

DIRECT COOLING/HEATING APPROACH FOR SOLAR-DRIVEN VAPOUR ABSORPTION COOLING SYSTEM

Shenyi Wu*, Saffa Riffat

School of Built Environment, University of Nottingham,
University Park, Nottingham, NG7 2RD, UK

Abstract

The conventional approach to discharge the heat from an absorber to the ground is through a second circulation loop. The same method is also used to convey the heat from the solar collector to the generator when using solar collector to supply the heat to the vapour absorption system. This indirect approach adds extra temperature difference in the heat transfer processes, which could affect the system's overall performance, particularly; when the system is driven by a low temperature heat source. This paper reports a theoretical investigation of a direct cooling approach in which the absorbent solution is directly cooled and heated in the ground and the solar collector, respectively. The theoretical analysis showed that the directly cooled ground-loop absorber would incur a higher-pressure loss compared to a configuration using a conventional absorber plus a second circulation loop. However, the overall performance is improved as a result of the elimination of the second circulation loops.

Keywords: Vapour absorption refrigeration, Ground heat exchanger, Solar Energy

* Corresponding author: Tel: +44 (0) 115 8467875, email: shenyi.wu@nottingham.ac.uk

Introduction

The overall efficiency of a solar driven vapour absorption cooling system is determined by the efficiencies of the solar collector and the absorption refrigerator. However, the efficiency of a solar collector in response to the temperature change is in opposite direction to that of a vapour absorption refrigerator, i.e., the efficiency of the absorption refrigerator increases with the heat source temperature while that of the

solar collector, served as the heat source in the system, decreases as working temperature increases. Therefore, an appropriate working temperature has to be determined for the solar collector and the refrigerator in order to maximise the overall efficiency. The upper limit on the working temperature does not allow the solar collector to supply high temperature heat to the vapour absorption refrigerator. As a result, the solar driven absorption refrigerator has to be working with a low temperature heat source. Under

these circumstances, lowering the condensing and absorption temperatures as well as reducing the temperature differences in the heat transfer processes is necessary to improve the system's efficiency. Using ground as a heat sink to cool the refrigerator's condenser and absorber is a good practice to achieve low condensing and absorption temperatures. However, conventionally, the heat transfer between the refrigerator and the ground (the heat sink) is via a second circulation loop in which a second medium, e.g. water, receives the heat from the condenser and absorber and then passes it to the soil. This process inevitably introduces extra temperature differences in the heat transfer process and offsets the effort on achieving low condensing and absorption temperatures. Similar problem also occurs in the heat transfer between the solar collector and the generator. The problem associated with the absorber can be resolved by employing a direct cooled ground loop absorber, i.e., the absorbent is directly cooled in the ground loop rather than cooled via a second loop. Since this approach does not rely on a second medium to convey the heat, the additional temperature difference caused by the second loop is eliminated. Similarly, the direct approach can also be applied to the solar driven generator to reduce the temperature difference in the heating side.

Comparison analysis of the direct and indirect approaches

Figure 1 shows the configurations of direct (A) and indirect (B) cooling approaches for the absorber. The study here only considers the directly cooled ground-loop absorber (direct approach) as analysed against the conventional second-loop (indirect approach) as the results from the following analysis can also be applied to the solar drive generator.

Aqueous lithium bromide solution is used in the analysis.

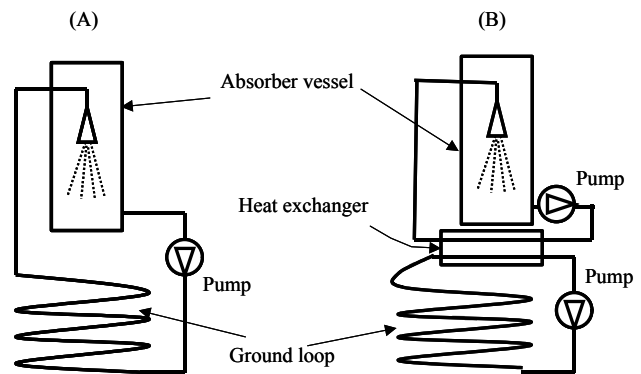


Figure 1 (A) Direct cooled and (B) indirect cooled

As shown in the Figure 1 (B), the indirect approach involves a heat exchanger to transfer the heat from the absorber to the ground loop while the direct approach does not have the heat exchanger but the ground loop itself has become part of the absorber.

In the direct approach, the absorbent solution, e.g., the aqueous lithium bromide solution is also used as a medium to convey the heat to the ground via the ground loop. Since the properties of the aqueous lithium bromide solution are quite different from that of water (or water-based anti-freeze liquids) commonly used as working fluids in the ground loops, it is necessary to analyse how the aqueous lithium bromide solution performs in terms of heat transfer and flow resistance in the ground loop because they will affect the power consumption of the circulation pump.

For a given heat transfer load $\dot{Q}$ applied to the ground loop and the temperature difference between its inlet and outlet, $\Delta T = T_{out} - T_{in}$, the required flow rate past

through the ground loop can be calculated from the energy balance as follows:

$$\dot{m} = \frac{\dot{Q}}{h_{out} - h_{in}} = \frac{\dot{Q}}{Cp\Delta T} \quad (1)$$

The flow resistance can be calculated from:

$$\Delta p = f \frac{l}{D} \frac{\rho V^2}{2} = f \frac{l}{D} \frac{8\dot{m}^2}{\pi^2 D^4 \rho} = f \frac{8l\dot{Q}^2}{\pi^2 D^5 \rho Cp\Delta T} \quad (2)$$

Since ρ and Cp are the function of temperature, average values within the operating temperature range should be used here. Under the fully developed turbulent flow assumption, the coefficient of heat transfer in ground loop may be obtained using Dittus and Boelter's [1]. Therefore:

$$Nu_D = 0.023 Re_D^{0.8} Pr^{0.3} \quad (3)$$

$$Re_D = \frac{4\dot{m}}{\pi D \mu} \quad (4)$$

$$\begin{aligned} Nu_D &= 0.023 Re_D^{0.8} Pr^{0.3} = 0.023 \left(\frac{4\dot{m}}{\pi D \mu} \right)^{0.8} Pr^{0.3} \\ &= 0.023 \left(\frac{4\dot{Q}}{\pi D \mu Cp \Delta T} \right)^{0.8} Pr^{0.3} \end{aligned} \quad (5)$$

For the same heat transfer load, $\dot{Q}$, and pipe diameter, the flow resistance and Nusselt number ratios of water over aqueous lithium bromide solution can be manipulated from Equations (1) to (5):

$$\frac{\Delta p_w}{\Delta p_l} = \frac{f_w l_w \rho_l Cp_l}{f_l l_l \rho_w Cp_w} \quad (6)$$

$$\frac{Nu_{Dw}}{Nu_{Dl}} = \left(\frac{\mu_l Cp_l}{\mu_w Cp_w} \right)^{0.8} \left(\frac{Pr_w}{Pr_l} \right)^{0.3} = \left(\frac{\mu_l}{\mu_w} \right)^{0.5} \left(\frac{Cp_l}{Cp_w} \right)^{0.5} \left(\frac{k_l}{k_w} \right)^{0.3} \quad (7)$$

Subscripts “w” and “l” denote water and aqueous lithium bromide solution, respectively.

The friction factor under turbulent is characterised by the Reynolds number and the nature condition of the pipe wall surface. For a smooth wall surface, empirical correlations give [1]:

$$f = \frac{0.3164}{Re^{0.25}} \quad \text{for } Re < 10^5 \quad (8)$$

Therefore, the ratio of friction factors can be expressed as:

$$\frac{f_w}{f_l} = \left(\frac{Re_{Dl}}{Re_{Dw}} \right)^{0.25} = \left(\frac{\mu_w Cp_w}{\mu_l Cp_l} \right)^{0.25} \quad (9)$$

The heat transfer between the fluid and pipe wall can be expressed as follows:

$$\dot{Q} = hA\Delta T = \frac{Nu_D k}{D} (\pi D l) \Delta T$$

For comparison of the pipe length required for different working fluids, it is assumed that the heat load $\dot{Q}$, temperature difference ΔT and pipe diameter D , are all kept same. Therefore, the following relationship exists when water and aqueous lithium bromide solution are used as working fluids,

$$Nu_{Dw} k_w l_w = Nu_{Dl} k_l l_l$$

Their length ratio can be written in the following form with reference of Equation (7):

$$\frac{l_w}{l_l} = \frac{Nu_{Dl} k_l}{Nu_{Dw} k_w} = \left(\frac{\mu_w}{\mu_l} \right)^{0.5} \left(\frac{Cp_w}{Cp_l} \right)^{0.5} \left(\frac{k_l}{k_w} \right)^{0.7} \quad (10)$$

Substituting Equations (9) and (10) into (6), we obtain the pressure drop ratio as:

$$\frac{\Delta p_w}{\Delta p_l} = \left(\frac{\mu_w}{\mu_l} \right)^{0.75} \left(\frac{Cp_l}{Cp_w} \right)^{0.25} \left(\frac{k_l}{k_w} \right)^{0.7} \frac{\rho_l}{\rho_w} \quad (11)$$

From these equations, the heat transfer and flow resistance in the ground loop using aqueous lithium bromide can be evaluated against the equivalent data for the case using water.

The effect on flow resistance

The ratios of pressure loss, coefficient of heat transfer and length of the ground loop were calculated for aqueous lithium bromide solution at 25°C, and are shown in Table 1. The properties of aqueous lithium bromide used in the calculation were taken from references [2, 3, 4]. The second column in Table 1 shows that the ratios of the pressure losses are less than 1, which means that the flow resistance in the case of the direct-cooled system is greater than that of the indirect-cooled. The higher pressure losses in the direct approach are due to the higher viscosity of the LiBr/H₂O solution and the longer ground loop required. The percentage of additional pressure loss in the direct-cooled approach increases with increasing

concentration of solution. Figure 2 shows that approximately 13% additional pressure loss is incurred when the solution concentration is 49.1%. However, the pressure loss rises to 33.3% when the concentration is 53.8%. This suggests that the solution concentration of the absorber should be kept as low as possible in the direct-cooled approach to avoid high power consumption by the pump. It is fortunate that ground temperature is well below atmosphere temperature in the summer season, as this allows the ground-loop absorber to reduce the absorbing temperature so that the system can operate at a lower concentration for the same evaporating temperature. When the temperature and concentration of aqueous lithium bromide solution are 25°C and 49.1% respectively, its equilibrium vapour temperature is 5.3°C which is highly suitable for the purpose of building air-conditioning.

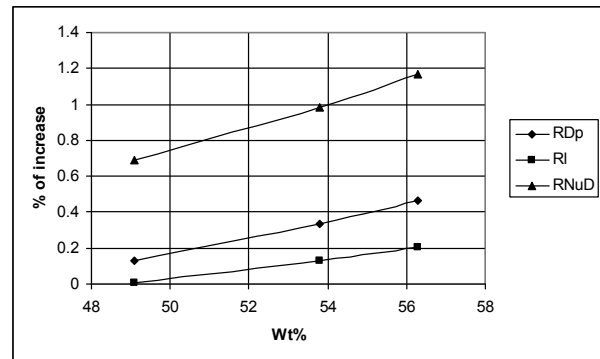


Figure 2 Percentage increase in pressure drop, loop length and Nusselt number against solution concentration

Table 1. Comparison of pressure loss, length of loop and coefficient of heat transfer

Concentration Wt %	$\Delta p_w / \Delta p_l$	L_w / l_l	Nu_{Dw} / Nu_{Dl}
49.1	0.885	0.996	0.591
53.8	0.750	0.884	0.505
56.3	0.683	0.829	0.462

Overall length of the ground loop

Compared with the indirect cooled approach, only a small increase (0.4%) in the overall length of the ground loop is needed for the direct-cooled approach when the solution concentration is 49.1%. This suggests that the indirect loop could be easily converted for the direct-cooled approach in terms of heat transfer capability. The small additional cost for the extra 0.4 % length of the pipe is offset by eliminating the need for a heat exchanger, otherwise required in the indirect configuration. The overall length of the ground loop increases significantly with increasing solution concentration. However, as it has been discussed previously, use of a high solution concentration can be avoided by the use of a ground-loop absorber.

Effect on the coefficient of heat transfer

In contrast to the increase in Nusselt number with increasing concentration in the direct-cooled approach, the coefficient of heat transfer decreases as evidenced by the fact that a longer pipe is required as the solution concentration increases. The decrease in the coefficient of heat transfer is due to a smaller thermal conductivity of the aqueous lithium bromide solution compared with that of water. The effect of this is not significant when the solution concentration is low.

The above analysis reveals that the only disadvantage of the direct-cooled approach is that additional power consumption may be needed to overcome the extra resistance to the flow. This can be reduced by optimising the flow and the pipe dimensions. The net increase in the power consumption is expected to be small compared with the improved overall efficiency of the system and its lower capital cost. The analytical results also indicate that benefits will be

obtained only when the direct cooled approach is applied to cases with low solution concentration.

Performance prediction

Using direct heating and a ground absorber can improve the overall system energy performance COP and lower the requirement for the heat source. Figures 3 shows the computed results for COP against reduction in absorber temperature, taking 30°C as the reference temperature for the absorber. The equation used to calculate the COP can be found in [5] and the losses, e.g., pressure drop are not taken into account. It can be found from Figure 4 that the system COP increases as the absorber temperatures is reduced. As we know that it is quite common to incur 5°C or more temperature difference in a heat exchanger. The use of ground-loop absorber means the system employs one less heat exchanger, which will give a reduction of 5°C or more in absorbing temperature. This boosts the COP of the system by at least 2.5% as shown in Figure 4. It is quite realistic to expect 5% or more increase if the absorber can operate at the low end of the temperature range.

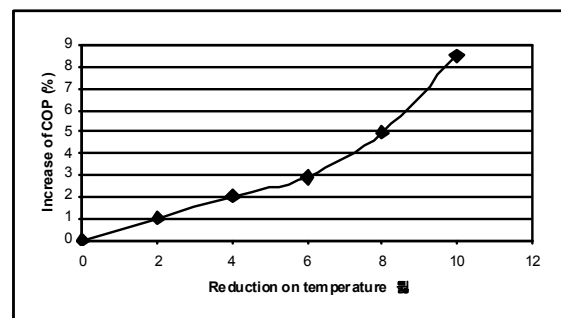


Figure 3 Performance improved with reduction of the absorber temperature (30°C is taken as the reference absorber temperature)

The reduction of absorber and condenser temperatures can also reduce the generator temperature. Their relationship can be derived from the P-T-X (vapour pressure-solution temperature-solution concentration) of the aqueous lithium bromide solution under the conditions that the vapour pressures of the generator and the absorber are equal to that of the condenser and evaporator, respectively. Figure 4 shows the relationship between the generator and absorber temperatures under a constant concentration difference (10%) between the strong and weak solutions. The figure shows that a 5°C reduction in absorber temperature could reduce the minimum required generator temperature by approximately 12°C. This will provide 1.5% improvement in the efficiency of the solar collector [6]. Considering at least a 5°C reduction provided by the direct heating at the generator, the total reduction to the required heat source temperature could be more than 17°C. This will result in a significant improvement of the solar-collector efficiency and allow the solar-driven cooling system to be driven by a low temperature heat source with up to a 10% increase in COP. The improvement in the efficiency of the solar collector will lower the capital cost of the system because less solar collectors are needed.

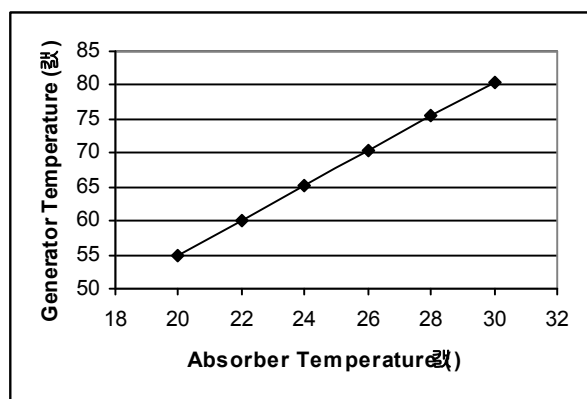


Figure 4 Relationship between generator temperature and absorber temperature (assuming $T_C = T_A$)

Conclusion

The direct cooling/heating approach can effectively reduce temperature differences required for the heat transfer, therefore, it can improve the performance of a solar driven vapour absorption system as the analytical results have shown. The viscosity of the absorbent fluid may increase the flow resistance; therefore, increase the power consumption of the circulation pump. However, this is not so significant when the concentration of the solution is low. As the direct approach can effectively reduce the absorption temperature, the system can be operated with a lower concentration of the solution. Therefore, the direct cooling/heating approach is a practical way to improve the system's performance.

Acknowledgement

This study has been carried out as part of a project funded by the EPSRC through the INREB Faraday Partnership.

Nomenclature

A	Surface area of a pipe, (m^2)
C_p	Specific heat, $kJ/(kg \cdot ^\circ C)$
D	Diameter of pipe; m
f	Friction factor
h	enthalpy; kJ/kg
k	Thermal conductivity; $W/(m \cdot ^\circ C)$
l	length of ground loop; m
$\dot{m}$	Mass flow rate; kg/s
Nu_D	Nusselt number
Pr	Prandtl number
$\dot{Q}$	Heat flow rate; W
Re	Reynolds number
V	Velocity; m/s

T_A	Absorber temperature
T_C	Condenser temperature
T_E	Evaporator temperature
T_G	Generator temperature

Greek

ρ	Density; kg/m ³
μ	Dynamic viscosity; Pa·s
Δp	Pressure loss, Pa
ΔT	Temperature difference; °C

Subscripts

l	Lithium bromide-water solution
w	water

References

1. Adrian Bejan, 1993. Heat transfer. John Wiley & Sons, Inc.,
2. ASHRAE handbook, Fundamentals. 1997. The American Society of Heating, Refrigeration and Air –Conditioning Engineers, Inc.
3. DiGuilio R. M., Lee R. J., Jeter S. M. and Teja A. S. 1990. Properties of Lithium Bromide-water Solutions at High Temperatures and concentrations-I: Thermal Conductivity, ASHRAE Winter Meeting, February 10-14, Atlanta, Georgia, USA, P702-708.
4. Lee R. J., DiGuilio R. M., Jeter S. M., and Teja A. S. 1990. Properties of Lithium Bromide-water Solutions at High Temperatures and concentrations-II: Density and Viscosity, ASHRAE Winter Meeting, February 10-14, Atlanta, Georgia, USA, P709-714.
5. Gosney W. 1982. Principles of Refrigeration, Cambridge University Press.
6. Vliet H. B. 1982. Solar Thermal Energy Systems, McGraw Hill.