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EXPERIMENTAL STUDY OF A DUAL-CHAMBER VORTEX GENERATOR FOR AN ABSORPTION CHILLER

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ABSTRACT

The dual-chamber vortex generator (DCVG) described in this paper lowers the generator pressure as a consequence of the conservation of rotational momentum which could permit an absorption chiller to function with improved capacity with relatively cooler sources of waste heat. In the present study, we used two kinds of nozzles (ID: 0.89mm and 1.5mm) to generate the swirl motion. The solution flow rate varied from 10GPH (10.5mL/s) to 30GPH (31.5mL/s). The LiBr-Water solution inlet temperature is tested between 60 to 90°C. The solution LiBr inlet concentration is 50wt%. The experimental results showed that the evaporation flow rate and water evaporation ratio in the DCVG are the function of the LiBr-H₂O solution inlet temperature, inlet velocity and solution mass flow rate. The result showed that at the solution inlet temperature of 90°C and solution flow rate of 20GPH, the water evaporation rate is 1.9mL/s, and the water evaporation ratio is 5.3% by weight. This would correspond to 4.6kW cooling capacity and a system COP of 0.83 for a typical absorption chiller. This amount of evolved refrigerant vapor is considered to be sufficient for a practical absorption cycle.

1. INTRODUCTION

Waste heat from industrial processes and power plants is widely accepted as a practical energy source for absorption heat pumps and chillers. The data (Wilfert, et al., 1983) show that there are large, 562 trillion kJ per annum thermal resources available at slightly lower temperatures between 60 and 99°C, which can be, used to power absorption chillers.

Conventional absorption heat pumps can be adjusted to use a lower temperature in the generator. However, this results in a 25 - 40% reduction in capacity. For instance, absorption chillers, which are adapted to operate at lower generator temperature with solar-thermal power, lose 18 to 40 % of nominal capacity (Bierman, 1980). In another case (1993), an absorption chiller for a solar powered operation is rated at 422 kW while the same equipment is rated at 563 kW at 105°C. One approach to a lower generator temperature involves lowering the generator pressure. Fineblum (1996) proposed a dual-chamber vortex generator (DCVG) described in this paper that can lower the generator pressure as a consequence of the conservation of rotational momentum and permits an absorption chiller to function with improved capacity with relatively cooler sources of waste heat. The DCVG is designed to replace current high temperature generators in commercial absorption heat pumps and chillers. In this paper the feasibility and the performance of DCVG for an absorption refrigeration system are verified through experiments.

2. EXPERIMENTAL SETUP

2.1 Testing System

In order to test the performance of the DCVG, an experimental setup was designed and constructed as shown in Figure 1. Main components in the system included: DCVG, a mixer replacing the function of an absorber, three plate heat exchangers (condensate, solution heat exchanger, and heat rejecter) and two electric water heaters. In this phase of the work, the system did not include an evaporator and an absorber.
The weak solution coming from solution pump (LiBr 50wt%) is heated by the heat exchanger using high temperature water, simulating waste heat supply. The solution enters the lower part of the DCVG. Water is evaporated in the generator. The vapor then enters the condenser through the upper chamber. Water vapor is condensed into liquid and goes through the “J” tube, which is used to lower the pressure of water and keep the pressure difference between the condenser and the mixer. Liquid water then enters the mixer and mixes with strong solution coming from the generator. Mixed weak solution repeats the cycle.

Because the LiBr-H\textsubscript{2}O solution is a corrosive liquid, all pipes and connections used in the solution loop are made of stainless steel. All connections and fittings are swage-lock or thread connections to maintain the vacuum of system. Copper tubes are used in the heating water loop. PVC pipes are used in the cooling water loop. All tubes and components were insulated.

Twenty-one T-type Copper-Constantan thermocouples were boned on the surface of tubes or chambers using OB Epoxy Adhesives 100 to measure the temperatures of the liquid in the tubes and chambers. Five pressure transducers were installed to measure the vacuum pressure at different locations. Two volumetric flow meters were used to measure the main solution flow rate at the pump outlet and condensate flow rate at the condenser outlet. Due to the complete condensation in the over-designed condenser, the water evaporation flow rate in the vortex generator was assumed to be equal to the measured condensation flow rate. A sample of LiBr solution was taken at the outlet of the solution pump to determine the concentration of LiBr.

### 2.2 Generator

The DCVG was designed and manufactured according to the results from the CFD analysis (Ramos, 2001). The generator consists of two chambers: an upper chamber and a lower chamber. The diameter and height of lower chamber are both 4" (101.6mm). The inlet nozzle, as shown in Fig.2, is located in the middle of the lower chamber. The nozzles were designed to achieve tangential inlet velocities reaching 30m/s. As shown in Fig. 3 there are two outlets from the lower chamber. One is located at the center of the bottom. The other is a tangential outlet located near the bottom on the chamber wall. The generator is made of stainless steel. The lower chamber and upper chambers are connected by a flange.

As the weak LiBr solution enters the lower chamber through the tangential inlet, a swirling flow is created inside the vortex chamber. This vortex motion results in a radial pressure gradient from the wall to the center.
Because of the lower pressure achieved at the center combined with a relatively high temperature, the refrigerant-rich solution gives up a portion of the refrigerant (water) as vapor. The water vapor flows out of the swirling mixture toward the center and upward into the upper chamber, toward the condenser. The strong solution (63wt%) comes out from the outlets at the bottom of generator, and then goes to the mixer.

The upper chamber is a cylindrical chamber with two outlets, one on each side. The swirling vapor is decelerated to recover some pressure in the upper chamber. To prevent LiBr solution splash into the upper chamber, a tempered borosilicate glass circle with a 2-1/4" (57.15 mm) hole in center was installed between lower and upper chamber. On the top of the upper chamber a sight glass was installed for observation.

The experiments were conducted with varying solution inlet temperatures (60–90°C), solution velocities (8–34 m/s), and nozzle sizes (0.89, 1.5 mm). In our experiments, only the condensate volumetric flow rate at the outlet of condenser was measured, the evaporation flow rate in the generator was assumed to be equal to the condensate flow rate due to the complete condensation in the condenser. The water vapor generation rate is related directly with the liquid-vapor interface area in generator. In order to maximize the evaporation rate in our experiments, the liquid-vapor interface area was optimized by adjusting the valve at the solution outlet as shown in Figure 4.

3. EXPERIMENTAL RESULTS

Ogawa [6] suggested an empirical equation of pressure drop ($\Delta P$) for a hydro cyclone as follow.

$$\Delta P = \xi_c \cdot \rho \cdot \frac{V_i^2}{2} \quad (1)$$

where $V_i$ is the mean inlet velocity, $\xi_c$ is the pressure drop coefficient that is a function of the cyclone geometry. In general, the higher solution inlet velocity may generate stronger vortex flow that could lead to lower pressure in the generator. The low pressure is a necessary condition for the vapor evaporation. Figures 5 (a) and (b) show the variations of the evaporation rate under different solution inlet velocity for two nozzle sizes. The evaporation rate increases almost linearly as the solution inlet velocity increases at all temperature ranges. The current experimental results implied that the pressure drop by the vortex flow in the current test range may have some impact on the vaporization process. Due to the measurement limitation, we did not measure the pressure in the generator directly. But comparing the results from both nozzles shows that at the same inlet velocity larger nozzle produces higher evaporation rates. Because the solution at the nozzle outlet is in the superheated condition, it will evaporate in the generator naturally. Therefore the increase of evaporation rate at higher inlet velocity may also come from the higher solution flow rate.

Figures 6 (a) and (b) show the effect of the solution inlet velocity on the evaporation ratio for both nozzles. The evaporation ratio $R$ is defined as the ratio of evaporation mass flow rate $m_e$ to the solution inlet mass flow rate $m_s$.

$$R = \frac{m_e}{m_s} \quad (2)$$

The evaporation ratio is a parameter that can indicate the economic performance of the system. A small value of R can be a result of higher power consumption from a pump supplying higher solution flow rates.

The experimental results showed that the evaporation ratio decreases as the velocity increases. The small nozzle (0.89 mm) with lower inlet velocity will have higher evaporation ratio. The large nozzle (1.50 mm) with relatively higher inlet velocity will get lower evaporation ratio. This implies that some vapor can not be released from the solution when the velocity increases. This result may be related to the geometry of the generator or the nozzle.
position in height. If we have a big enough generator, the solution would have time to stay in the generator, and then release more vapor.

Figures 7(a) and (b) show the variation of evaporation flow rate at different solution inlet temperatures (60, 70, 80 and 90°C) for the nozzle size tested: 1.50mm and 0.89mm. The evaporation flow rate is related directly to the DCVG performance. In these figures, it can be seen that the evaporation flow rate increases with the solution inlet temperature for both nozzles. Higher solution inlet temperature allows more energy to be added resulting in the production of more vapor in the generator. The solution enters the DCVG at high temperature and high pressure and becomes superheated as it leaves the nozzle. The vapor is liberated because the solution temperature is higher than the water saturation temperature, and the remaining solution is cooled in the process. When the solution inlet temperature is increased, more vapor could be generated if the temperature difference between the solution inlet temperature and the saturation temperature which is based on the inlet solution concentration and generator pressure will increase.

Figures 8(a) and (b) show the effect of solution inlet temperature on the evaporation ratio for both nozzle sizes (1.5mm and 0.89mm). As shown in Figure 8, the evaporation ratio increases almost linearly with the solution inlet temperature.
From the above experimental results, three main factors can be considered to affect the evaporation in the generator. The first factor is the solution inlet temperature. As the solution inlet temperature increases, more vapor will be released from the solution. The second, free surface area, which is the interface area of liquid and gas in the generator, will also affect the evaporation in the generator. Because the evaporation occurs on the interface, the more free surface area created, the more vapor will be able to come out under the same conditions. The third factor is the pressure drop in the generator. The heated solution enters the generator tangentially through a nozzle and has a circulation flow that will produce a lower pressure at the center compared to the outside. Due to the pressure reduction, the saturated temperature at the center will be decreased, and then the solution releases more vapor at the same solution inlet temperature.

In the current test system, a liquid mixer was used to replace the evaporator and absorber which are typical components in an absorption chiller. Here, we assumed that all vapor from generator will be fully condensed in the condenser, evaporated totally in an evaporator, and then absorbed in a absorber to finish a cycle. So that, the energy efficiency, coefficient of performance ($\text{COP}_{\text{en}}$), can be defined as the ratio of energy input into the generator $Q_g$ and energy output from evaporator $Q_e$. The definition is:

$$\text{COP}_{\text{en}} = \frac{Q_e}{Q_g}.$$
\[ \text{COP}_{\text{en}} = \frac{Q_e}{Q_g} \]  \hspace{1cm} (3)

\[ Q_e = \dot{m}_e h_{fg} \]  \hspace{1cm} (4)

\[ Q_g = \dot{m}_g C_p (T_{11} - T_{10}) \]  \hspace{1cm} (5)

where \( \dot{m}_e \) is the solution inlet mass flow rate. \( T_{10} \) and \( T_{11} \) are solution temperatures in Figure 1. Based on the above definition and our experimental data, the \( \text{COP}_{\text{en}} \) value was determined and shown in Figs. 9(a) and (b). The results showed the \( \text{COP}_{\text{en}} \) value increases with the inlet solution temperature and can reach as high as 0.83 in current test conditions.

The exergy efficiency, \( \text{COP}_{\text{ex}} \), is defined as the ratio of the exergy input into the system \( \Delta E_g \) including the pumping exergy \( W_p \) (equal to the pumping energy \( W_p \) measured directly in the experiments) and the exergy output from the evaporator \( \Delta E_e \).

\[ \text{COP}_{\text{ex}} = \frac{\Delta E_e}{\Delta E_g} \]  \hspace{1cm} (6)

\[ \Delta E_g = -Q_g \left(1 - \frac{T_0}{T_g}\right) W_p \] \hspace{1cm} \[ \Delta E_e = -Q_e \left(1 - \frac{T_0}{T_e}\right) \]  \hspace{1cm} (7)

where \( T_0 \) is the room temperature (20°C), \( T_e = 5^o \text{C}, T_g = T_{14} \) in Figure 1. The \( \text{COP}_{\text{ex}} \) calculation results are shown in Figs 10(a) and (b). The the exergy efficiency looks very low, but the heat source is considered to be either waste heat or solar energy.

5. CONCLUSIONS

The feasibility and practicality of Dual Chamber Vortex Generator (DCVG) for absorption refrigeration system was verified through current experiments. The evaporation flow rate and the evaporation ratio are the function of solution inlet temperature, flow rate and nozzle size. Using the current design of DCVG, the \( \text{COP} \) value of an absorption refrigeration system can reach 0.83 even with the heat source temperature below 95°C.

![Figure 9](image_url)

**Figure 9** Effect of solution inlet temperature on \( \text{COP}_{\text{en}} \)
Figure 10 Effect of solution inlet temperature on COP_{ex}

### Nomenclature

- \( \text{COP}_{en} \): Coefficient of performance (energy base), -
- \( \text{COP}_{ex} \): Coefficient of performance (exergy base), -
- \( Cp_s \): Capacity of heat, J/kg·K
- \( h_{fg} \): Latent heat, J/kg
- \( \dot{m}_e \): Evaporation mass flow rate, kg/s
- \( \dot{m}_s \): Solution inlet mass flow rate, kg/s
- \( Q_e \): Energy output from the evaporator, W
- \( Q_g \): Energy input into the generator, W
- \( R \): Evaporation ratio, -
- \( T_{10}, T_{11} \): Solution temperatures at Points 10 and 11 in Figure 1, °C
- \( v_i \): Solution inlet velocity, m/s
- \( W_p \): Pumping power, W
- \( \Delta E_e \): Exergy output from the evaporator, W
- \( \Delta E_g \): Exergy input to the system, W
- \( \Delta P \): Pressure drop over a cyclone, Pa
- \( \rho \): Solution density, kg/m³
- \( \xi_c \): Pressure drop coefficient, -

### References

