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Feasibility study of desalination technology utilizing the temperature difference between seawater and inland atmosphere

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Abstract

A new desalination technology named Desalination Pipeline is proposed. The Desalination Pipeline system enables simultaneously desalination and efficient transport of distilled water by applying the working principle of a heat pipe without its liquid recirculation function. The energy source for the operation of the Desalination Pipeline system is the temperature difference between seawater and inland atmosphere. A formulation for the model calculation of the Desalination Pipeline system is established and verified by a laboratory experiment. And then, an estimation of the production and the transportation rates of distilled water is performed on the basis of the existing environmental and climate data of two target regions, Sana'a, the capital of Republic of Yemen, and El-Quren in Hashemite Kingdom of Jordan. The estimation result indicates that the Desalination Pipeline system can supply distilled water through one year for some inland area about 100 km apart from the coastal area at a distilled water production rate of 3.2–35.0 L/min (about 10,000 m^3/y) for a pipe with a diameter of 2 m, 19–205 L/min (about 60,000 m^3/y) for a pipe with a diameter of 4 m. The latter nearly matches the flow rate through a small qanat 60–1500 L/min.

Keywords: Renewable energy; Thermal desalination; Pipeline; Sustainable water resource; Qanat; Water transportation; Self-driven system; Heat pipe

1. Introduction

Desalination technology has already been put to wide practical use in some regions that have few water resources, as typified by various Middle Eastern oil-producing countries. The cost of seawater desalination has been reduced to approximately 0.5–0.6 US\$/m^3 in recent years, and desalinated water is now used for both domestic and industrial purposes [1].

However, it is likely that a depletion of energy-providing resources may lead to a consequential depletion of water resources in regions that mainly

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rely on desalination plants for water resources. This is due to the fact that most desalination plants that are presently in practical use consume an abundance of energy-providing resources such as oil. Furthermore, the use of desalinated water in inland areas that are far from raw water supply areas may face financial difficulties, because the financial burden of transporting desalinated water must be further added to the cost of desalination.

In this work, we, accordingly, propose a new desalination technology that enables simultaneous desalination and efficient transport of desalinated water by applying the working principle of a heat pipe [2] without its liquid recirculation function. Consequently this technology is named Desalination Pipeline. It is a distinctive feature of the Desalination Pipeline that it can transport water desalinated in its own system without consuming external energy (e.g. electric power, fossil fuels) in main parts. In construction a pipe that has sufficient buckling strength even under internal vacuum condition is laid down between sea or salt lake area where the thermal daily range is very small and inland area is located in an arid land where the temperature rapidly decreases at night because of radiation cooling. In the pipe the air is fully evacuated and wholly filled with water vapor, which flows towards the end in the inland area due to the difference in the vapor pressure caused by the temperature difference. The water condenses in the inland area and is extracted from the pipe as desalinated water. In this work, the experimental demonstration of the working principle and the model calculation for the desalination capability based on the actual environmental and climate data of target regions are conducted for the purpose of confirming the fundamental validity of the Desalination Pipeline and estimating the production rate of water desalinated by the technology.

2. Outline of the Desalination Pipeline system

The outline of the Desalination Pipeline system is schematically shown in Fig. 1. The facility consists of the following 4 parts:

- Evaporation part: a part where evaporation of raw sea or salt lake water takes place.
- Transport part: a part between the evaporation part and the condensation part where water vapor is transported.
- Condensation part: a part where water vapor condenses and distilled water is transported to the outlet.
- Outlet: a part where distilled water is extracted.

Physical principles and laws relating to water vapor behavior as the basis of this technology are as follows:

- Vapor pressure as a function of temperature becomes high as the temperature rises.
- Under the condition where the local pressure is lower than the vapor pressure, no matter how the pressure difference is small, water evaporates very much.
- Vapor flows from a high pressure side to a low pressure side.
- More water than the amount of saturated water vapor cannot exist as vapor.

As a result, the following phenomena are caused in the Desalination Pipeline system.

- Evaporation part: As the vapor pressure of water is somewhat higher than the pressure inside the pipe, as far as raw water of higher temperature is always supplied, water boils or evaporates from the free surface resulting in vapor pressure rise inside the pipe.
- Transport part: Water vapor flows from the evaporation part to the condensation part driven by the difference in the vapor pressure, or in the temperature, between both parts.
- Condensation part: The water vapor that flows through the transport part condenses, and distilled water is produced.

The above phenomena can, in fact, arise under the condition where the temperature of raw water in the evaporation part is higher than that of the

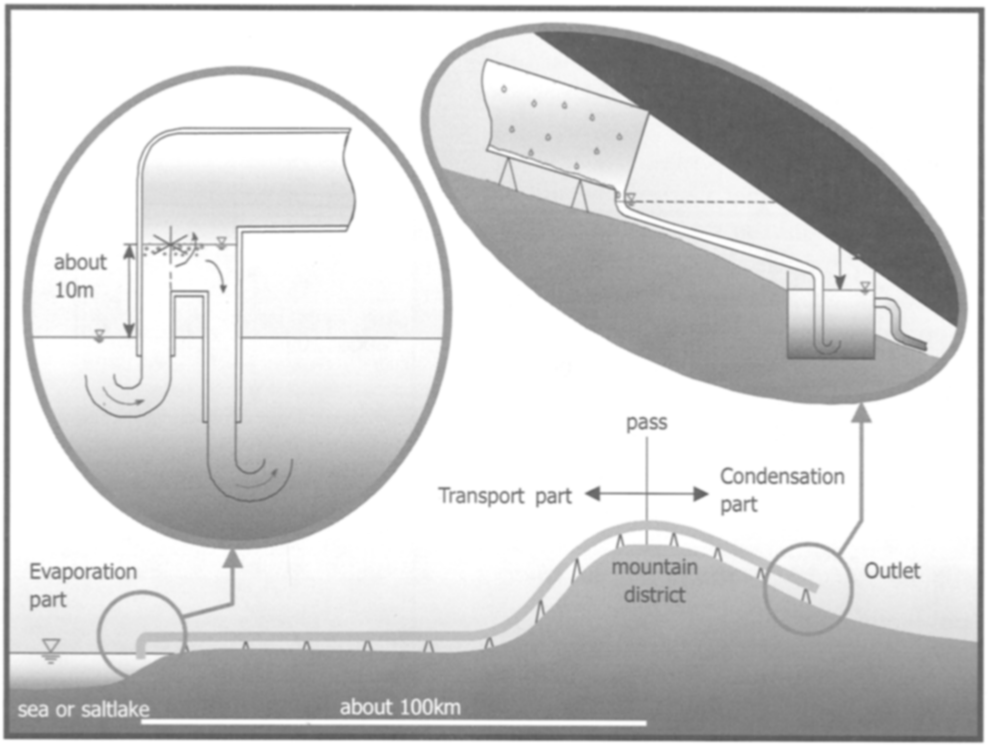

Fig. 1. Outlines of the Desalination Pipeline system.

pipe wall in the condensation part. It should be taken into account that the consumption and release of latent heat of vaporization causes the decrease in the temperature of raw water in the evaporation part and the rise in the inner wall temperature of the pipe in the condensation part. Therefore, this facility needs some mechanism to prevent the temperature of the raw water from decreasing by circulating raw water to renew in the evaporation part, and needs to prevent the inner wall temperature of the pipe wall from rising by extending the length of the condensation part to enhance the cooling rate. In the outlet, about 10-m water level difference, equivalent to 1 atm of the pressure difference, is required to allow distilled water to flow out of the pipe system, because the pressure difference between the inside and outside pats of the pipe system is about 1 atm.

3. Formulation for the model calculation

In this chapter, equations to calculate the production rate of distilled water as a function of temperature of raw water and inland climate condition are introduced respectively for the above-mentioned 3 parts (evaporation, transport and condensation parts). For each fundamental phenomenon ideal situation is assumed.

3.1. Fundamental assumptions

Fundamental assumptions for the general framework of the calculation are as follows:

- Steady state is assumed for each process.
- The transport and the condensation parts consist of straight circular pipes.
- Water vapor is treated as an incompressible fluid.

- Latent heat of vaporization is supplied from raw water in the evaporation part.
- Thermal insulation in the transport part is assumed to be perfect.
- The mode of heat transfer between water vapor inside the pipe and inner wall of the pipe in the condensation part is assumed to be film condensation, for which the averaged heat transfer coefficient is used over the total length of the condensation part.
- Outside air temperature is assumed to be uniform around the condensation part.
- The heat transfer coefficient between the outer wall of the pipe and the outside air is assumed to be uniform.

3.2. Derivation of equation system for each part

The production rate of distilled water m (kg/s) is equal to the following mass flow rates because of mass conservation;

m
= (The evaporation rate in the evaporation part)
= (The mass flow rate through the pipe) (1)
= (The condensation rate in the condensation part)

In view of the importance of the distilled water the production rate m is adopted as a fundamental parameter in the derivation of the equation system.

3.2.1. Evaporation part

In the evaporation part evaporation of raw water takes place driven by internal energy stored in seawater or salt lake water. The schematic drawing of this part is shown in Fig. 2. In this part, raw water, whose temperature tends to decrease as a result of evaporation, must be circulated to replace old cooled raw water by warm water. As the amount of heat extracted from raw water resulting in temperature decrease is equal to the latent heat of vaporization, the following equation holds:

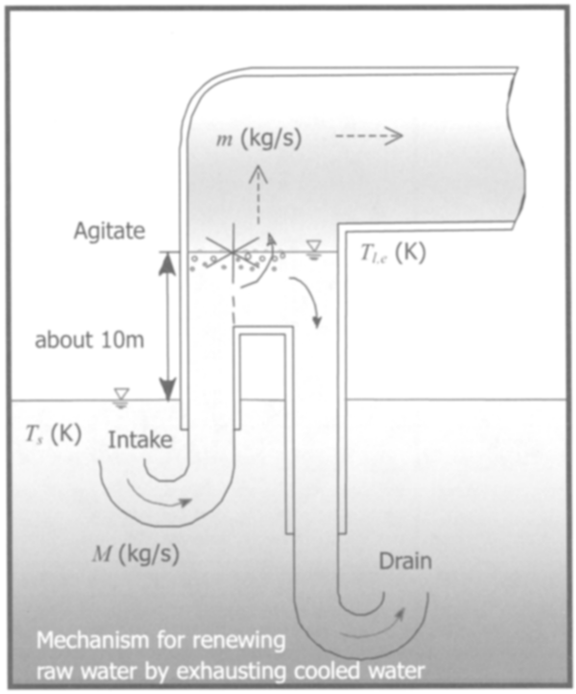

Fig. 2. Schematic drawing of the evaporation part.

$$C_P\left(T_s - T_{l,e}\right)M = m\lambda \tag{2}$$

Here C_P is the specific heat of raw water (J/K·kg), T_s is the temperature of the original raw water (K), $T_{l,e}$ is the liquid (cooled raw water) temperature around the evaporation surface (K), M is the circulated mass flow rate of raw water (kg/s), m is the evaporation rate (kg/s), and λ is the latent heat of vaporization of water (J/kg).

For a set of assumed values of the circulated mass flow rate of raw water M and the temperature decrease of raw water $T_s - T_{l,e}$, the evaporation rate m can be calculated by Eq. (2). In fact, this must be calculated through the iterative calculation described in Chapter 5.3.

The pressure loss due to evaporation ΔP_e (Pa) is described by Hertz–Knudsen equation [3,4] as follows:

$$\Delta P_e = \frac{\sqrt{2\pi\left(P_e/\rho_e\right)}\left(m/A_e\right)}{\alpha_c\left\{1-(1/2)\left(P_e/\rho_e\lambda\right)\right\}} \tag{3}$$

where P_e is the vapor pressure in the evaporation part (Pa), ρ_e is the density of water vapor in the evaporation part (kg/m^3), A_e is the evaporation area (m^2), and α_c is the evaporation/condensation coefficient.

For the circulation of raw water, a sort of single-phase thermosyphons [5] can be used, in addition to the method based on forced circulation with a pump driven by external energy. The method is based on the natural convection induced by the density difference resulting from the difference in the temperatures before and after evaporation. In the case of natural convection, enlarging the diameter of the circulation pipe can increase the circulated mass flow rate. The detail of the method of circulating raw water will be described elsewhere because it is beyond the scope of this paper.

3.2.2. Transport part

In the transport part, water vapor that is evaporated in the evaporation part is transported to the condensation part without condensing. Water vapor is driven by the vapor pressure difference caused by the temperature difference of the water between the evaporation part and the condensation part. This pressure difference ΔP (Pa) balances with the sum of the pressure loss due to the viscous drag of the vapor flow ΔP_V (Pa) and the hydrostatic pressure difference due to the difference in the elevation ΔP_H (Pa), and thus the following equation is derived:

$$\Delta P = \Delta P_V + \Delta P_H \tag{4}$$

Here the hydrostatic pressure difference is given by

$$\Delta P_H = \rho_{ave} g H \tag{5}$$

where ρ_{ave} is the average density of water vapor in this part (kg/m^3), g is the acceleration due to gravity (m/s^2), and H is the difference in the elevation (m).

The viscous drag of a pipe flow can be estimated by the following Blasius formula in the range of Reynolds number between 3×10^3 and 10^5 [6]:

$$\Delta P_V = 0.3164\,\mathrm{Re}_t^{-1/4} \frac{L}{D} \frac{\rho_{ave} u^2}{2} \tag{6}$$

where Re_t is the Reynolds number based on D, L is the total length of the transport part and the condensation part (m), D is the internal diameter of the pipe (m), and u is the mean vapor velocity in this part (m/s).

Substituting the expression for Reynolds number ($\mathrm{Re} \equiv \rho u D/\mu$) into Eq. (6) gives:

$$u = \left(\frac{2\Delta P_V}{0.3164L}\right)^{4/7} \left(\frac{D^5}{\rho_{ave}^3 \mu}\right)^{1/7} \tag{7}$$

where μ is the viscosity of water vapor (Pa·s).

The mass flow through the pipe is given by

$$m = \rho_{ave} \frac{\pi D^2}{4} u \tag{8}$$

which is evaluated for a set of parameters, D, L, H, m and ΔP through Eqs. (4), (5), (7), and (8). In fact, this value can be determined through the iterative calculation mentioned later (Chapter 5.3).

3.2.3. Condensation part

In the condensation part, water vapor condenses and the distilled water is extracted from the outlet.

The cross-sectional view of the condensation part is shown in Fig. 3. The following equation is derived in terms of three thermal resistances,

$$Q = \frac{T_{l,c} - T_f}{\dfrac{1}{2\pi r_1 h_c} + \dfrac{\ln(r_2/r_1)}{2\pi k_p} + \dfrac{1}{2\pi r_2 h_f}} \tag{9}$$

where Q is the amount of heat flow extracted per unit length of this part (W/m), r_1 is the internal

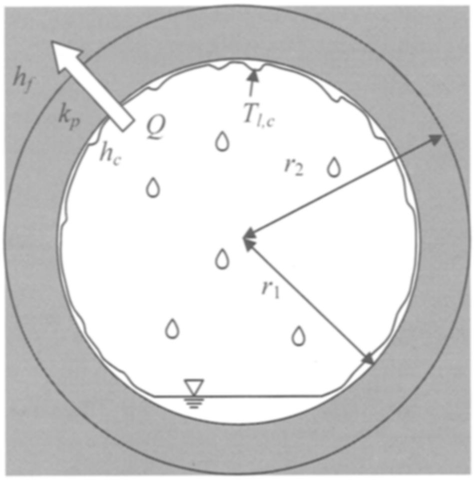

Fig. 3. Cross sectional view of the condensation part.

radius of the pipe (m), r_2 is the external radius of the pipe (m), k_p is the thermal conductivity of the pipe material (W/mK), h_c is the average heat-transfer coefficient between the water vapor in the pipe and the inner wall of the pipe (W/m^{2}K), h_f is the convective heat-transfer coefficient between the outside air and the outer wall of the pipe (W/m^{2}K), $T_{l,c}$ is the liquid temperature around the condensation surface (K), and T_f is the outside air temperature (K).

The thermal balance between the amount of heat flow exhausted to the outside air and the latent heat released by condensation of water vapor demands the relation for the condensation rate m (kg/s) as

$$m = \frac{Ql}{\lambda} \tag{10}$$

where l is the length of the condensation part (m), and λ is the latent heat of condensation of water (J/kg).

It is, consequently, seen that for a set of parameters, l, r_1, r_2, k_p, h_c, h_f, $T_{l,c}$ and T_f the rate of condensation can be calculated by Eqs. (9) and (10). This value can be determined through the process of iterative calculation (Chapter 5.3).

The pressure loss associated with condensation, ΔP_c (Pa) is described by Hertz–Knudsen equation [3,4] similar to the pressure loss due to evaporation:

$$\Delta P_c = \frac{\sqrt{2\pi(P_c/\rho_c)}\,(m/2\pi r_1 \ell)}{\alpha_c\{1-(1/2)(P_c/\rho_c\lambda)\}} \tag{11}$$

where P_c is the vapor pressure in this part (Pa), ρ_c is the density of water vapor in this part (kg/m^3) and α_c is the evaporation/condensation coefficient.

For the film condensation heat transfer inside the pipe, Shah equation [7,8] presented the following expression for the heat transfer coefficient

$$h_{c,x} = h_L\left\{(1-x)^{0.8} + \frac{3.8x^{0.76}(1-x)^{0.04}}{p_r^{0.38}}\right\} \tag{12}$$

where $h_{c,x}$ is the local heat transfer coefficient at the value of the vapor quality x (W/m^{2}K), p_r is the reduced pressure (actual pressure/critical pressure), and h_L is the heat-transfer coefficient in the case where all mass is assumed to flow as liquid (W/m^{2}K). Integrating Eq. (12) from 0 to 1 with respect to x gives the following equation as the average heat transfer coefficient h_c (W/m^{2}K):

$$h_c = h_L\left\{\frac{1}{1.8} + \frac{2.043}{p_r^{0.38}}\right\} \tag{13}$$

Here, h_L is calculated by the Dittus–Boelter equation [7]:

$$h_L = 0.023\,\mathrm{Re}_L^{0.8}\,\mathrm{Pr}_l^{0.4}\,k_l/D \tag{14}$$

where Re_L is the Reynolds number in the case where all mass is assumed to flow as liquid, Pr_l is the Prandtl number of liquid, k_l is the thermal conductivity of liquid (W/mK), D is the internal diameter of the pipe (m).

It should be noted that the mass flow in the transport part must be calculated before calculating the film condensation heat-transfer coefficient because Dittus–Boelter equation contains the mass flow rate through the pipe in the form of Reynolds number.

4. Experimental verification

A series of experiments were conducted utilizing the temperature difference between the indoor (laboratory) and the outdoor in winter to simulate the temperature difference between seawater and inland atmosphere. In the present simulation experiment tap water was used as raw water instead of saline water.

4.1. Objective

It is the purpose of the experiment to verify the working principle that distilled water can actually be obtained in a small simulation model of the Desalination Pipeline system, and the validity of the equation system.

4.2. Experiment

The system diagram and the picture of the key portions of the experimental set-up is shown in Fig. 4.

The experimental set-up consists of the following 4 parts:

- Evaporation part: The primary part is made of transparent PVC pipe with an external diameter of 114 mm and a thickness of 5 mm. A circulation pump can stabilize the circulation mass flow rate for raw water renewal, and a heater can maintain the raw water temperature at a constant level. The pipe joints are completely submerged in water seal assembly to prevent air from leaking-in.
- Transport part: This part is composed of a hard nylon tube with the length of 82 m, an internal diameter of 9 mm, and an external diameter of 12 mm. The tube is tied round in a diameter of about 50 cm, and it is placed in the laboratory where the temperature is controlled at almost the same temperature as the raw water in the evaporation part.
- Condensation part: The nylon tube with a length of 18 m, connected to the transport part, is placed in a spiral form supported by a shelf with a height of about 2 m so that the water accumulation part should be located at the bottom end.
- Accumulation part: A part where the water condensed in the condensation part accumulates. This part is composed of three pieces of pipes of transparent PVC with external diameters of 38 mm, 60 mm and 114 mm, respectively and with a thickness of 5 mm. A branch tube is connected with the vacuum pump through a valve. The vacuum pump is only used for initial air evacuation prior to experiments. All tube joints are completely submerged in a water seal assembly to prevent air from leaking-in.

The experimental procedure, whose flow chart is shown in Fig. 5, is as follows:

- The laboratory is warmed up to a prescribed temperature between 20 and 30°C.
- Tap water is introduced into the evaporation part as raw water, and the water is warmed up to nearly the same temperature as the laboratory temperature while circulating in the heater loop.
- The raw water is deaerated with the vacuum pump for about 30 min.
- The air that remains around the bottom of the accumulation part is evacuated with the valve V2 opened occasionally with an interval of a few minutes.
- The vacuum pump is turned off, after shutting the valve V1 while the valve V2 is opened.
- The water level in the accumulation part is measured every 30 min.
- The measurement is continued for 2–5 h until the distilled water level change is stabilized, and then the experiment is completed.

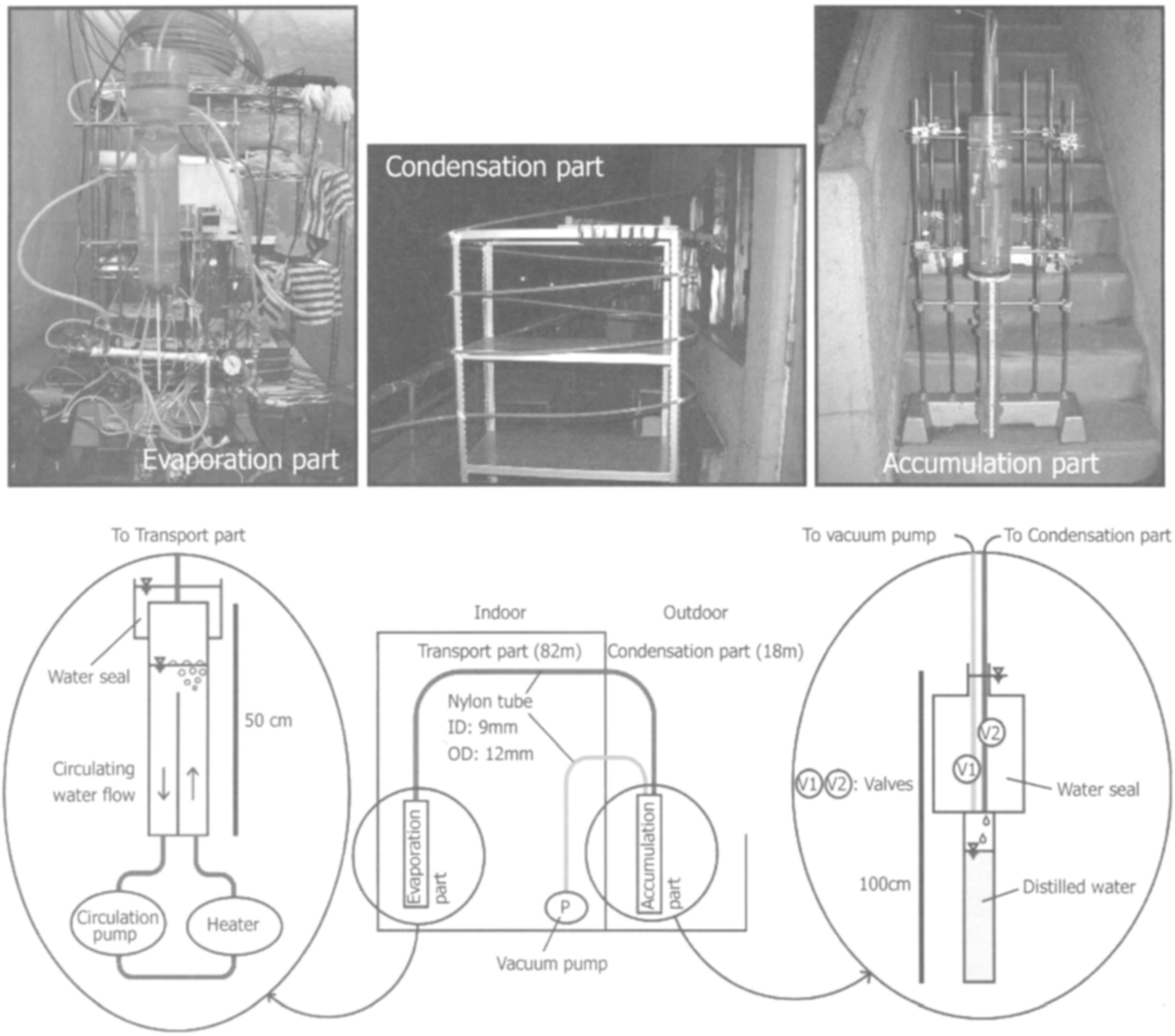

Fig. 4. System diagram of the experimental set-up.

The data of the circulated mass flow rate of the raw water, the temperature and the pressure are recorded every 30 s with a data logger, and the water level, a measure of the production rate of distilled water, is manually measured to an accuracy of 0.1 mm every 30 min. All the data utilized for the data analysis are averaged values for 2.5–5 h.

4.3. Experimental result

The list of the experimental result is shown in Table 1 together with the corresponding calculated values. It is evident that the expected amount of distilled water was produced under every experimental condition conducted in the series. This fact indicates the validity of the working principle and

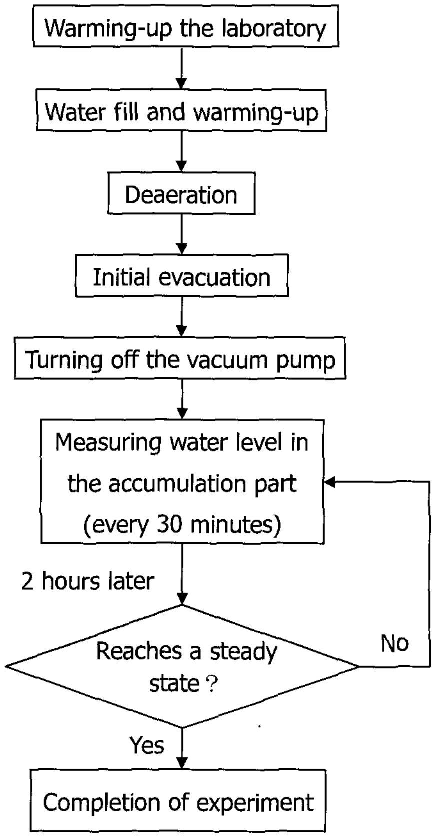

Fig. 5. Flow chart of the experimental procedure.

the thermal condition that the total temperature difference about 10–20°C is sufficient for the Desalination Pipeline system to work for distilled water production and transportation.

Shown in Fig. 6 is the relationship between the temperature difference and the production rate of distilled water as a function of the original raw water temperature. The production rate of distilled water increases with the increase of the temperature difference between the raw water and the outside air. It also increases with the rise of the overall temperature level for a constant temperature difference. It is, however, found that the production rate is not simply proportional to the temperature difference. The reason for this fact is that the transport efficiency of water vapor in the transport part rises at a higher temperature where the vapor pressure curve becomes steeper and thus a larger pressure difference is created for the same temperature difference. The other reason is that the density of water vapor is higher at a higher temperature because of a higher vapor pressure and thus the mass flow rate increases.

The calculated values presented in the table are the estimation on the basis of the same temperatures of water in the evaporation part and

Table 1
List of the experimental result

Number	Inside pressure		Original raw water temp.	Outside air temp.	Production rate of distilled water				
					Measured values	Calculated values			
	E.P.[1]	A.P.[2]				$w = 0.01$ m/s	$w = 1$ m/s	$w = 5$ m/s	$w = 10$ m/s
	(kPa)	(kPa)	(°C)	(°C)	(g/h)	(g/h)	(g/h)	(g/h)	(g/h)
1	3.7	2.0	29.2	9.8	24.9	25.9	32.2	32.5	32.8
2	3.3	1.4	27.9	5.1	23.5	25.8	29.6	29.7	29.7
3	3.5	1.4	29.1	3.8	26.4	30.1	34.4	34.6	34.8
4	2.7	1.3	24.8	4.5	17.0	17.9	19.8	19.9	20.1
5	2.2	1.0	21.0	3.8	10.6	11.3	12.3	12.3	12.3
6	2.4	1.2	23.0	3.6	12.1	14.6	15.9	15.9	16.1
7	2.7	1.0	25.1	1.7	17.9	19.7	21.6	21.7	21.7

E.P.[1]: Evaporation part
A.P.[2]: Accumulation part

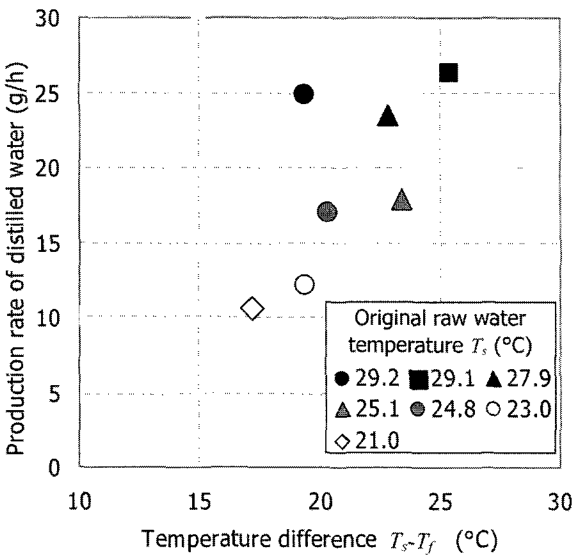

Fig. 6. Relationship between the temperature difference and the production rate of distilled water as a function of original raw water temperature.

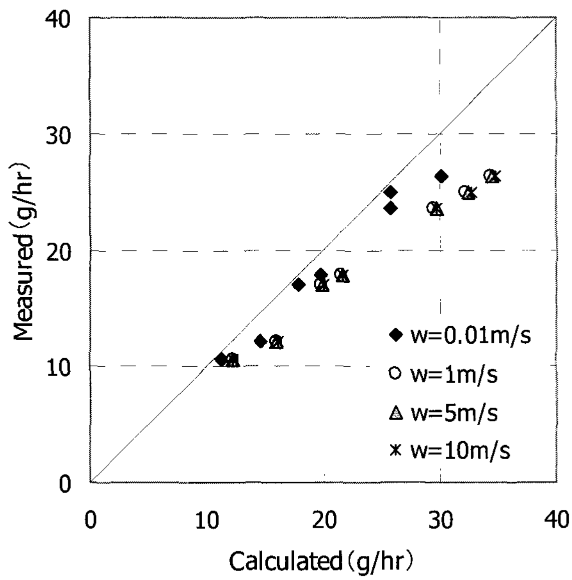

Fig. 7. Comparison between calculated and measured values for the production rate of distilled water.

outside air as those for the experiment. It should be noted that the tube flows in the experiment were laminar at the Reynolds number less than 1,000 because of smallness of the diameter of the tube. Therefore Hagen–Poiseuille formula is applied to the estimation of the pressure drop in the transport part instead of Blasius formula. The calculation was conducted for a number of wind speed w (m/s), w = 0.01 m/s, 1 m/s, 5 m/s and 10 m/s, for convective cooling in the condensation part, because the wind speed was not measured in the present experiment. It is seen that the influence of the wind speed is appreciable only for the speed of w = 0.01 m/s and w = 1 m/s, but almost no effect between w = 1 m/s and w = 10 m/s. The reason for this is that the mass transport capability in the transport part saturates for the cooling capability in the condensation part at the cooling wind speed higher than 1 m/s.

The comparison between the calculated and the measured values is presented in Fig. 7. It is evident that every measured value is slightly below the calculated value, though the discrepancy is not so serious. This fact suggests that some amount of heat leaked out through the tube wall of the transport part and, furthermore, the calculation model has room for some improvement. Nevertheless it may be concluded that the calculation model is basically valid for a rough estimation of the production rate of distilled water. This calculation does not need any particular kind of simulation software, and the estimation of the production rate of distilled water can be made only by using an Excel spreadsheet, etc. Therefore the calculation model is thought to be highly effective for narrowing down candidate regions for the construction of the Desalination Pipeline system.

In this preliminary stage of research, the present experimental system is rather small in scale, tap water is used instead of saline water as raw water and no attention is paid to the thermal insulation in the tube in the transport part. Therefore, there are a number of technical concerns regarding possible negative effect of scaling-up of the system, such as degradation of material of the system resulting from saline water, malfunction of the system caused by salt deposition, failure of transport performance of water vapor due to heat leak to surroundings around the transport part, and the difficulty to obtain initial vacuum in a very long pipe which all must be clarified before realization of the idea. It is believed that the Desalination Pipeline system can be realized if the above-mentioned problems are solved.

5. Model calculation

The laboratory experimental result confirmed that the calculation model is fundamentally valid for the estimation of the production rate of distilled water in the Desalination Pipeline system. It is thought that the calculation software can be used for the estimation of the production rate of distilled water based on the actual environmental and climate data in the potential target regions.

5.1. Selection of target regions for construction of Desalination Pipeline system

The Desalination Pipeline system can be applicable to the regions where the following two conditions are satisfied at the same time, because the energy source for the operation of the system is the temperature difference between raw water, that is sea or salt lake water, and inland atmosphere.

- Regions where sea or salt lake water, whose temperature remains relatively high even in winter, is available.
- Regions that have desert climate where radiation cooling is intense or highland climate where the temperature is low throughout the year.

We selected two regions, Sana'a (Yemen) and El-Quren (Jordan) around the Red Sea that satisfy these two conditions. Shown in Fig. 8 are the data of air temperature and seawater temperature of

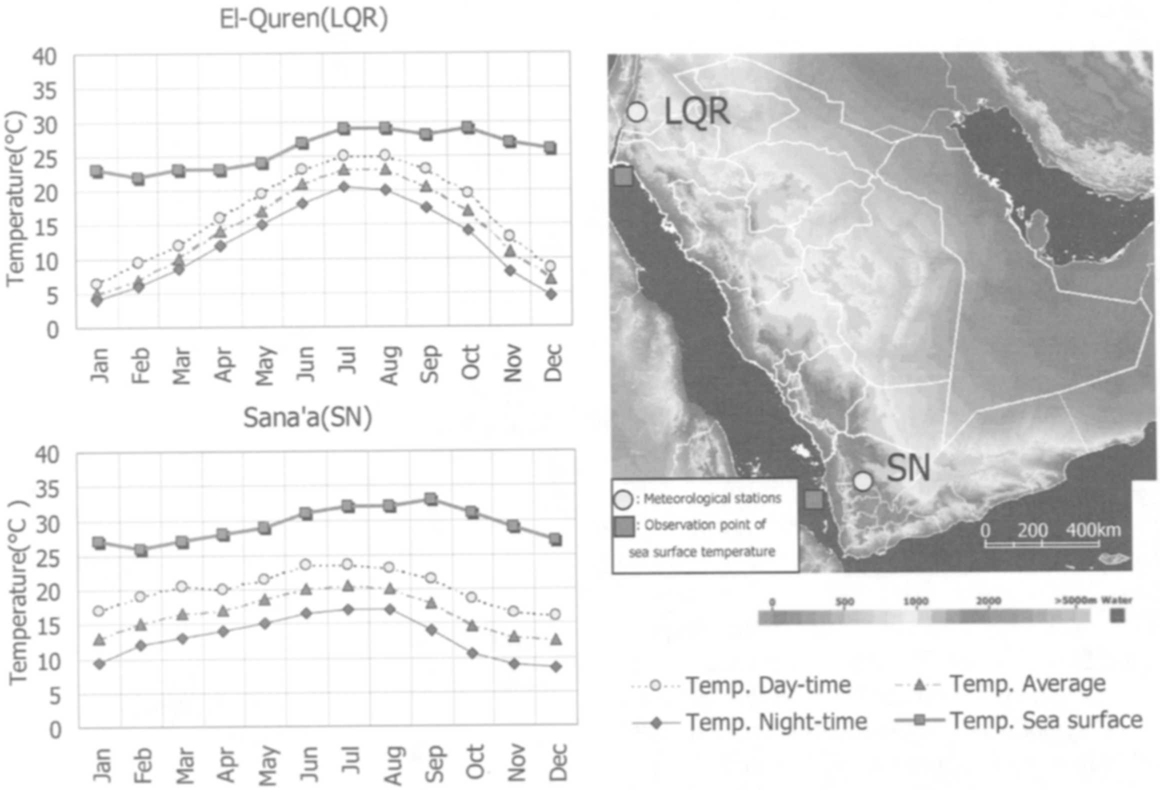

Fig. 8. Air temperature and seawater temperature of target regions.

these target regions cited from the meteorological data that UN Food and Agriculture Organization (FAO) announced in 2003 [9], and the sea surface temperature chart in 2002 from NOAA Optimum Interpolation Sea Surface Temperature Analysis [10].

It is seen that both regions satisfy above-mentioned two conditions, where the seawater temperature is higher than 20°C even in winter, and the air temperature is lower than the seawater temperature throughout the year.

5.2. Calculation conditions

The conditions and data for the calculation are listed in Table 2. The thermo-physical property data are reproduced from Rika Nenpyo (Chronological Scientific Tables) [11], and the estimations of the convective heat-transfer coefficient between the outside air and the outer wall of the pipe and of the condensation heat transfer coefficient on the inner wall of the pipe are performed on the basis of the equations described in JSME Mechanical Engineers' Handbook [8,13]. The environmental and climate data presented in Fig. 8 are used for the seawater temperature, the raw water temperature in the evaporation part, and the outside air temperature around the condensation part. Two values of the diameters of the transport part are assumed to be 2 m, a general size of large diameter pipelines, and 4 m, the diameter of the pipe adopted in the Great Man-Made River Project [14] that is under construction in Libya. The evaporation area is assumed to be 4 times of the cross-section area of the pipe of the transport part so that the pressure loss due to evaporation is lower than one tenth of the pressure loss due to viscous drag of vapor flow.

The structures and functions of the hypothesized Desalination Pipeline system are listed in Table 3, which are set so that the Desalination Pipeline system can perform efficiently in the month when the temperature difference is maximum.

5.3. Calculation result

The flow chart of the iterative calculation is shown in Fig. 9. The estimation of the production rate of distilled water is conducted by the following procedure. In the present calculation, the pressure loss in condensation process (ΔP_c) is ignored, because it is smaller than the pressure loss due to viscous resistance (ΔP_V) by more than four figures.

- The appropriate inside pressures (vapor pressure) in the evaporation part (P_e) and in the condensation part (P_c) are assumed within the realistic range specified by the corresponding local temperature.
- The mass flow rate through the pipe in the transport part (m) is calculated using Eqs. (4), (5), (7) and (8) on the basis of the pressure difference assumed above.

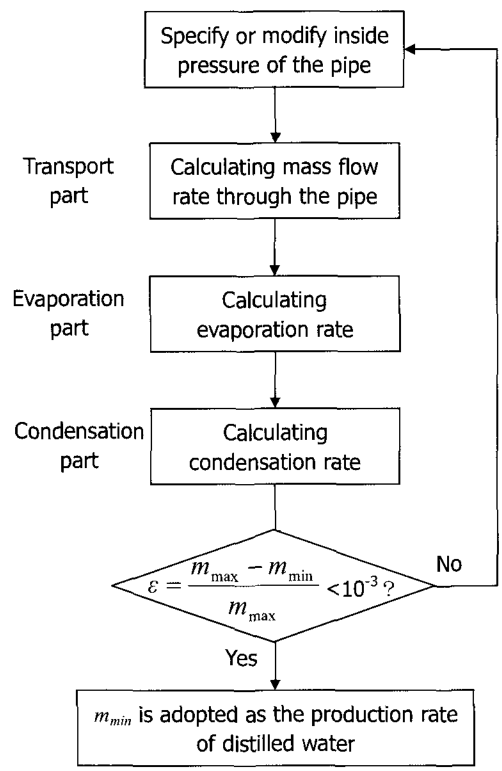

Fig. 9. Flow chart of the iterative calculation.

Table 2
List of calculation condition

Items	Values	Remarks
General		
Air temperature T	Measurement data	Fig. 7. [9,10]
Seawater temperature T.		
Vapor pressure of water	—	Rika Nenpyo [11].
Diameter of pipe D, m	2, 4	Large diameter pipelines [14].
Gas constant, J/mol·K	8.31	—
Molecular weight of water, g/mol	18	—
Gravity acceleration g, m/s^2	9.8	—
Evaporation part		
Vapor pressure reduction rate, %	2[1)]	3.5%NaCl, Raoult's L aw.
Latent heat of vaporization of water λ, MJ/kg	2.44	Rika Nenpyo [11].
Specific heat of seawater C_P, kJ/K·kg	3.9	Rika Nenpyo [11].
Evaporation area A, $\pi(D/2)^2$	4	4 times of cross-section area of the pipe.
Evaporation coefficient α	1	Clean liquid surface [2].
Transport part		
Length of transport part, km	160, 70	Approximate direct distance between coastline and target regions.
Viscosity of water vapor μ	—	Rika Nenpyo [11]. Sutherland approximation is applied.
Density of water vapor ρ	—	Ideal gas approximation
Condensation part		
Elevation of condensation part H, m	2200, 1500	Approximate elevation of target regions.
Thermal conductivity of pipe k_p, W/mK	50	Steel. Rika Nenpyo [11].
Thermal conductivity of water, W/mK	0.6	Rika Nenpyo [11].
Specific heat of water, kJ/K·kg	4.2	Rika Nenpyo [11].
Critical pressure of water, MPa	22.1	Rika Nenpyo [11].
Convective heat-transfer coefficient between outside air and outer wall of pipe, W/m^{2}K	3.3 (D = 2 m) 2.7 (D = 4 m)	Wind speed 1m/s, empirical formula of Zhukauskas [8,12]
Thickness of pipe, cm	2 (D = 2 m), 4 (D = 4 m)	Thickness that can withstand external pressure of 1 atm [13].
Latent heat of condensation λ, MJ/kg	2.44	Rika Nenpyo [11].
Condensation coefficient α	1	Clean liquid surface [2].

[1)]: 2% of seawater vapor pressure

- The pressure loss caused by evaporation (ΔP_e) in the evaporation part is calculated from Eqs. (1) and (3) on the basis of the evaporated mass flow rate in the transport part. The liquid temperature at evaporation surface ($T_{l,e}$) is derived from the vapor pressure curve. Then the evaporation rate (m) is calculated using Eq. (2) from the circulated mass flow rate of the raw water (M) and the temperature difference between the original raw water temperature (T_s) and the liquid temperature at the evaporation surface ($T_{l,e}$).
- The liquid temperature at condensation surface ($T_{l,c}$) is derived from the vapor pressure curve. The average heat-transfer coefficient (h_c) between the water vapor and inner wall of the

Table 3
Structures and functions of the hypothesized Desalination Pipeline system

	Sana'a, October, night-time		El-Quren, December, night-time	
Seawater temperature T_s, °C	31		26	
Inland air temperature T_f,°C	10.5		4.5	
Condensation part elevation H, m	2,200		1,500	
Pipe diameter D, m	2	4	2	4
Circulated mass flow rate of seawater M, kg/s	200	1000	200	1000
Length of condensation part l, km	10	37	6.4	23
Reynolds number in transport part Re_t	3.9×10^4	1.1×10^5	4.0×10^4	1.2×10^5
Production rate of distilled water m, kg/s	0.56	3.3	0.57	3.3

pipe is calculated using Eqs. (13) and (14) on the basis of the mass flow rate (m) in the transport part. Then the condensation rate in the condensation part is calculated using Eqs. (9) and (10).

- The above procedure is iterated until the maximum relative error ε defined below becomes lower than 10^{-3}.

$$\varepsilon = \frac{m_{\max} - m_{\min}}{m_{\max}} \quad (15)$$

Here $m_{\max}$ and $m_{\min}$ are respectively the maximum and minimum among the mass flow rate in the transport part, the evaporation rate and the condensation rate calculated above.

- m_{min} is adopted as the production rate of distilled water when ε becomes lower than 10^{-3}.

Shown in Fig. 10 are the monthly production rate of distilled water derived from the above iterative calculation and the total production rate of distilled water for a year. The production rate of distilled water is found to be 3.2–35.0 L/min (about 10,000 m^3/y) in the case of a pipe diameter of 2 m, and 19–205 L/min (about 60,000 m^3/y) in the case of a pipe diameter of 4 m, which seems to match the flow rate through small qanat, 60–1500 L/min [15–17]. The calculation result indicates that the Desalination Pipeline system can supply distilled water through one year, though the production rate of refined water increases with the increase of the temperature difference between seawater and inland atmosphere. As the Reynolds number for the vapor flow through the transport part is 1.0×10^4–1.2×10^5, this estimation can be generally conducted within applicable range of the Blasius formula.

The Desalination Pipeline system does not depend on existing freshwater resources such as groundwater or stream water, but depends on seawater or salt lake water. Therefore this work indicates that the Desalination Pipeline can supply sustainable water resource completely free from drying up, as far as the facility is appropriately maintained.

6. Conclusions

This work proposes a new desalination technology, the Desalination Pipeline system that enables simultaneously desalination and efficient transport of distilled water to inland area, though existing desalination plants have not capability in distilled water transportation. In the present work, a demonstration of the working principle was performed using the laboratory model, and the estimation of the production and transportation rates of distilled water was also done on the basis of the existing environmental and climate data of the target areas. The following conclusions are drawn:

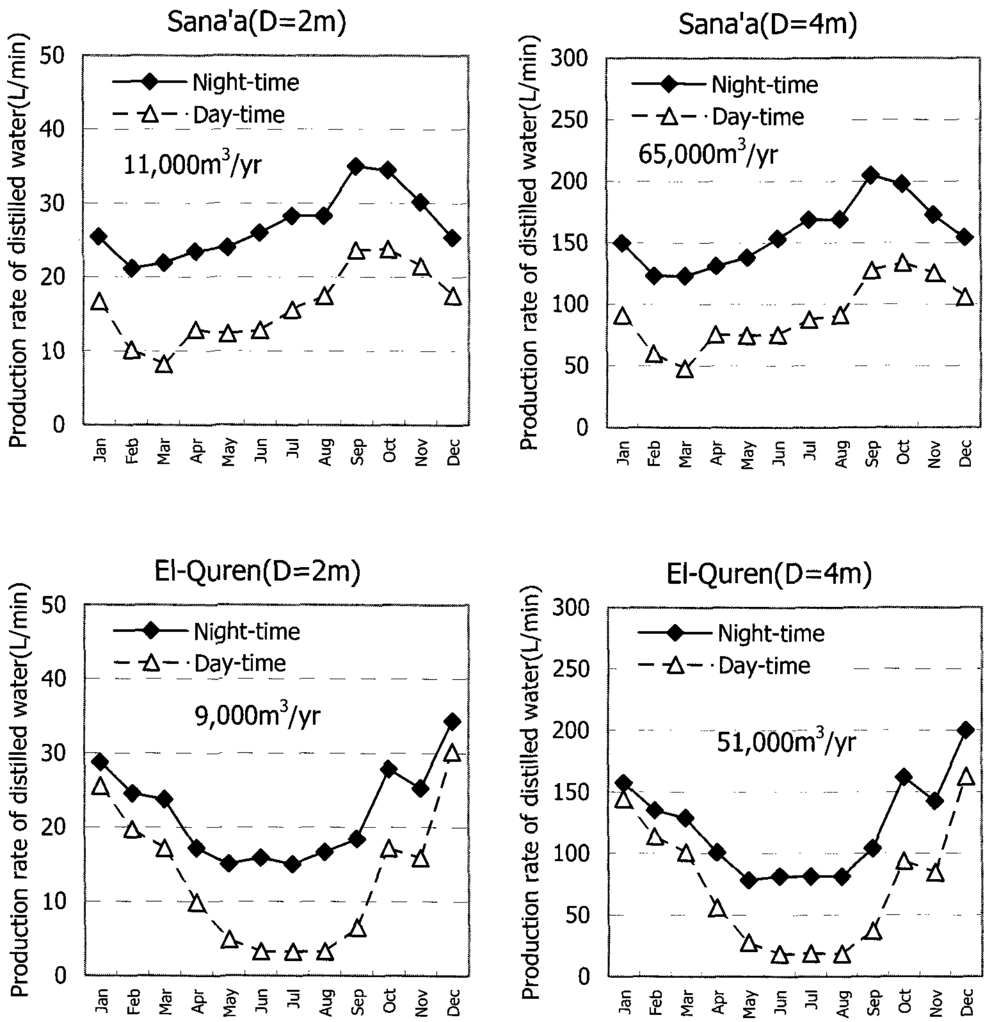

Fig. 10. Monthly production rate of distilled water.

- The laboratory model experiment demonstrated the validity of the fundamental principle of the Desalination Pipeline system in refining and transporting distilled water under the condition of the temperature difference of 10–20°C. It may be concluded that the calculation model has sufficient accuracy for the estimation of the production rate of distilled water, though there is still more room for improvement.
- The estimation result on the basis of data of ideal target regions, Sana'a, the capital of Republic of Yemen, and El-Quren in Hashemite Kingdom of Jordan where the maximum temperature difference between seawater and inland atmosphere is about 20°C, and the distance between the two ends of the pipeline is about 100 km, indicates that the Desalination Pipeline system can supply distilled water through one year and the production rate of distilled water is 3.2–35.0 L/min (about 10,000 m^3/y) for a pipe with a diameter of 2 m, 19–205 L/min (about 60,000 m^3/y) for a pipe with a diameter

of 4 m. The latter nearly matches the flow rate through small qanat, 60–1500 L/min.

- The Desalination Pipeline system does not depend on existing freshwater resources such as groundwater or stream water, but depends on seawater or salt lake water. It is, therefore, suggested in this work that the Desalination Pipeline can provide a sustainable water resource completely free from worrying about drying up, as far as the facility is appropriately maintained.

7. Symbols

A_e — Evaporation area, m^2
C_P — Specific heat of raw water, J/K·kg
D — Internal diameter of pipe, m
g — Acceleration due to gravity, m/s^2
H — Difference in elevation, m
h_c — Average heat-transfer coefficient between water vapor in pipe and inner wall of pipe, W/m^2K
$h_{c,x}$ — Local heat-transfer coefficient between water vapor in pipe and inner wall of pipe at x, W/m^2K
h_L — Heat-transfer coefficient assuming all mass to be flowing as liquid, W/m^2K
h_f — Convective heat-transfer coefficient between outside air and outer wall of pipe, W/m^2K
k_p — Thermal conductivity of pipe material, W/mK
k_l — Thermal conductivity of liquid, W/mK
L — Length from evaporation part to end of condensation part, m
l — Length of condensation part, m
M — Circulated mass flow rate of raw water, kg/s
m — Production rate of distilled water (= Evaporation rate = Mass flow rate through pipe = Condensation rate), kg/s
m_{max} — Maximum among mass flow rate through pipe, evaporation rate and condensation rate, kg/s
m_{min} — Minimum among mass flow rate through pipe, evaporation rate and condensation rate, kg/s
P_c — Inside pressure in condensation part, Pa
P_e — Inside pressure in evaporation part, Pa
p_r — Reduced pressure (Actual pressure/Critical pressure)
Pr_l — Prandtl number of liquid
ΔP — Difference in pressure between evaporation part and condensation part, Pa
ΔP_c — Pressure loss due to condensation, Pa
ΔP_e — Pressure loss due to evaporation, Pa
ΔP_H — Hydrostatic pressure difference due to the difference in the elevation, Pa
ΔP_V — Pressure loss due to viscous drag of vapor flow, Pa
Q — Amount of heat flow extracted per unit length in condensation part, W/m
Re — Reynolds number
Re_t — Reynolds number in transport part
Re_L — Reynolds number assuming all mass flowing as liquid
r_1 — Internal radius of pipe, m
r_2 — External radius of pipe, m
T_f — Outside air temperature, K
$T_{l,c}$ — Liquid temperature in condensation surface, K
$T_{l,e}$ — Liquid temperature around evaporation surface, K
T_s — Original raw water temperature, K
u — Mean vapor velocity in transport part, m/s
w — Wind speed for convective cooling in condensation part, m/s
x — Thermodynamic vapor quality

Greek

α_c — Evaporation/condensation coefficient
ε — Maximum relative error
ρ — Density, kg/m^3
ρ_{ave} — Average density of water vapor in transport part, kg/m^3
ρ_e — Density of water vapor in evaporation part, kg/m^3

ρ_c — Density of water vapor in condensation part, kg/m^3
λ — Latent heat of vaporization/condensation of water, J/kg
μ — Viscosity of water vapor, Pa·s

Subscripts

ave — Average
c — Condensation part
e — Evaporation part
l — Liquid
max — Maximum
min — Minimum
t — Transport part

References

[1] M. Abu-Zeid and A. Hamdy, eds., Water Vision for the Twenty-first Century in Arab World, Tecnomack Digital Print, Bari, 2002.
[2] K. Oshima, T. Matsushita and M. Murakami, Heat Pipe Kougaku (Heat Pipe Engineering), Asakura Shoten, Tokyo, 1979 (in Japanese).
[3] H. Hertz, Uber die Verdunstung der Flussigkeiten, insbesondere des Quecksilbers, im Luftleeren Raume, Annalen der Physik und Chemie, 17 (1882) 177–193 (in German).
[4] M. Knudsen, Die Maximale Verdampfungsgeschwindigkeit des Quecksilbers, Annalen der Physik, 47 (1915) 697–708 (in German).
[5] M. Maiani, W.J.M. de Kruijf and W. Ambrosini, An analytical model for the determination of stability boundaries in a natural circulation single-phase thermosyphon loop, Int. J. Heat Fluid Flow, 24 (2003) 853–863.
[6] The Japan Society of Mechanical Engineers, ed., JSME Mechanical Engineers' Handbook A. Fundamentals A5: Fluids Mechanics, Maruzen, Tokyo, 1986 (in Japanese).
[7] M.M. Shah, A general correlation for heat transfer during film condensation inside pipes, Int. J. Heat Mass Transfer, 22(4) (1979) 547–556.
[8] The Japan Society of Mechanical Engineers, ed., JSME Mechanical Engineers' Handbook A. Fundamentals A6: Thermal Engineering, Maruzen, Tokyo, 1985 (in Japanese).
[9] http://artmet.fao.org/default.htm
[10] http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/
[11] National Astronomical Observatory, ed., Rika Nenpyo (Chronological Scientific Tables 2003), Maruzen, Tokyo, 2002 (in Japanese).
[12] A.Zhukauskas, Heat transfer from tubes in crossflow, Adv. Heat Transfer, 8 (1972) 93–160.
[13] The Japan Society of Mechanical Engineers, ed., JSME Mechanical Engineers' Handbook A. Fundamentals A4: Strength of Materials, Maruzen, Tokyo, 1984 (in Japanese).
[14] P.J.A. Gijsbers and D.P. Loucks, Libya's choices: Desalination or the Great Man-made River Project, Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, 24(4) (1999) 385–389.
[15] M. Okazaki, Qanat Underground Waterway of Iran, Ronsousya, Tokyo, 1988 (in Japanese).
[16] D.R. Lightfoot, Syrian qanat Romani: history, ecology, abandonment, J. Arid Environments, 33 (1996) 321–336.
[17] R. Nishimaki, T. Hotta, K. Oshima and S. Takahashi, Irrigation system of traditional water-use facilities, Khettara in Morocco –Constraints and remedies aiming for effective use of Khettara water, J. Arid Land Studies, 15(2) (2005) 79–88 (in Japanese).