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Two-effect distillation of a seawater distiller utilizing waste heat of a small electric generator

Chang-Dae Park*, Byung-Ju Lim, Kyung-Yul Chung

Energy Plant Research Division, Korea Institute of Machinery and Materials, 171 Jangdong, Yuseonggu, Daejeon, 305-343, Korea
Tel. +82 42 868-7931; Fax +82 42 868-7355; email: parkcdae@kimm.re.kr

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ABSTRACT

We have designed and developed a stand-alone small-scale desalination unit using waste heat of exhaust gas from a small diesel electric generator which is used in various places such as islands and remote areas. The distiller developed consists mainly of a multiple-effect diffusion still and an evaporation chamber that recovers waste heat of exhaust gas from the generator engine. With experimental results of two-effect distillation of this distiller, we have shown its production capability of 6.80 kg/d fresh water and have estimated at least 19.4 kg/d for a ten-effect distiller. The distiller suggested is considered to be applicable for a small-scale distillation unit, comparing to performance of a solar thermal distillation unit. Moreover, the distillation part of our designed unit is easily converted to a solar still type-distiller by changing the evaporation chamber to a solar-heating wall, if the engine is not available.

Keywords: Seawater distiller; Waste heat; Electric generator; Multi-effect; Desalination; Small-scale

1. Introduction

Technologies to secure clean water from nature have been developed in various ways such as filtration and distillation. The available fresh water resources like river, lake, and dam are comparatively decreasing due to increasing population and climate changes. Seawater which is more than 97% of the earth's water was regarded as a substitute water resource even in the past and as a promising resource nowadays in order to meet rapidly increasing demand for fresh water. Therefore desalination process of obtaining fresh water from saline/brackish water has been well developed easily and economically.

Major desalination technologies such as multi-stage flash distillation (MSF), multi-effect distillation (MED), and reverse osmosis (RO) have been developed almost only for application to large-capacity plants of produced water. Scale-up of production capacity of desalination plants is indeed a suitable process to decrease costs of produced water. However, there are still lots of regions which do not have social (water and electricity) infrastructure. In these places such as remote areas, islands, and developing countries, a large-scale desalination plant is not useful due to initial high construction cost, operation and maintenance cost and/or skills [1]. Such undeveloped regions without electric grid have used electric generators of small (portable) or medium capacity and demand a small amount of fresh water generally less than 200 m^3/d. The desalination technology suitable for these situations may consider distributed-type small distillation facility utilizing renewable energy such as solar stills and utilizing waste heat from the engine of the electric generator.

* Corresponding author.

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In this research, we have focused on a small-scale distiller using waste heat from a portable diesel electric generator as a heat source. The waste heat from a small generator engine is just thrown away to the surroundings, because the energy density of the waste heat is not sufficient to be utilized effectively. However, we assumed that it may be a useful energy as heat source of evaporation for distillation, at least as additional heat energy for a solar still. We have tried to find out applicability of waste heat of small engine to small-scale distillation device. The distiller designed in this study consists mainly of vertical multiple-effect diffusion still and evaporation chamber that is recovered waste heat of exhaust gas from small diesel electric generator. We present both its design process including simple heat balance in the evaporation chamber and experimental results of two-effect distillation.

2. Design and setup of seawater distiller

Fig. 1 shows the experimental apparatus depicted as four-effect distillation for convenience sake. It consists mainly of a portable electric generator, evaporation chamber, feeding distributor and distillation part. Vacuum devices widely used in an MED type distiller are not adopted for structural simplification of the system, considering maintenance difficulties in island areas. The distillation part consists of closely-spaced vertical parallel plates as much as effect number, wicks, and water pockets at its bottom. Each plate of the distillation part is a thin stainless plate having a wick attached on its back side. Exhaust gas from the diesel engine flows into the copper tubes in the evaporation chamber in which water is heated to evaporate. The evaporated vapour is condensed on the front side of the first plate. This condensation latent heat is conducted through the plate and transfers heat to seawater flowing along the wick. The vapour evaporated from the first wick is diffused across a thin air layer between the plates and condensed on the front side of the second plate. This condensate flows down to be gathered in a water pocket installed at the bottom of each plate. These processes of evaporation, vapour diffusion, condensation, and conduction are repeated by an optimum number of the effects.

Design parameters of the distiller using waste heat from the diesel engine may consider flow rate and temperature of exhaust gas of the engine, temperature and flow rate of feeding seawater, feeding method, wick material, number of effects, space between plates, and evaporation chamber sizing.

Flow rate and temperature of the exhaust gas affect significantly the distiller performance as a role of primary heating source, and depend on the capacity of the engine employed and on its operation conditions. Table 1 shows the specifications of the diesel electric generator which is selected in this experiment by considering general model used in domestic islands and expansion of application to various type of waste heats. Electric generator (Honda SG6500DX model) has 4 stroke, single cylinder engine and 5.6 kVA of rated AC power. Exhaust gas from the engine flows into copper tubes which are connected to heat exchange tubes in the evaporation chamber. The heat exchange tubes diverge to two tubes before inlet of the chamber, in order to vary the experiment conditions such as heat exchange area and gas flow rate. The heat exchange tubes are diameter of 23 mm and 2 m length for each inside the evaporation chamber.

Fig. 2 and Fig. 3 show measured temperatures and flow rates of the exhaust gas from this generator engine.

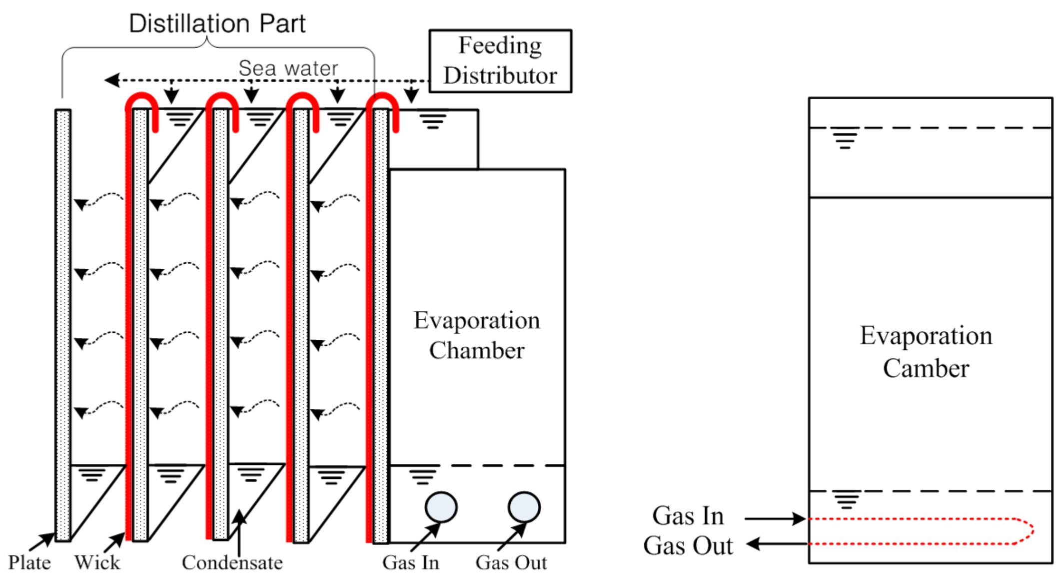

Fig. 1. Schematic diagram of seawater distiller using waste heat(left: front view, right: side view).

Table 1
Specifications of the diesel electric generator

Model		Honda SG6500DX
Generator	Rated AC power, kVA	5.6
	Rated DC power, kVA	6.5
Engine	Model	GX340
	Type	Forced air-cooled, 4-stroke, single cylinder
	Displacement	337 cc
	Net horse power output	11.0 PS (8.2 kW) /3600 rpm
	Starting system	Recoil
	Fuel tank capacity, ℓ	28
	Continuous operation times, h	9.0
Dimension	Length × width × height, mm	690 × 580 × 525
	Exhaust pipe inner diameter, mm	23
	Dry mass, kg	78

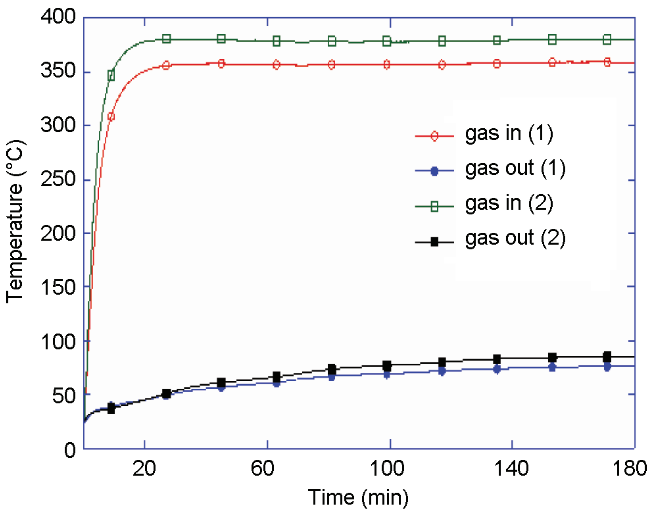

Fig. 2. Inlet/outlet temperatures of exhaust gas.

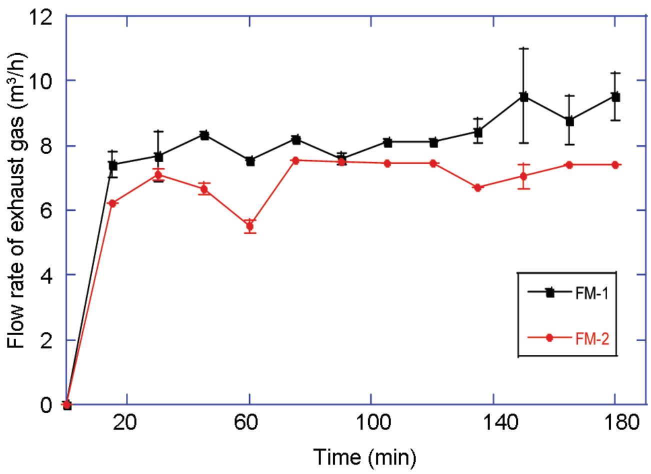

Fig. 3. Flow rate of exhaust gas.

The gas temperatures at inlet of the evaporation chamber increase to be 356°C and 348°C, and become the steady-state after approximately 15 min. The outlet gas is exhausted at 66°C and 73°C after heat exchange with water inside the chamber. The temperature difference between the diverged tubes is attributed to the different flow rate and flow path length in each tube, as shown in Fig. 3. Total heat energy obtained by water inside the chamber from the exhaust gas was calculated by measured flow rates and temperatures of the gas as to be 2,973 kJ/h (0.83 kW).

Temperature and flow rate of feeding seawater depend on local climate conditions at the seawater intake area and on a feeding method to a wick, respectively. There are two types of feeding methods: active feeding device by overflowing weir and passive feeding type by capillary force of the wick which is sunk and soaked in seawater in the feeding seawater pocket. In the passive type device, seawater is fed to the wicks by absorbing seawater from the seawater pocket due to capillary force of the wick itself and then flows down by gravity along the plate. Wick material employed is cotton flannel which has good absorptiveness of water to keep a certain flow rate in order to prevent appearance of dry spots on the wick. Feeding flow rate in this feeding device depends on the surface tension of the wick material and seawater.

The optimum number of effects of the distiller is an important design parameter and can technically be determined by heat balance calculation based on temperature of a primary heat source and effective temperature difference between evaporation and condensation at each effect. Generally, the number of effects is not more than 13. Space distance between the plates determining vapour diffusing length through the air layer is set as 5 mm that is considered to be the optimum spacing length in this system. The shorter is the length, the higher is treated water production, because thermal resistance of the air layer between the plates decreases the heat flux [2,3]. It can be theoretically decreased to the size of a condensed droplet, and Tanaka et al. [4] have suggested a theoretical minimum distance of 3 mm in the case of vertical plates, which prevents mixing of condensed water with concentrated brine flowing down. However this minimum length may be a bit larger because of deformation of the plate by thermal stress and swollen area of the wick by dry region or unpredictable reasons.

We calculated the heat balance of the heat exchange pipe in the evaporation chamber based on Table 2 and Fig. 4 in order to estimate the required heat exchange area in the evaporation chamber and time for water to evaporate inside the chamber. Heat loss Q_g of exhaust gas in the control volume of length ΔL is expressed as follows:

$$Q_g = G \times \rho_g \times c_{p,g} \times (T_i - T_{i+1}) \quad (1)$$

where G is the gas flow rate, ρ_g — gas density, and c_p — specific heat. Convection heat Q_{in} in the heat exchange pipe is:

$$Q_{in} = \pi d \Delta L \times Nu_{in} \times \frac{\lambda_g}{d} \times (T_m - T_w) \quad (2)$$

where λ_g is thermal conductivity of the gas and

$$T_m = (T_i + T_{i+1})/2$$

$$\mathrm{Nu}_{in} = 3.66 + \frac{0.068\left(\mathrm{Re}\cdot\mathrm{Pr}\cdot\frac{d}{L}\right)}{1+0.04\left(\mathrm{Re}\cdot\mathrm{Pr}\cdot\frac{d}{L}\right)^{2/3}} .$$

Convection heat Q_{out} from heat exchange pipe to water inside the evaporation chamber is

$$Q_{out} = \pi d \Delta L \times \mathrm{Nu}_{out} \times \frac{\lambda_w}{d} \times (T_w - T_\infty) \quad (3)$$

where $\mathrm{Nu}_{out} = 0.53\ (\mathrm{Gr} \cdot \mathrm{Ra})^{1/4}$ and λ_w is thermal conductivity of the pipe.

Then heat balance in the evaporation chamber can be calculated as follows:

$$Q_g = Q_{in} = Q_{out} \quad (4)$$

Fig. 5 is one of the calculation results showing variation of water temperature in the evaporation chamber with diameter d and length l of the heat exchange pipe. Water temperature increases from 20°C to 100°C within about 45 min after operation of the engine in the case of d = 23 mm and l = 4 m. Therefore, with this design of the distiller, we may expect that condensed fresh water can be produced at least in 1 h after the engine operation.

Fig. 6 shows a photograph of the experimental unit of the distiller taken before close attachment of the wick to the first plate and installation of the second plate. The apparatus except the electric generator is occupied with 1.0 m × 0.21 m footprint area. Nine T-type thermocouples are attached on the inner wall of the evaporator chamber and two flow meters measure the flow rate of the exhaust gas. Construction of this distiller costs totally about $16,000 including material costs of $4,600 and engine generator of $1,500.

The experiment was performed with two-effect stills for 5 h from operation start of the diesel generator.

Table 2
Heat balance conditions in evaporation chamber

Cylinder volume, cc		300
Revolution per minute, rpm		3600
Gas flow rate G, cm^3/min		300 × 1800 = 540,000
Gas input temperature, °C		250
Water volume, m		1 ×0.1 × 0.1
Heat exchange pipe	Diameter, mm	10 and 23
	Length, m	2 and 4

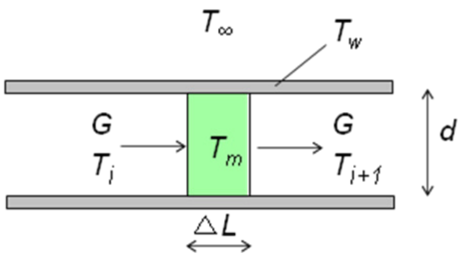

Fig. 4. Exhaust gas flow in the pipe in the evaporation chamber.

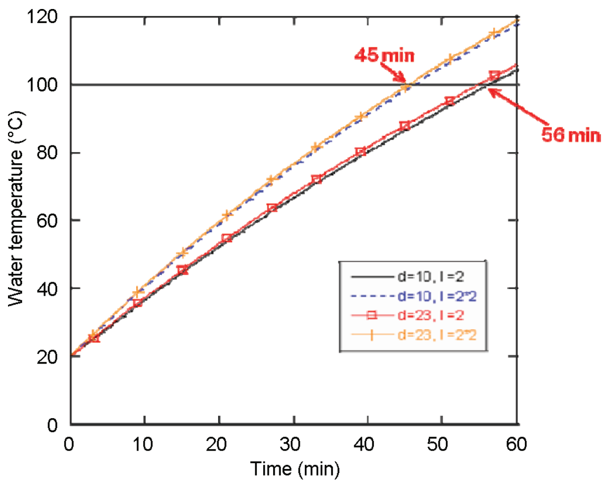

Fig. 5. Water temperature in the evaporation chamber.

3. Results and discussion

Fig. 7 shows the temperature variations of the inner

Fig. 6. Photograph of the seawater distiller using waste heat of the engine.

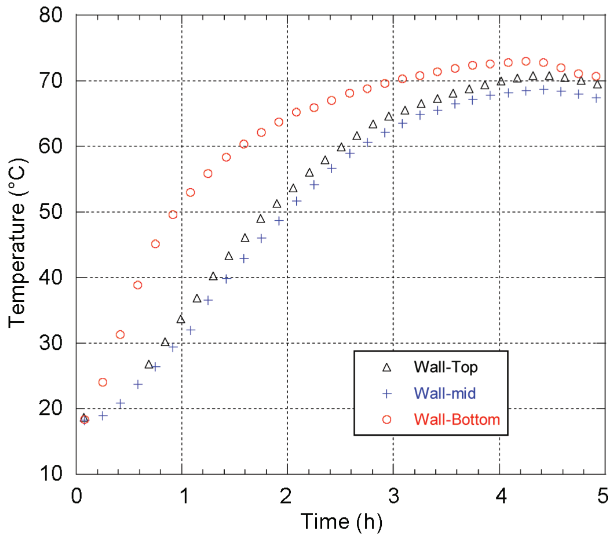

Fig. 7. Wall temperatures with operation time.

wall of the evaporation chamber with operation time of the generator. All temperatures increase with the time to be 73.2°C of maximum temperature at the bottom of the chamber. It is worth noting that the temperature rise with time is faster on the wall bottom where the heat source is located, and is almost saturated in 3 h. Temperature differences between the wall bottom and the wall top areas are large during initial 3 h and become smaller with operation time. Temperatures at the bottom area of the chamber are the highest and those in the middle areas are the lowest, because of the presence of the heat source and falling-down condensate of risen-up vapour, respectively. The temperature rise of the water in the chamber shows a little different tendency compared to those in Fig. 5. This may be attributed to a continuous heat loss taken by fed seawater from the chamber, which was not considered in the calculation of Fig. 5. It is important that even the first plate having the highest evaporating temperature can keep the temperature below 80°C to be able to suppress the scale generation by seawater in the MED system.

The condensed droplets start to produce on the bottom of the plate after about 30 min and on the whole area of the plate in 43 min, as shown in Fig. 8. In Fig. 8, the second stainless plate was temporally substituted by the glass plate to observe the condensation phenomena. White dots and lines are condensate droplets and flow paths on the glass plate, respectively. It is interesting to note that estimated time to produce fresh water from Fig. 5 is almost the same as that of the experimental result. Fig. 9 shows the amounts of produced fresh water with operation time of the generator. The condensated water starts to be produced after about 1 h and then sharply increases with time to be maximum at 4 h. These results show almost the same tendency as the wall temperature variation with time shown in Fig. 7. The produced condensate during 5 h is 711 ml for the first effect and 299 ml for the second effect, corresponding to 4.79 kg/d and 2.01 kg/d, respectively. The total produced water with two-effect distillation is 6.80 kg/d for the evaporation area of 0.8 m^2 and for the footprint area of 0.21 m^2. This amount corresponds to 19.4–25.0 kg/d in the case of ten-effect distillation, which is estimated from previous research [4].

Fig. 8. Distilled water on the condensing glass plate.

4. Conclusions

A seawater distiller with a multiple-effect diffusion

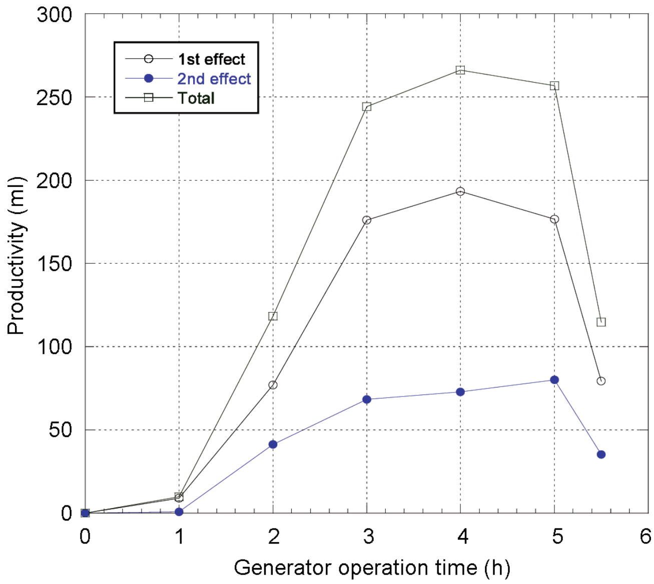

Fig. 9. Productivity with operation time.

type was designed, utilizing the waste heat from a portable electric generator. The performance test with the two-effect distiller shows that condensate is produced on the whole area of the condensation plate in 43 min after the generator starts to operate. The produced distillate amounts to 1.01 kg during the diesel engine operation of 5 h. This is equivalent to productivity of 6.80 kg/d and is expected to produce 19.4–25.0 kg/d in the case of a ten-effect distiller, considering the results of the previous studies [4] which were demonstrated by a solar distiller with the distillation part of a similar structure. This productivity is 1.5–1.9 times [4] and 7.1–9.1 times [5] larger than the experimental results in the previous studies on the solar thermal distiller. We have found that the distiller designed in this study is useful when a portable small engine generator runs for more than consecutive 3 h. Therefore the distiller suggested in this study may be available for a small-capacity distributed seawater distiller in various areas where waste heat can be obtained and a large desalination plant cannot be constructed and operated. In addition, this system may be constructed as a hybrid distiller with other renewable energy sources such as solar energy and wind power.

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