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Scaling of low-temperature thermal desalination plants – design space exploration

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ABSTRACT

Low-temperature thermal desalination (LTTD) process uses naturally available ocean thermal gradient that is environmentally friendly with the advantage of minimum maintenance. The process deals with evaporating the warmer surface seawater at low pressures and condensing the resultant vapour using deep sea cold water available at about 350–400 m below sea level. Ministry of Earth Sciences (MoES) – National Institute of Ocean Technology (NIOT) has established LTTD plants with fresh water generation capacity of 1 Lakh Liters Per Day (LLPD) at Agatti, Minicoy and Kavaratti Islands and those plants were being run by UT administration using local manpower. The construction works are in progress for setting up the similar plants in six more islands with a capacity of 1.5 LLPD. In the view of rapidly growing population, tourism activities and to meet the long term needs in remote islands, the design studies were carried out for scaled-up LTTD plants, from 1.5 to 7 LLPD. The studies presented in this paper, facilitate us to instantly identify the size of major components and determine the preliminary cost for implementation for any capacity of the plant up to 7 LLPD, which ultimately results in significant reduction in design lead time.

Keywords: Low-temperature thermal desalination; Design; Capacity of plant; Preliminary cost estimation

1. Introduction

Climatic change and population explosion in conjunction with the rapid urban development induce stress on the traditional sources rivers, lakes and ground water and consequently there is an increasing demand for potable water in many countries. Many regions in India, are experiencing severe shortage of drinking water. Seawater desalination, using reverse osmosis (SWRO) and thermal desalination plants such as multi-effect desalination (MED) and multi-stage flash (MSF), is being implemented by the most of the developed and under developing countries for meeting their water needs. Reverse osmosis that needs intensive maintenance with most products being imported and strict pretreatment and post treatment/brine disposal requirement faces constraints in operation.

Most of the existing desalination systems are energy-intensive, imposing a heavy burden on the primary energy supply due to the need for motive steam for operation etc. Solar desalination, that uses the incident solar rays to heat the surface seawater in conjunction with an MED process is another technology that is apt for Indian conditions, especially water stressed remote coastal communities. Shahzad et al. [1] examined the efficacy of a multi-effect distillation (MED) system operated with thermocline energy from the sea and the system increased the desalination efficiency

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by two folds, attaining 18.8% of the thermodynamic limit. Chen et al. [2] proposed a desalination system combining the direct-spray technology and multi-effect distillation (MED), which is named spray-assisted multi-effect distillation (SMED). This study included reduced internal losses, higher productivity, and smaller heat transfer areas which resulted in increase in fresh water productivity by 35%, while the pumping power consumption and required heat transfer area are reduced by 58% and 17%, respectively. Chen et al. [3] presented a study with thermocline desalination system using the direct spray method. Thermodynamic and techno-economic analyses were conducted for the thermocline-driven spray desalination system. The major design and operating parameters are observed to have conflicting effects on the water productivity, required heat transfer area, and specific energy consumption. An optimal trade-off of these effects is observed when the system has 2 stages and the cooling water flowrate is 33% higher than the seawater flowrate. Under the optimized conditions, the life-cycle desalination cost ranges from \$1–1.5/m^3.

Ministry of Earth Sciences (MoES) – National Institute of Ocean Technology (NIOT) developed low-temperature thermal desalination (LTTD) technology and installed 100 m^3/d plants in Kavaratti (2005), Minicoy and Agatti (2011) islands of UT Lakshadweep. The naturally occurring ocean thermal gradient is used in the process to evaporate surface water at low pressure and condense the resulting fresh vapour using deep sea cold water at 12°C from about 350–400 m water depth. The process is environmentally friendly and requires low maintenance. An experimental floating barge mounted 1,000 m^3/d desalination plant was established in 2007, about 40 km off Chennai coast to demonstrate the utility of the process for the mainland applications. A desalination plant with 150 m^3/d capacity was established in 2009 in North Chennai Thermal Power Station (NCTPS) to demonstrate the utility of the process for any coastal thermal power plant that discharges huge amounts of condenser reject water into the nearby sea. Salient features of these plants were presented and provided the intangible benefits, like aqua culture if used in the context of the ocean thermal gradient and reduction of thermal pollution if used in the context of power plant discharge [4,5]. Balaji et al. [6] conducted the performance improvisation studies at existing plants such as water quality studies. The results based on the experimental studies showed a significant improvement in the water quality ranging from 4 to 45 ppm between low and high tides when implementing the elevated demister configuration. Al-Shayji and Abdul Mohsen [7] demonstrated application of modular and equation-solving approaches for steady-state and dynamic simulations of large-scale commercial MSF desalination plants using commercial software. Helal and Odeh [8] predicted the optimal design for a selected configuration where the total heat transfer area is minimal. The total number of stages was varied stepwise from 20–40 stages. A rigorous mathematical model has been used to solve the optimization problem taking into consideration the nonlinearity of the thermo-physical properties of seawater and steam. Results showed that, the LT-OT design will be favorable when the total number of stages is 40 or more. El-Ghonemy [9] indicated that, running the large scale thermal desalination MSF plant in cold regions is more economic than hot regions for pumping power energy saving considerations.

Despite of its abundant potential, thermocline desalination is still at its infancy stage. Most of the literatures only focus on improving the spray evaporator with little coverage on the whole system. It is felt that, there is a lack of parametric study on the most important variables, for example, the cooling water flowrate and process equipment parameters such as heat exchanger area etc. In the view of above and rapidly growing population, tourism activities and to meet the long term needs in remote islands, the design studies were carried out for scaled-up LTTD plants, from 1.5 to 7 LLPD (Lakh Liters Per Day). The results were presented in this paper. These studies enable us to instantly identify the size of major components and determine the preliminary cost for implementation for any capacity of the plant up to 7 LLPD, which ultimately reduces the design lead time significantly.

2. Components of LTTD plant

The major essential components for a LTTD plant include process equipment, Deep sea cold water pipe and marine structures. Each component and its function are detailed below. LTTD plant Commissioned at Kalpeni Island is shown in Fig. 1.

(1) Process equipment
  (a) Condenser to facilitate heat transfer between vapor and colder water without mixing;
  (b) Flash chamber to evaporate the warmer water;
  (c) Vacuum system to maintain the necessary vacuum in flash chamber and condenser;
  (d) Seawater pumps to draw warm and cold water from sea;
(2) Deep sea cold water pipe to draw cold water from a depth of 350–400 m;
(3) Marine structures
  (a) Intake structure/Sump to house the seawater pumps and to draw the water from the sea;
  (b) Bridge to carry the intake pipeline from the sump to the plant building;
  (c) Plant building to house all the process equipment and the control systems.

2.1. System and components design of LTTD plant

2.1.1. System design and thermal design conditions

The warm surface seawater at 28°C–30°C enters into the flash chamber maintained at a pressure of 27.3 mbar and the vapour generated in the flash chamber is liquefied inside the condenser with deep sea cold water at about 12°C. Schematic diagram of LTTD process is shown in Fig. 2. Three sets of pumps are mainly needed to run the plant, namely the warm water pumps to supply the surface seawater to flash chamber, the cold water pumps to supply the cold water to the condenser and the vacuum system to generate the required vacuum levels in flash chamber and condenser. The operating cost of the plant is mostly governed by the power utilized by these three sets of pumps.

Fig. 1. Commissioned plat at Kalpeni Island.

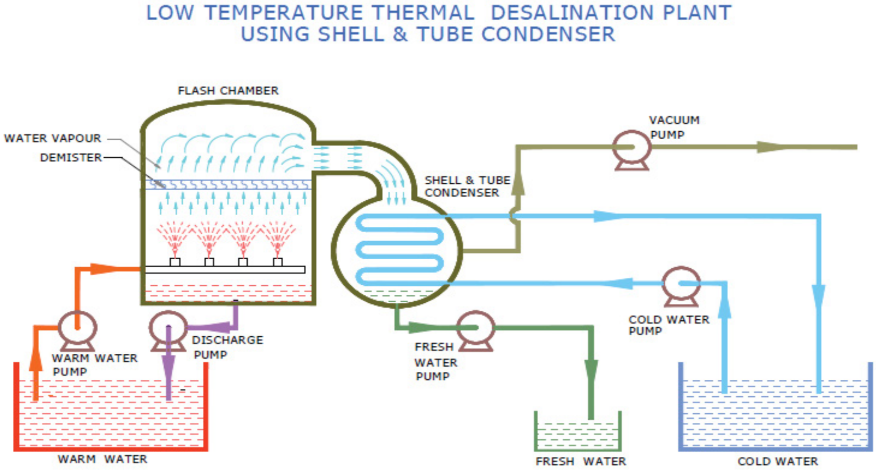

Fig. 2. Schematic diagram of LTTD working principle.

The sample heat and mass balance for the process of LTTD plant commissioned at Kalpeni Island with a capacity of 1.5 LLPD is shown in Fig. 3. A temperature drop of 4.75°C is allowed for warm water in the flash chamber and a temperature rise of 5.5°C is allowed for the cold water in the condenser. The inlet temperature of warm seawater is taken as 28°C and that of cold water 12°C. The vacuum level in the flash chamber and the condenser is maintained at 27.3 mbar abs so that the evaporation/condensation temperature is maintained at 22.5°C. It was found that the plant requirements would be optimal for this design. A comprehensive list of the thermal design parameters is provided in Table 1.

2.1.2. Design methodology

The total heat load in the system is calculated using the fresh water generation capacity and total warm water and cold water requirements were determined using heat and mass balance equations. The flow chart indicating the design methodology is shown in Fig. 4. Condenser, flash chamber, CW/WW pumps were designed using CW/WW flow rates as shown in Fig. 4. The equations used for process equipment design is provided in Table 2.

2.1.3. Deep sea cold water pipe

Inverse catenary configuration was found to be more suitable for Lakshadweep coral Islands. This configuration had the advantage of the natural buoyancy of the pipe to traverse very rugged and often very steep bottom terrain with no physical contact. The HDPE pipe was designed with inverse catenary configuration between 30 and 400 m depth and a heavily weighed down steel/HDPE pipe along the ground between 5 and 30 m depth. Necessary weights were attached to the pipe to withstand the local forces in various zones.

2.1.4. Marine structures

Marine Structures for establishing LTTD desalination plants in islands consists of (i) Intake structure/Sump to house the pumps and to draw the water from the sea. (ii) Bridge to carry the intake pipeline from the sump to the shore. (iii) Plant building to house all the process equipment and the control systems. The selection of site, design and execution of marine structure for desalination plant is critical for the timely completion of the project. All these structures were designed as per the relevant standards

(IS4651, IS456, and IS800) suitable to the prevailing environmental conditions at site.

Progressive trends in thermal desalination and general design guidelines for LTTD plant were presented in the literature [13] which includes the various thermal desalination methods including MSF, MED etc. for enhancing the domain expertise.

2.2. Major challenges in marine environment

Complex site, environmental and weather conditions are the major challenges for the design and execution of all the marine structures and also for the design of cold water pipe. Other challenges include non-availability of construction materials and equipment due to remoteness of islands, transportation of the process equipment from the port to plant location such as 5–8 m long condenser with 1–3 m diameter. Erection of the process equipment with minimum available infrastructure in remote islands. In addition to the above, there are many challenges in logistics and accommodation at remote islands including ship tickets from main land to island. With the above design methodology, design space is explored for the plant capacity starting from 1.5 LLPD to 7 LLPD. All the process equipment, Cold water pipe and marine structures were designed at conceptual level and performed the preliminary cost estimation. Also, the sensitivity studies were performed for the key system parameters such as cold water inlet and outlet temperature, saturation temperature, vapour velocity etc.

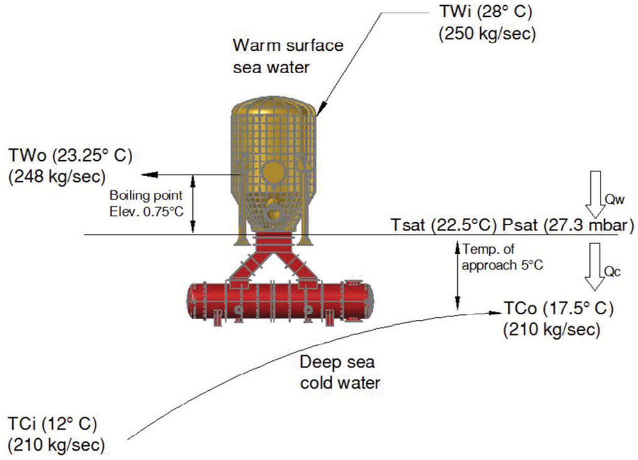

Fig. 3. Typical process heat and mass balance.

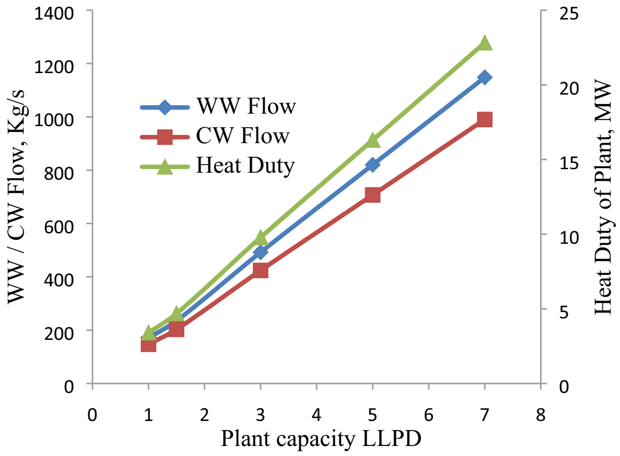

Fig. 5. System parameters of typical LTTD plant.

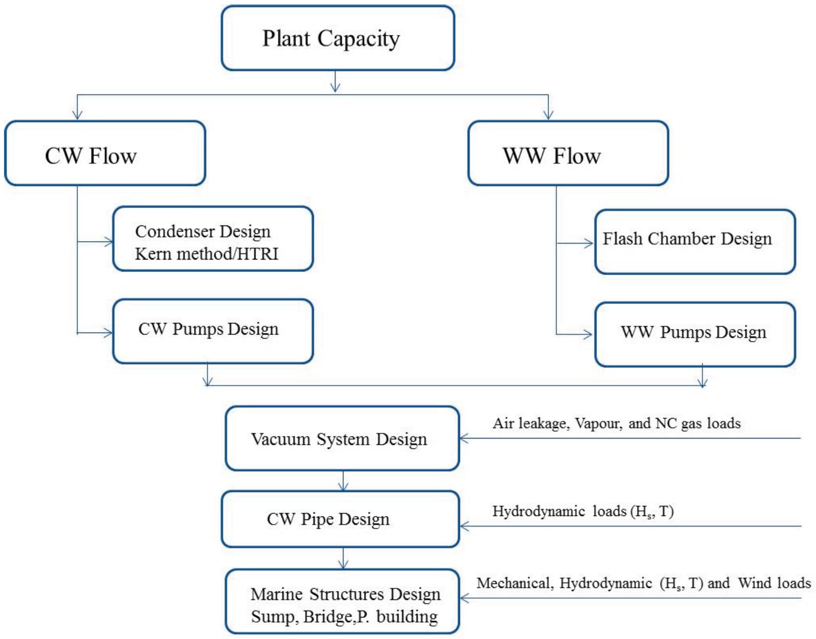

Fig. 4. Design methodologies for LTTD plant.

Table 1
System design parameters

1	Nominal capacity of the plant, L/d	1–7 Lakh
2	Design margin used, %	15
3	Fresh water generation rate, L/d	Capacity × 1.15
4	Warm water inlet temperature, °C	28
5	Cold water inlet temperature, °C	12
6	Working fluid	Seawater
7	Operation, h/d	24
8	Vacuum pressure maintained in flash chamber, mbar	27.3
9	Saturation temperature of water at 27.3 mbar, °C	22.5
10	Warm water outlet temperature T_{wo}, °C	23.25
11	Proposed cold water outlet temp T_{co}, °C	17.5

Table 2
Design equations used for process equipment

Flash chamber [10]	$k = V_v\left(\frac{\rho_v}{\rho_w}\right)^{0.5}$ $Q = m_f \times \text{LH}$
Condenser [11]	$N_T = \frac{m_c \times 4}{U_c \times \rho_c \times \pi \times d_i^2}$ $\text{Nu} = \frac{\left(\frac{f}{2}\right)\cdot \text{Re}\cdot \text{Pr}}{1.07 + \left[12.7\cdot\left(\frac{f}{2}\right)^{\left(\frac{1}{2}\right)}\cdot\left(\text{Pr}^{\frac{2}{3}}-1\right)\right]}$ $\text{LMTD} = \frac{\left(T_{\text{sat}} - T_{\text{ci}}\right) - \left(T_{\text{sat}} - T_{\text{co}}\right)}{\ln\left[\frac{T_{\text{sat}} - T_{\text{ci}}}{T_{\text{sat}} - T_{\text{co}}}\right]}$ $A_c = \frac{Q_c}{F \cdot \text{LMTD} \cdot U_m}$
Vacuum system [12]	Total load = Air leakage + Non condensable (NC) + Uncondensed vapour

and evaluated the system parameters. These results will provide the flexibility in designing the components.

2.3. Costing

Based on the previous experience, preliminary cost for components and plant is arrived. The cost of existing plant of 1.5 LLPD plant is taken as base for all the components and scaled them as per the weight increment ratio for higher capacity plants. However, this cost is preliminary and it has to be refined during the detail design.

3. Results and discussion

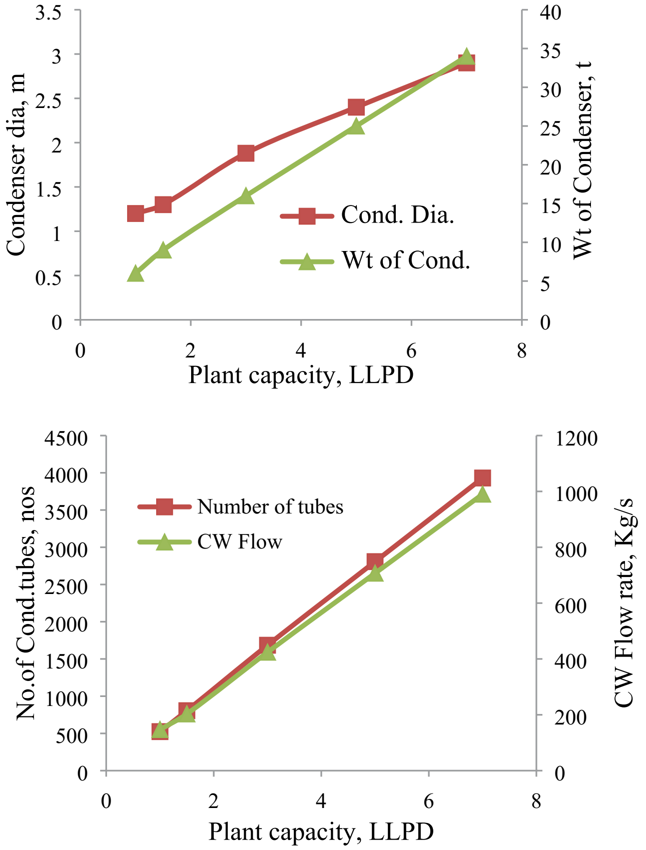

Fig. 6. Variation of condenser parameters of LTTD plant.

Design of process equipment, cold water pipe and marine structures was carried out for the plant capacity of 1, 1.5, 3, 5 and 7 LLPD using the similar inlet conditions, essentially for Lakshadweep islands conditions. The system parameters such as cold water flow and warm water flow for different capacities of the plant were obtained and flash chamber, condenser parameters were arrived based on the system parameters. Variation of System, Condenser and Flash chamber parameters are provided in Figs. 5–7, respectively. Fig. 5 shows the variation of system parameters such as heat duty of the plant, WW flow and CW flow with the change in capacity of the plant. It is observed

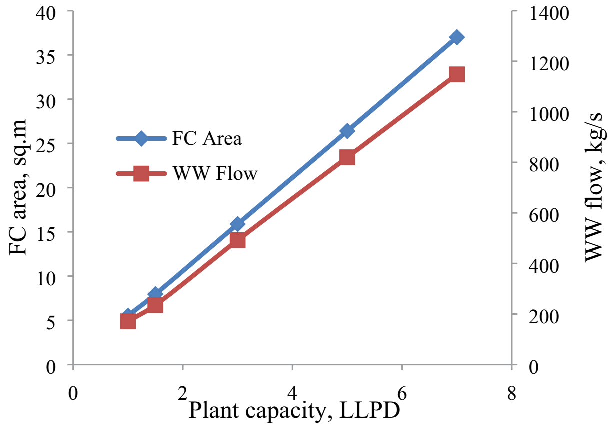

Fig. 7. Variation of flash chamber parameters of LTTD plant.

that, the rate of increase of WW flow and Heat duty is more than that of CW flow as the capacity of the plant increases from 1 to 7 LLPD.

Fig. 6 shows the trend in condenser parameters with variation of plant capacity. These parameters include condenser weight, shell diameter, number of tubes and cold water flow rate. It is clear from the plots that, condenser size and weight increases from lower capacity to higher capacity of the plant and difference in variation at lower capacities is more than that of higher capacity plants. Also, it is clear that CW flow and number of tubes follows the similar trend with the change in capacity of plants.

Fig. 7 indicates the variation of Flash chamber parameters such as flashing area/WW flow with increase in plant capacity. It is observed that, rate of increase of flashing area is more that of WW flow as the capacity of plant increases

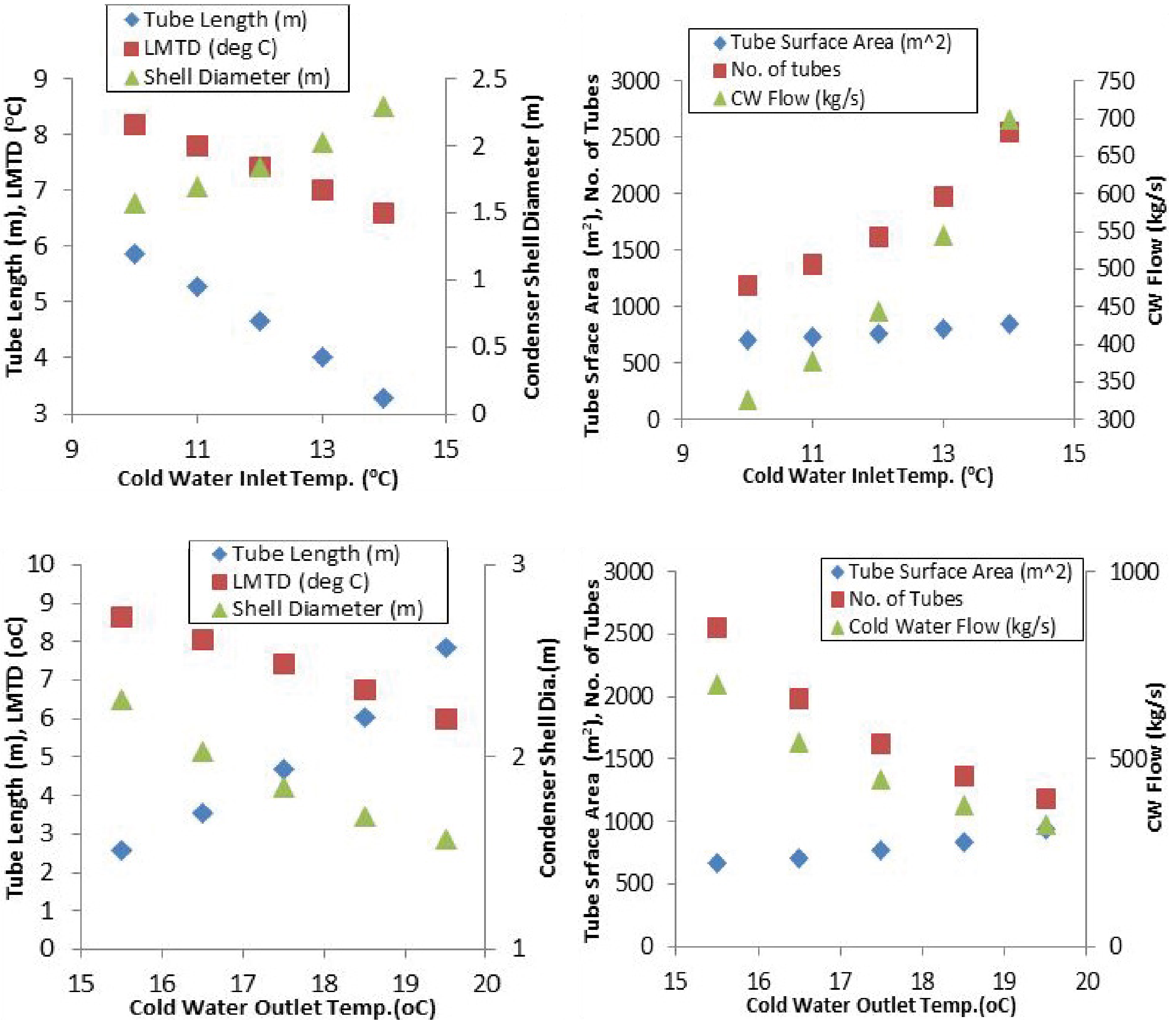

Fig. 8. Cold water inlet/outlet temperature vs. condenser parameters.

from lower capacity to higher capacity. As the flashing area increases for higher capacities, one has to think about the sizing of the flash chamber in the view of fabrication and transportation issues at the location of the plant.

Design space is explored for the condenser design by varying the saturation temperature in the range of 19.5°C–25°C and condenser approach temperature in the range of 2°C–6°C. Cold water inlet/outlet temperature were studied against the condenser parameters. Fig. 8 shows the trends and variation of key parameters with CW inlet and outlet temperatures. It is observed that, LMTD, condenser tube length decreases and shell diameter, number of tubes, CW flow increases with increase in CW inlet temperature, which my result in bigger size condenser and can lead to fabrication and transportation issues at site location. Also, observed that, LMTD, shell diameter, CW flow, number of tubes decreases and condenser tube length increases with increase in CW outlet temperature. Hence, it is necessary to identify the optimal inlet temperature and it lies between 11°C to 13°C for this study which is validated with existing plat data [11].

Preliminary cost of the components and entire plan was estimated based the cost of present and past experience of the NIOT. The cost indicated is a preliminary estimation only and the actual cost may vary during the detailed design of components. Fig. 9 shows the cost variation of process equipment, CW pipe and marine structures with that of capacity of the plants. It is identified that increment in process equipment cost is higher than that of CW pipe and marine structures. That means process equipment sizes will be keep on increasing, whereas only minor increment in CW pipe and marine structures.

Fig. 10 provides the total cost variation of the plant with respect to the capacity of the plant. The total cost of the plant includes all equipment, CW pipe, and marine structures cost, hence it refers to the capital cost of the plant. Fig. 11 variation of levelized cost of water per litre with capacity of the plant. The levelized cost is estimated with preliminary cost of the plant that is capital cost. Operational cost is very minimal for these types of plants and hence not considered for levelized cost estimation.

4. Summary and conclusions

In this work, design space is explored for different capacities of the LTTD plants from 1.5 to 7 LLPD and all the components such as flash chamber, condenser, vacuum system, seawater pumps, seawater intake structure, plant building and approach bridge were designed as per the relevant standards. The results provide the customized designs for various capacities of the plants. System level parameters, heat duty, CW flow and WW flow increases with the increase in capacity of plant and can be determined easily from Fig. 5 instantaneously. Similarly, condenser and flash chamber parameters such as number of tubes, condenser shell diameter, flash chamber area etc. can be arrived quickly from Fig. 6, which are ultimately reduces the design lead time significantly. Also, sensitivity studies performed for the key parameters such as cold water inlet and outlet temperature, saturation temperature, vapour velocity etc. will provide the flexibility in designing the individual components as shown in Fig. 7. Based on the past experience, the preliminary cost variation for the entire plant up to 7 LLPD and levelized cost of water has arrived, which ultimately helps in making decisions at higher level/the policy level.

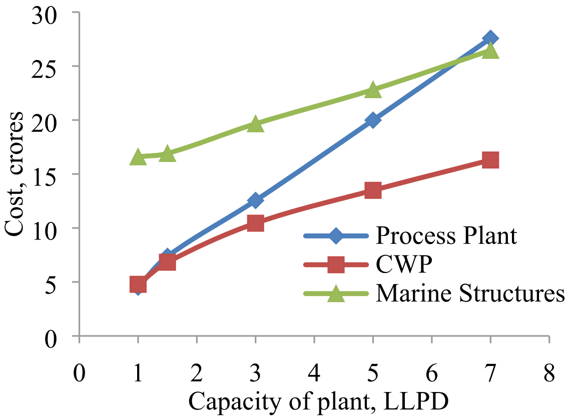

Fig. 9. Variation of cost of components of LTTD plant.

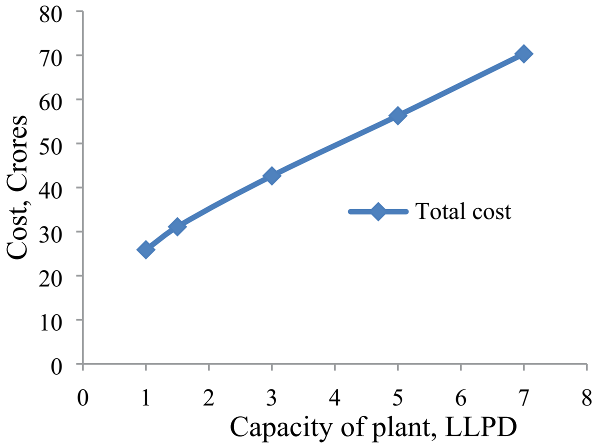

Fig. 10. Overall plant cost variation of LTTD plant.

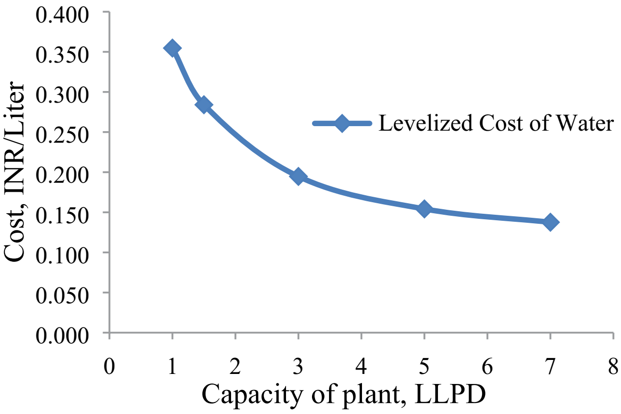

Fig. 11. Levelized cost of water per liter.

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Symbols

A — Area of the heat exchanger, m^2
Cp — Specific heat, J/kg K
LHw — Latent heat of vaporisation, J/kg
L — Length of heat exchanger, m
m — Mass flow rate, kg/s
M — Molecular weight, kg/mol
P — Pumping power, kW
Δp — Pressure drop, kPa
Q — Vacuum load, kg/hr
R — Gas constant, J/k mole K
U — Overall heat transfer coefficient, $W/m^2 K$
V — Volume, m^3
K — Entrainment factor
CW — Cold water
WW — Warm water

Subscripts

w — Warm water
c — Cold stream, cold water, condenser
h — Hot stream
i — Inner, inlet
o — Outer, outlet
f — Vapor
v — Vacuum
N — Non condensable
a — Air
sat — Saturated

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