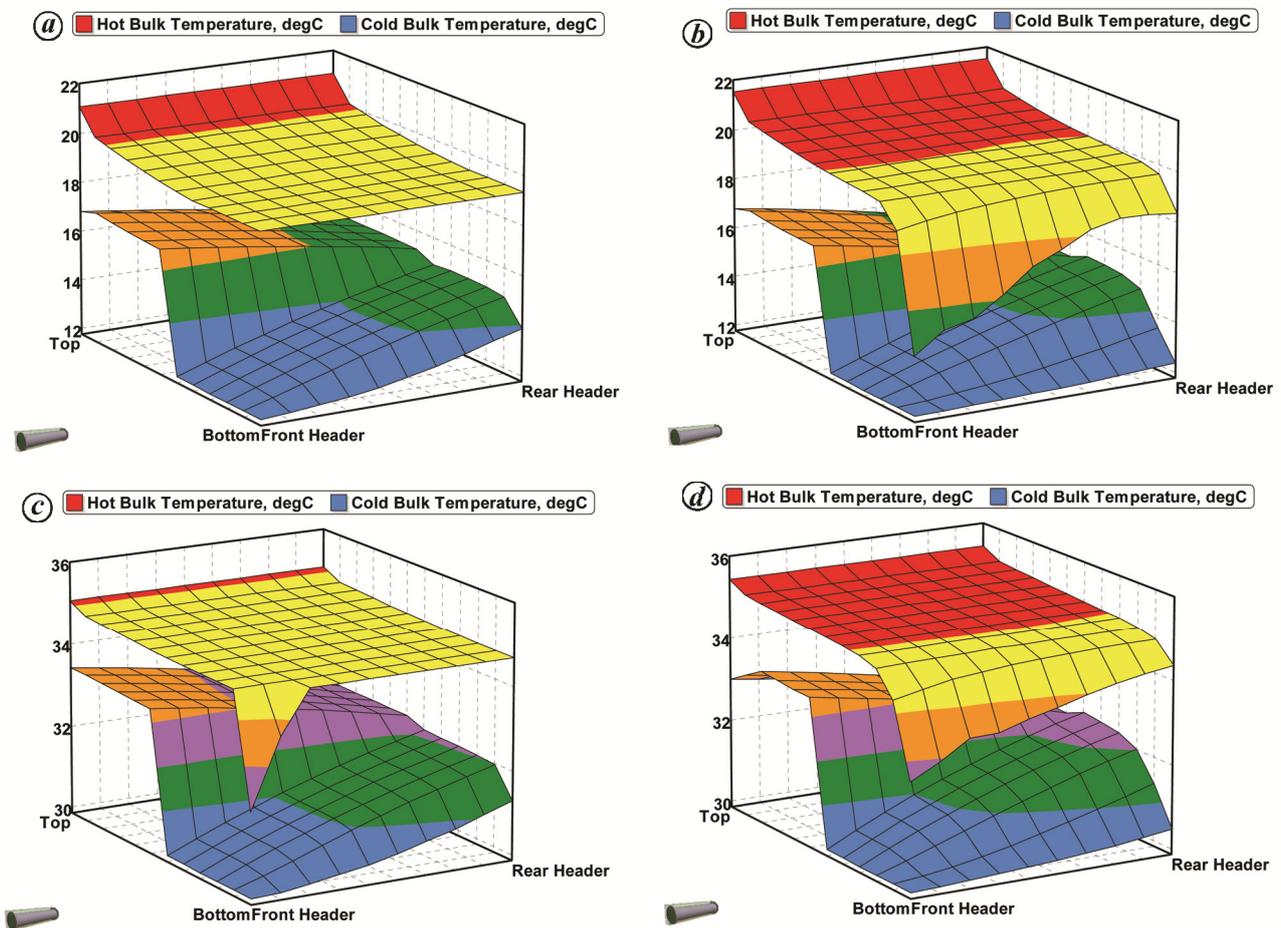

Figure 3. Hot and cold stream temperature profile for: *a*, case I(a); *b*, case I(b); *c*, case II(a); *d*, case II(b).

transfer area and cold water flow rate to achieve the maximum possible condensation. Even so, it results in certain amount of uncondensed water vapour. This is due to the drop in saturation temperature of hot stream similar to that of cold stream, where further heat

transfer is not possible even by providing extra heat transfer area.

Comparing case I(b) with case II(b), percentage of uncondensed water vapour is less in the former case, due to the availability of higher total temperature gradient
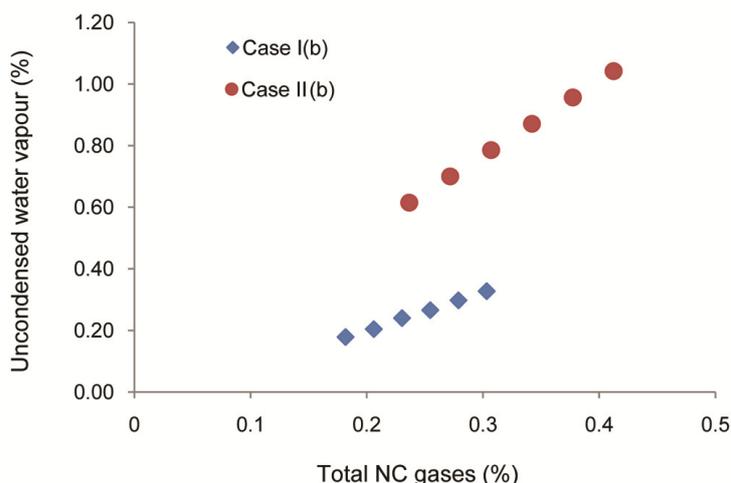
Figure 4. Effect of total percentage of NC gases on uncondensed water vapour for cases I(b) and II(b).
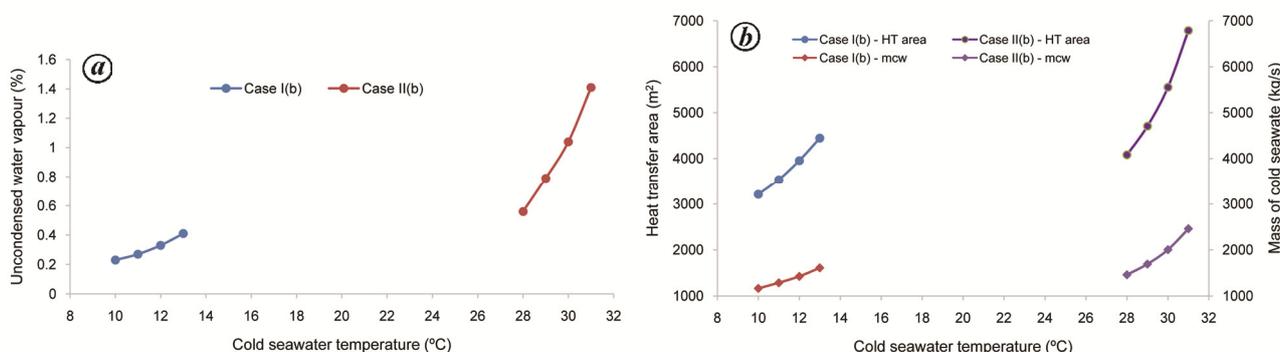

Figure 5. *a*, Influence of cold seawater temperature on uncondensed water vapour for cases I(b) and II(b); *b*, Influence of cold water temperature on heat transfer area and mass flow rate of cold seawater for cases I(b) and II(b).

across the process. This allows more scope for drop in hot stream saturation temperature to achieve maximum condensation thereby resulting in low percentage of uncondensed water vapour.

NC gases significantly affect the performance of the condenser, hence it is better to avoid these gases during condensation. A de-aerator operates on vacuum degasification principle and is used to remove the dissolved gases in seawater. The percentage of total NC gases out of total mixture was varied in steps of 10% of de-aerator efficiency and up to 50% to verify the performance of the condenser under the same process conditions and limits. Figure 4 shows the decrease in uncondensed water vapour with decrease in percentage of total NC gases. This is due to mass ratio of water vapour to NC gases increases with reduction in NC gases. Hence partial pressure of NC gases becomes lower and results in small drop of saturation temperature of water vapour during condensation process. Without de-aeration of NC gases, the total NC gases in the inlet mixture (water vapour and total NC gases) of condenser is 0.3% and 0.41% for case I(b) and case II(b) respectively. At the maximum de-aeration they are 0.18%

and 0.24%, correspondingly. So the reduction in the percentage of total NC gases was observed as 40% and 42.6% for the case I(b) and case II(b) respectively. This results in reduction in the percentage of associated uncondensed water vapour of about 45% and 41%, correspondingly.

The temperature of cold stream has a significant effect on the condenser performance. Deep seawater temperature varies with depth and is mostly constant at the given depth. Surface seawater temperature may vary seasonally. Hence the effect of cold seawater temperature was studied for the cases of water vapour condensation in the presence of NC gases alone. Figure 5 *a* shows the effect of cold stream temperature on the percentage of uncondensed water vapour for cases I(b) and II(b).

For the same hot stream conditions for the respective cases as taken in the previous analysis, decrease in cold stream temperature reduces the percentage of uncondensed water vapour. It is more significant in case II(b), because it greatly varies the percentage of availability of total temperature gradient across the system, whereas in the other case this variation is less. Heat transfer area and mass flow rate requirement also get reduced with

reduction in cold stream temperature for both the cases as shown in Figure 5 *b*.

Conclusions

NC gases show adverse effect on the thermal performance of the desalination condenser. A methodology was demonstrated to quantify the NC gases liberated during the seawater evaporation process and validated with experimental results available in the literature. The deviation was found to be about 4.4%. The computational investigation was performed using HTRI Xchanger Suite software for the mentioned process parameters and limits. Between the two cases of LTTD applications, natural ocean temperature gradient and waste heat recovery from the thermal power plant, simulation results showed that NC gases reduce the overall HTC by about 8% and 10%, require extra heat transfer area by about 3.5% and 1.9% and additional cold seawater flow rate of 2.5% and 1.1% respectively. Certain amount of uncondensed water vapour was also observed about 0.33% and 1.04% for the respective cases. Hence an equal amount of uncondensed water vapour has to be generated in addition to the actual requirement to achieve net output.

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