Proceedings of the IASTED International Conference
POWER AND ENERGY SYSTEMS
May 13-15, 2002, Marina del Rey, California, USA

THE EFFICACY OF HYDROGEN IN DIRECT CONTACT SEAWATER DESALINATION

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ABSTRACT

Possible usage of hydrogen over a hydrocarbon (propane) in direct contact evaporation of seawater is evaluated. Selection of propane was made for two reasons: First, it is a representative fuel of hydrocarbon family and second it is often used because of its clean burning characteristics. For the same heat input requirements, an equal amount of seawater can be evaporated with 38% less hydrogen fuel on a mass basis. On the other hand, hydrogen costs an order of magnitude more compared to propane. Although environmentally advantageous, the use of hydrogen fuel will probably be dalyed until its production costs are competitive.

KEY WORDS: Hydrogen Energy, Hydrogen Efficacy, Direct Contact Seawater Evaporation.

1. INTRODUCTİON

Fresh water is in short supply throughout many parts of the world.

In typical indirect contact thermal evaporation of seawater, the seawater evaporates usually on the outer pipe surface. The water vapor rises due to its lower density relative to the air and is received from the top of the evaporator while the high concentration brine is received from the bottom. The inner-section of the pipe carriers the heat source, usually the high temperature combustion products. In this kind of indirect contact arrangement, the net rate of heat transfer from the combustion gases into the seawater relies on the transmitting material (pipe) and fouling occurring on this transmitting material surface. On the other hand, in direct contact heat transfer processes such a transmitting medium is not present and the overall heat transfer coefficient depends on the continuous phase (combustion products) and dispersed phase (seawater) heat transfer coefficients. In the analysis of such direct contact heat transfer systems, resistance of the one of the phases, e.g. seawater, is ignored and the results are given based solely on the heat transfer coefficient of one phase. This is the continuous phase in general [1].

Possible usage of hydrogen as a substitute for conventional fuels has taken increasing attention. This is because hydrogen is a clean and powerful energy source. Hydrogen can be produced via chemical reaction of C, C_nH_m, or an active metal such as Na (or K) with water. Mines, oils, and gas wells are main hydrogen production sources. Electro-chemical reactions include electrolysis while biochemical hydrogen production includes using bacteria and other microorganisms releasing molecular hydrogen (H_2). The photo-conversion process deals with the mechanism of photosynthesis, in which hydrogen is harnessed by using H_2O and light. Although hydrogen can be produced via a variety of processes, its production cost is by no means a negligible factor in its possible consideration as an alternative fuel [2].

In the present analysis, the heat output for propane and hydrogen fuels combustion is considered. The heat output is assumed to be completely utilized in the evaporation of seawater. In this regard, the result of the present study is established on the basic principle of first law of thermodynamics, or energy balance equation.

2. ANALYSIS

Figure 1 shows the direct contact evaporator analyzed in the current study. The main advantages of the use of direct contact heat transfer are [1]:

a. It is possible in direct contact heat transfer processes to attain higher heat transfer rates than in indirect contact heat transfer processes. This fact is due mainly to the lack of heat transmitting material (pipe) and fouling occurring on this transmitting material surface.
b. Due to absence of piping, the cost of direct contact heat transfer units may be considerably lower than that of indirect contact heat transfer units.
c. Scaling that causes corrosion is not a problem of direct contact heat transfer processes.

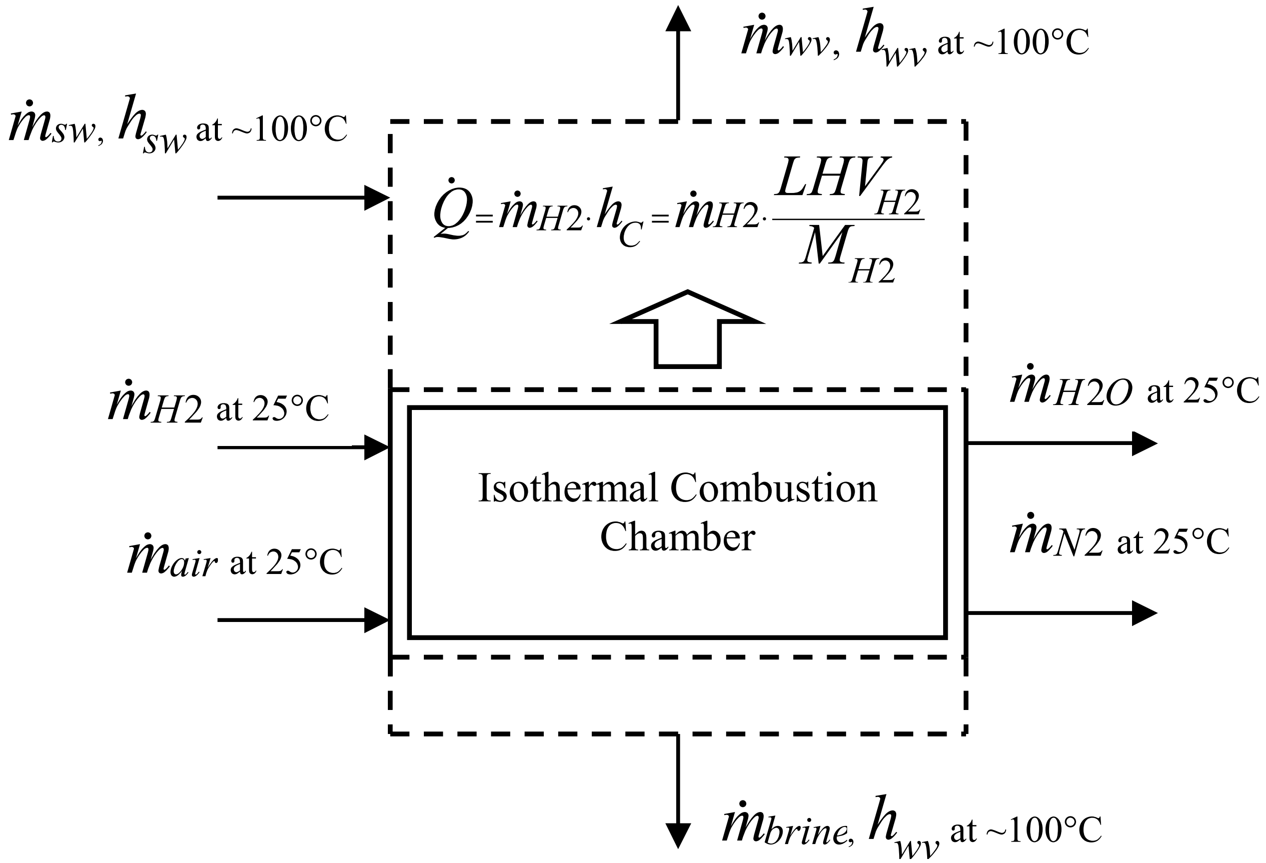

Fig. 1. Schematic of the direct contact evaporator for equal rate of heat of combustion values ($\dot{Q}$) of both fuels. Broken lines show the system boundary analyzed.

Despite many advantages of the direct contact heat exchange processes, there are some situations where the use of direct contact heat transfer may not be beneficial. These are the situations where [3]

a. Incompatible fluids are used in an immiscible process.
b. Mass transfer between phases is not desirable.
c. Large volumes of fluid circulation are not available.
d. Higher pumping cost (especially in spray and bubble column design) is not desired.
e. Large vessel volumes and fluid inventory are not possible.

When products are also brought to the same standard reference state of 1 atm and 25 ºC as reactants, an isothermal combustion chamber can aptly utilize the excess heat. Under the premise that the heat is transferred without relying on any transmitting material, the heat output from this combustion process is maximum (under ideal conditions). This heat output can be used to evaporate the seawater. The complete combustion equations of both fuels are given as

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O_{(g)} + 18.8N_2 \tag{1a}$$

$$H_2 + 0.5(O_2 + 3.76N_2) \rightarrow H_2O_{(g)} + 1.88N_2 \tag{1b}$$

Although the seawater salinity changes with altitude, location, depth, and geologic factors, average values for different type of water sources can be estimated as in Table 1 [4].

The seawater boiling point rise is given from the Raoult's Law [5] by

$$\Delta T \approx \frac{R_u (T_{sat}^{*})^2}{\Delta h} y_s \tag{2}$$

Table 1. Average Salinity of Seawater (by mass) [4]

Type	Fresh water	Slightly saline water	Moderately saline water	Highly saline water	Ocean water
(% mass)	0.08	0.2	0.35	1.25	3.529
(ppm)	800	2000	3500	12500	35290

where ΔT is the boiling point rise, R_u is the universal gas constant, T_{sat}^{*} is the saturation temperature of the solvent, Δh is the enthalpy of vaporization for the solvent, and y_s is the solute mole fraction in the solution. Table 2 tabulates the results using Eq. (2) for several sea water saturation temperatures.

Table 2. Boiling point rise of seawater at differing saturation temperatures.

ϕ (ppm)	ϕ (%)	T_{sat} (°C)	ΔT (°C or K)
35290	3.529	25	0.17
35290	3.529	40	0.19
35290	3.529	60	0.22
35290	3.529	100	0.28

In the light of theoretical Raoult's law, it is concluded from Table 2 that when the saturation temperature is 100°C, the boiling point rise is only 0.28°C. Therefore, it was concluded that the Raoult's Law may well represent boiling point rise values when the solute fraction is considerably high. Table 3 represents the seawater and pure water enthalpy values.

Table 3. Seawater and pure water enthalpy values at different saturation temperatures. Salinity of seawater is ϕ = 3.529% [6].

Saturation temperature (°C)	Seawater enthalpy (kJ/kg)	Pure water enthalpy (kJ/kg)
60	244.33	251.13
80	324.73	334.91
100	405.75	419.04

Global Model Assumptions. 1) The seawater enters the evaporator at 100.28°C with preheating. 2) The seawater contains 3.529% salt in weight. 3) The seawater enthalpy is taken from the graph of Billet [6]. 4) Evaporator is a steady flow adiabatic system. 5) Kinetic and potential changes of the streams relative to each other are neglected. 6) Dissociation and association of products in Eq. (1) are neglected. 7) The entrainment or escape of the seawater together with the evaporated vapor can be minimized by placement of demister or mist eliminators at the evaporator vapor outlet. 8) The brine enthalpy is determined via interpolation in the brine salinity range from 2.5% to 10% and above that range by using the Gregory-Newton backward linear extrapolation [7] taking into account only two terms.

The ratio of the mass flow rate of hydrogen to that of propane is determined to be

$$\frac{\dot{m}_{H2}}{\dot{m}_{C3H8}} = \frac{LHV_{C3H8}}{LHV_{H2}} \cdot \frac{M_{H2}}{M_{C3H8}} \qquad (3)$$

$$\frac{\dot{m}_{H2}}{\dot{m}_{C3H8}} = 0.38 \qquad (4)$$

On the system shown with dashed lines in Fig. 1, there are three balance equations to be written:

1) Mass balance

$$\dot{m}_{sw} = \dot{m}_{wv} + \dot{m}_{brine} \qquad (5)$$

where $\dot{m}_{sw}$, $\dot{m}_{wv}$, and $\dot{m}_{brine}$ are the seawater, water vapor (from evaporation), and brine mass flow rates, respectively.

2) Salt concentration balance

In addition to the mass balance equation, a salt concentration balance equation is also utilized. This equation represents the salt part balance on the evaporator.

$$\phi\, \dot{m}_{sw} = \phi_{brine}\, \dot{m}_{brine} \qquad (6)$$

where ϕ and ϕ_{brine} are the seawater and brine salinities, respectively. Eq. (6) assumes that the evaporator products are free of salt. In Eq. (6), values of ϕ_{brine} and $\dot{m}_{brine}$ are to be determined.

3) Energy balance

From the first of law of thermodynamics, we have

$$\dot{m}_{sw}\, h_{sw} + \dot{Q} = \dot{m}_{wv}\, h_{wv} + \dot{m}_{brine}\, h_{brine}(\phi_{brine}) \qquad (7)$$

Eqs. (5), (6), and (7) are simultaneously solved for unknown $\dot{m}_{wv}$, ϕ_{brine}, and $\dot{m}_{brine}$ values. The results, $\dot{m}_{wv}$, ϕ_{brine}, and $\dot{m}_{brine}$, are given as a function of hydrogen mass flow rate if propane fuel mass flow rate is known a priori.

Table 4 lists the input data, which were used in the Eqs. (5) through (7). The LHV of a particular fuel is defined as the amount of energy released when a fuel is burned completely in a steady-flow process, the products are returned to the state of the reactants, and the H_2O in the products is in vapor form. The unique equal heat input values, Q's, are given based on the LHV of fuels and the four mass flow rate levels of fuels used. The reason in choosing four mass flow rate levels was experimental. Four sample mass flow rate levels were recorded from the experimental where the propane was burned in a bunsen burner. A mass flow rate was used to record the four mass flow rates of the propane used and then Eq. (1) was used to evaluate the products mass flow rates.

Table 4. Input data for the equal energy input case.

h_{sw} at $T_p = 373.43\,K$, $\frac{kJ}{kg}$	405.75
$\dot{Q}$, W	1.4, 5.6, 9.8, 14
$h_{brine}(\phi_{brine})$, $\frac{kJ}{kg}$	Interpolation [6] between 2.5% and 10% and extrapolation [7] above 10%.
$\dot{m}_{sw}$, $\frac{g}{s}$	1200
$\dot{m}_{cp}$, $\frac{g}{s}$ (propane)	0.403, 1.611, 2.819, 4.027
$\dot{m}_{cp}$, $\frac{g}{s}$ (hydrogen)	0.313, 1.251, 2.189, 3.127
ϕ, %	3.529

3. CONCLUSION

The macro scale evaluation of the basic energy balance equation represents the results taking into account only the energies of incoming and outgoing streams. In this macro scale evaluation, the process inside the evaporator was not taken into account. Thus, the comparative model aimed to represent the overall efficacy of hydrogen in direct contact evaporation of seawater when the other fuel was propane.

Figure 2 shows the water vapor mass flow rate change with fuel mass flow rate using Eqs. (5) and (7). In the present analysis, the recovery ratio is defined as the ratio of the mass flow rate of water vapor coming from the seawater evaporation, $\dot{m}_{wv}$, to that of incoming seawater, $\dot{m}_{sw}$. Figure 3 shows the recovery ratio change with fuel mass flow rate. It is clear from Figures (2) and (3) that at the same fuel mass flow rate, hydrogen yields more water vapor and higher recovery ratio, respectively.

- Bare prices, i.e., prices excluding energy surcharges, tank rent, transportation, taxes, etc. were obtained for propane and hydrogen from the suppliers. Price for hydrogen came from Air Products and Chemicals, PA, USA and for propane, it came from Cornerstone Propane, Reno, NV, USA. The given prices are as of July, 2001. The price of propane is about \$0.81/kg and the price of hydrogen is about \$29.9/kg in bulk amounts. When converted to per kmol consumption, the price for hydrogen is \$60.28/kmol and the price for propane is \$35.42/kmol. Hence, it can be concluded on equal mass or mole consumption of both hydrogen and propane fuels that, operation with hydrogen is proven more expensive.

- Equal rate of heat input case based on the Lower Heating Value (LHV) of both propane and hydrogen fuels showed that to evaporate the same amount of seawater, the required hydrogen mass flow rate was about 0.38 times that of propane. At the upper bound, $\dot{m}_{C3H8} = 0.3\frac{g}{s}$ corresponding to $\dot{m}_{H2} = 0.115\frac{g}{s}$, operation with propane costs about \$0.87/hr whereas operation with hydrogen costs about \$12.38/hr. Hence, hourly operation with hydrogen costs about 17 times more compared to propane on equal rate of heat input case.

- Hydrogen production, by no means, is a cheap process. Works done and to be done on hydrogen production should be followed and improved if it is desired to use the hydrogen as a heat source of the direct contact evaporator.

- Consideration of use of hydrogen may require additional equipment that will ensure its safe operation. Careful leakage control is very important since hydrogen is the lightest element in the universe and will escape through even very small cracks. Thus, it can be predicted that an explosion risk is more highly possible in the use of hydrogen than in that of propane.

- Greenhouse gas carbon dioxide (CO_2) contributes to about 63.5% of global warming whereas other gases such as CFCs, nitrous oxide (N_2O), and methane (CH_4) contribute 36.5% of total effect [8]. Hydrogen combustion products pollute air less and have less adverse effects on human body. Hence, the products of hydrogen-air combustion can help reduce greenhouse effect, which is an approaching global threat.

- For future work, a prototype direct-contact evaporator should be constructed using the propane combustion products and experimental data collected. After evaluation of its operation, this evaporator can be simulated for the run with hydrogen combustion products.

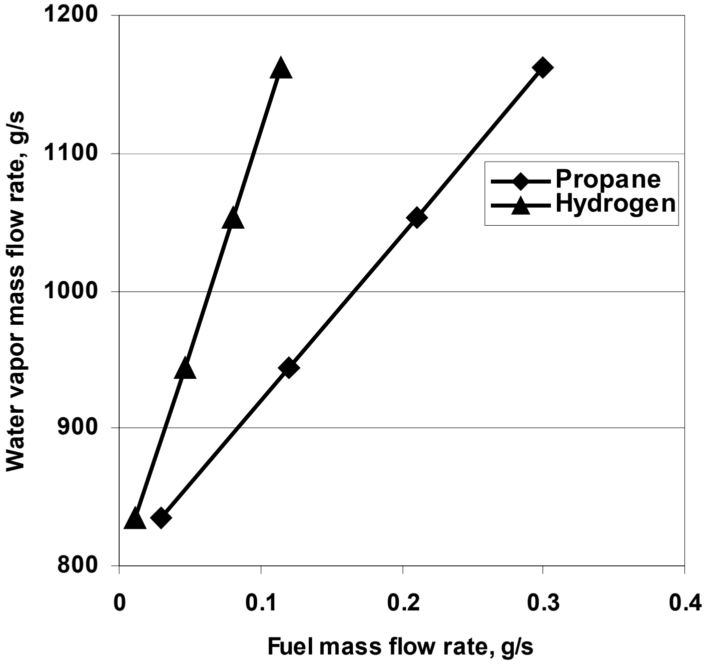

Fig. 2 Water vapor mass flow rate versus fuel mass flow rate.

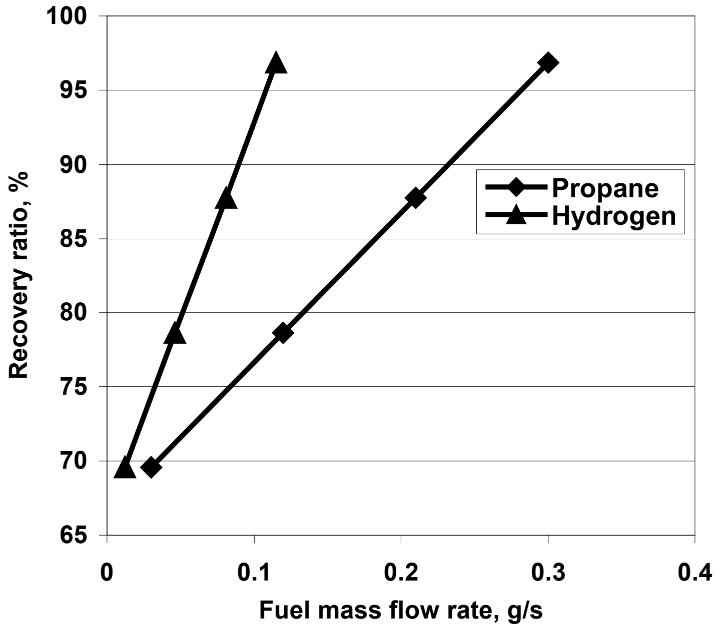

Fig. 3 Recovery ratio versus fuel mass flow rate.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the US Bureau of Reclamation, which supported in part this project.

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