Performance analysis of direct-expansion solar-assisted heat pump water heating system using carbon dioxide as refrigerant

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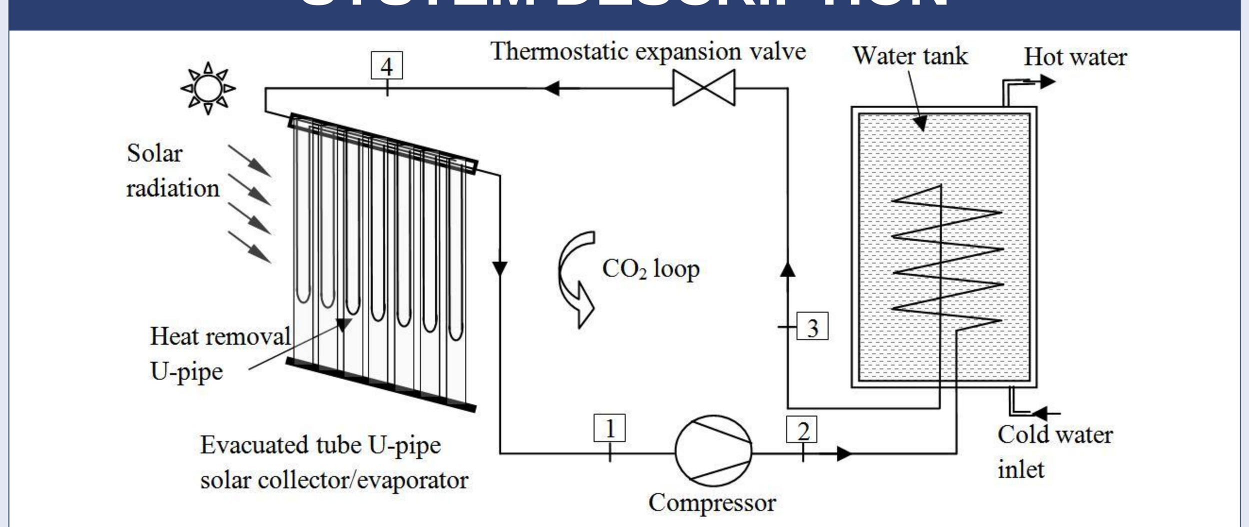
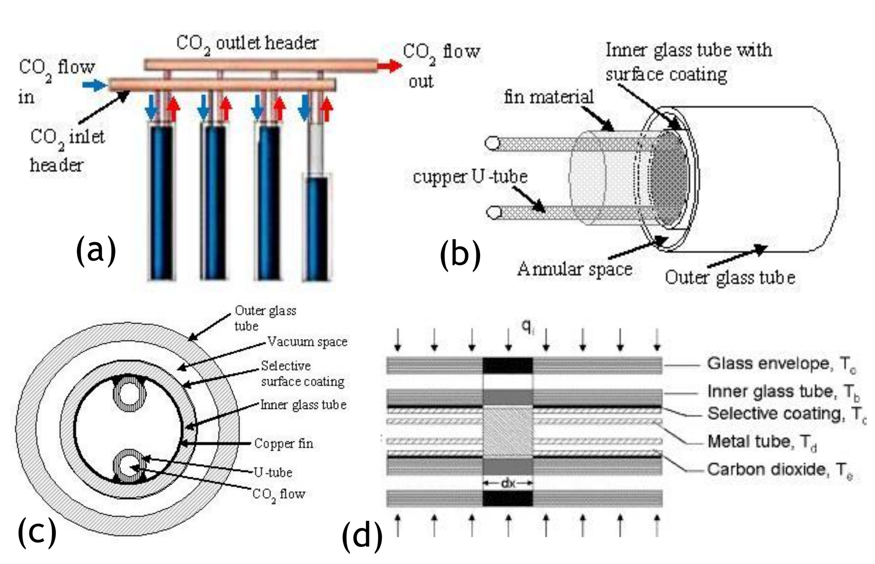
ABSTRACT

Details of the numerical analyses of a CO_2 transcritical cycle on solar assisted heat pump water heating system is analyzed in this study. Due to high evaporation temperatures that are achieved when using solar radiation as dominant heat source for evaporation, solar heat pumps can yield remarkably higher values of COP. Inconsistent weather conditions may affect the performance of heat pump, and hence such system should be carefully optimized in terms of solar collector area, capacity of compressor, evaporating and condensing temperatures. This analytical studies were carried out considering evacuated tube U-pipe solar collector as evaporator for the R744 (CO_2) refrigerant, a variable speed reciprocating compressor, an immersed heat exchanger and an expansion valve. The average value of COP ranged from 2 – 3 and collector efficiencies from 40% - 60% using the average fall and winter meteorological conditions of North Dakota [1]. The developed simulation model is used for the optimization of the system components and operating parameters.

SYSTEM DESCRIPTION



Schematic diagram of a direct-expansion solar assisted heat pump water heating system



Evacuated tube U-pipe solar collector and its components. (a) CO_2 flow direction; (b) construction of the unit glass tube; (c) cross-sectional view of the collector tube; and (d) differential control volume used in the present analysis [2]

Evacuated tube U-pipe solar collector

- Better efficiency compared to flat-plate collector
- Minimizes convection heat losses by placing solar absorbing surface in the vacuum
- Reduces the radiative heat loss by using low emissivity absorber surface
- Attains high temperatures very easily
- Best fit in the cold region

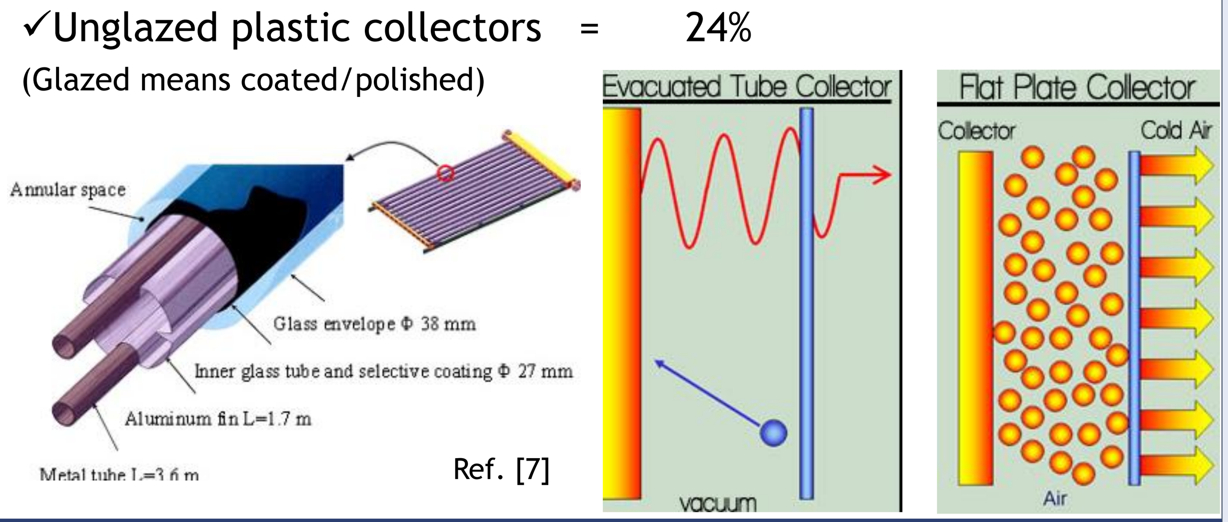
Efficiency Criterion:

✓Evacuated tubes collectors = 44-50%

✓Glazed flat plate collectors = 34%

✓Unglazed plastic collectors = 24%

(Glazed means coated/polished)



Ref. [7]

MODEL

Governing Equations

Useful heat gain [8] $Q_u = A_c F'\left[I\left(\tau_g \alpha_g\right) - U_L\left(T_f - T_a\right)\right]$

Plate temperature [9] $\frac{d^2 T_p}{dx^2} = \frac{-S + U_L\left(T_p - T_a\right)}{\lambda\delta\left(1 + U_L/C_b\right)}$

Working fluid temperature $\frac{dT_f}{dz} = \frac{\tau_g^2 \alpha_c r_p I + \tau_g \alpha_g r_p I + \alpha_g r_g I - r_g \sigma \varepsilon_g \left(T_g^4 - T_a^4\right) - r_g h_a \left(T_g - T_a\right)}{2 m_f C_p}$

Pressure drop in 2-phase region $-\frac{dp}{dz} = \frac{\frac{2C_f G^2}{d_i}\left(v_f + x v_{fg}\right) + G^2 v_{fg}\frac{dx}{dz}}{1 + G^2\left(x\frac{dv_g}{dp} + (1-x)\frac{dv_f}{dp}\right)}$

Solar collector efficiency $\eta_{coll} = \frac{Q_u}{A_c I}$

Mass flow rate of CO_2 $m_f = \rho_{suc}\eta_v V_s \frac{N}{60}$

Compressor work $W_{com} = m_f\left(h_2 - h_1\right)$

Expression for non-stratified storage tank $M_w C_{pw}\frac{dT_w}{dt} = Q_{cond} - (UA)_t\left(T_w - T_a\right) - Q_{load}$

Numerical computation model has developed using MATLAB and REFPROP 8.0 software

PROPERTIES OF CO_2

CO_2 as a refrigerant (R744)

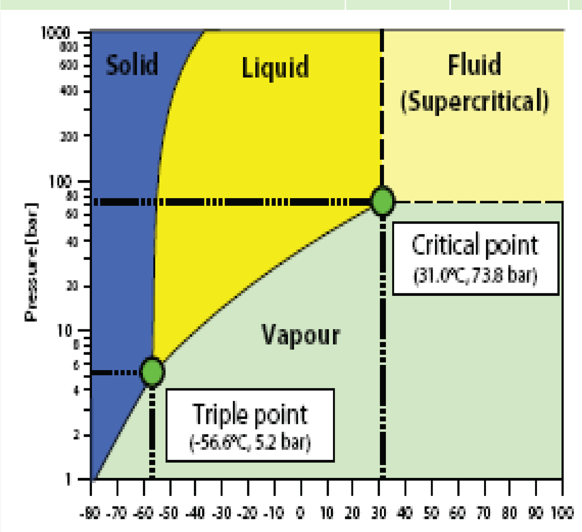
- Superior Environmental Qualities
- Superior in terms of heat transfer properties
- Low critical temperature provides opportunity to use CO_2 in a supercritical cycle

Performance advantages of CO_2

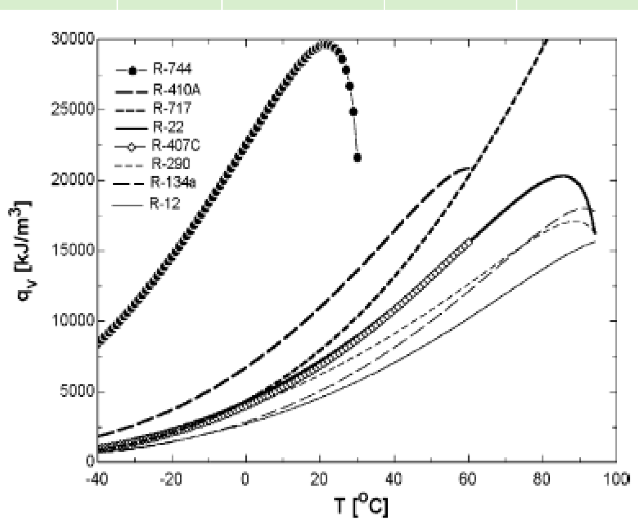
- Lower compression ratios typically 3:1 or 4:1
- High volumetric refrigeration capacity $h_{fg}*\rho_{sat\ vap}$ (kJ/m^3) means lower charge volume and flow rate
- Greater heat transfer coefficients
- Low cost

Table: Environmental characteristics of various refrigerants

Refrigerant	CO_2	R-407C	R-410A	R-22	Ammonia	R-134a	R-404A
Natural substance	Yes	No	No	No	Yes	No	No
ODP	0	0	0	0.05	0	0	0
GWP	1	1610	1725	1700	0	1300	3260
Flammable or Explosive	No	No	No	No	Yes	No	No
Toxicity	Low	Low	Low	Low	High	Low	Low



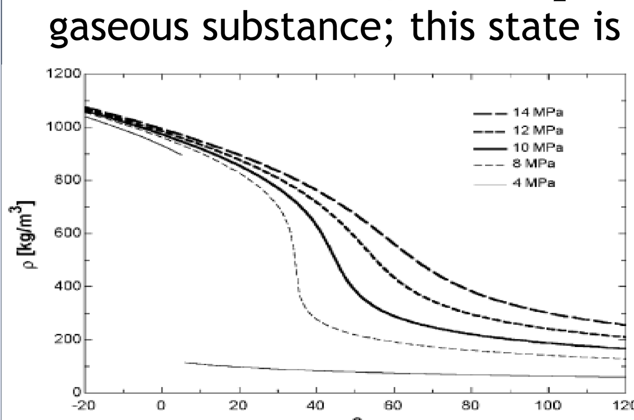
CO_2 *P-T* diagram [4]



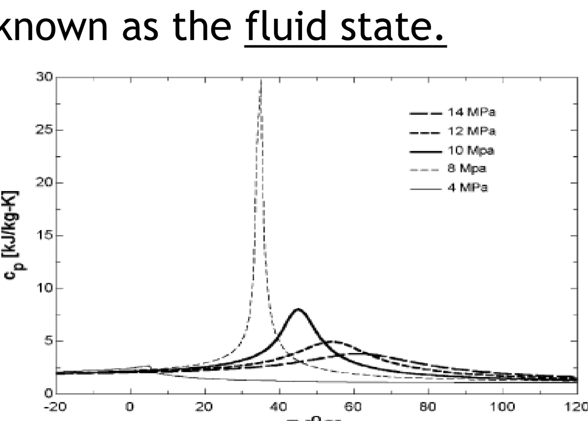
Volumetric refrigeration capacity of the refrigerants [6]

Supercritical state

- Above the critical point, CO_2 behaves as a mixture of liquid and gaseous substance; this state is known as the fluid state.



Density variation of CO_2 [6]



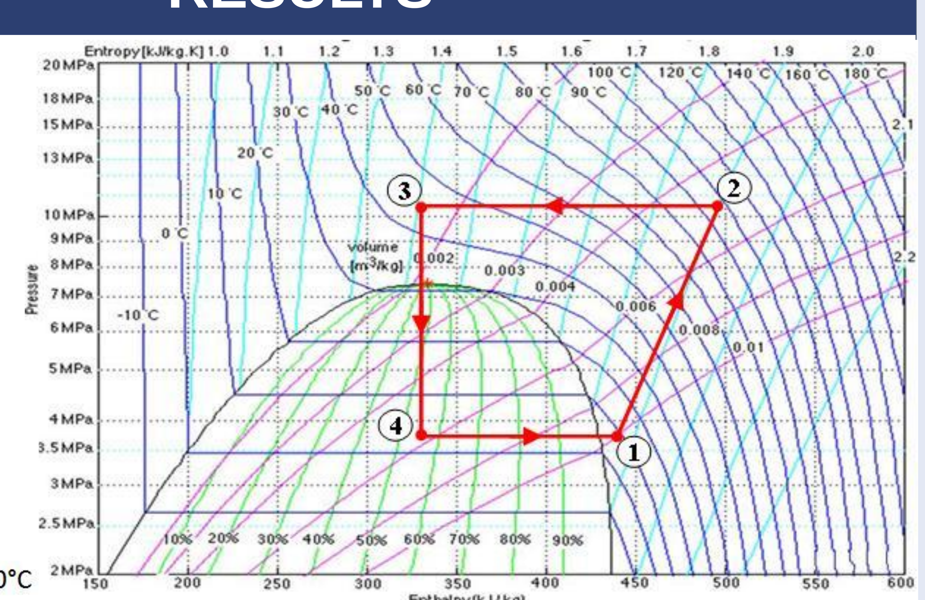
Isobaric specific heat of CO_2 [6]

Pseudo Critical Property changes

- For a constant pressure above P_{crit}, there is a temperature called as the pseudo-critical point where c_p is maximum [6]
- Thermo physical properties variation are high near the pseudo-critical temperature region

RESULTS

P-h diagram of CO_2 in a steady-state cycle of simulated model



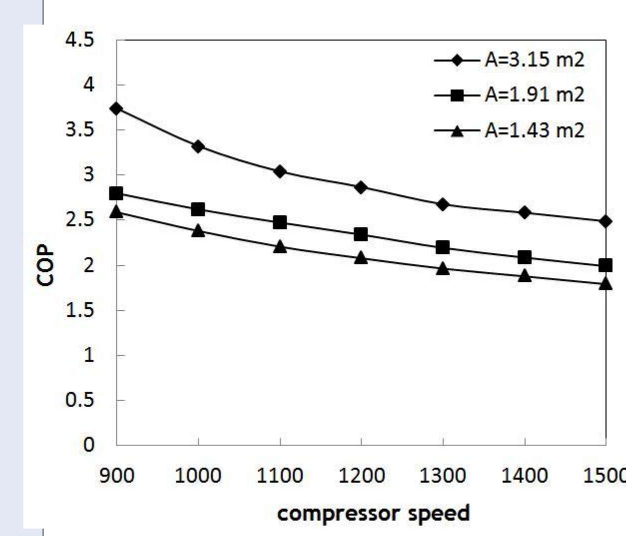
Process④→①: Evaporation P_1 = 3.75 Mpa, P_4 = 3.8 Mpa, T_4 = 4.5°C; T_1 = 10°C

Process①→②: Compression P_2 = 11.2 Mpa, T_2 = 95°C

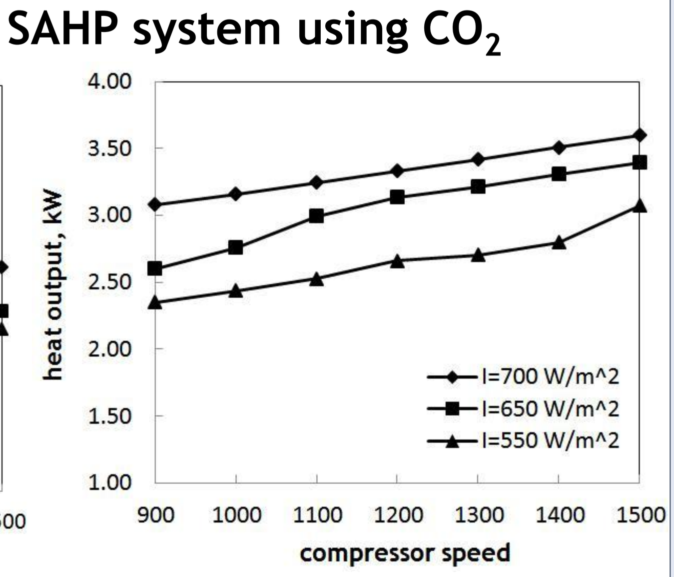
Process②→③: Condensation P_3 = 11.2 Mpa, T_3 = 45°C

Process③→④: Expansion $h_3 = h_4$ = 380 [KJ/Kg]

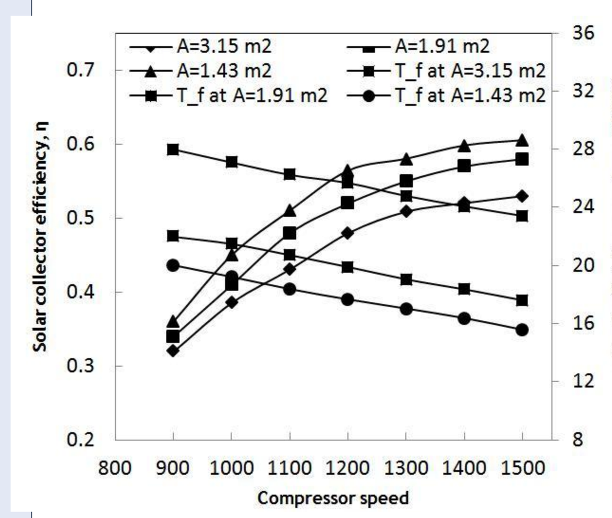
Performance of SAHP system using CO_2



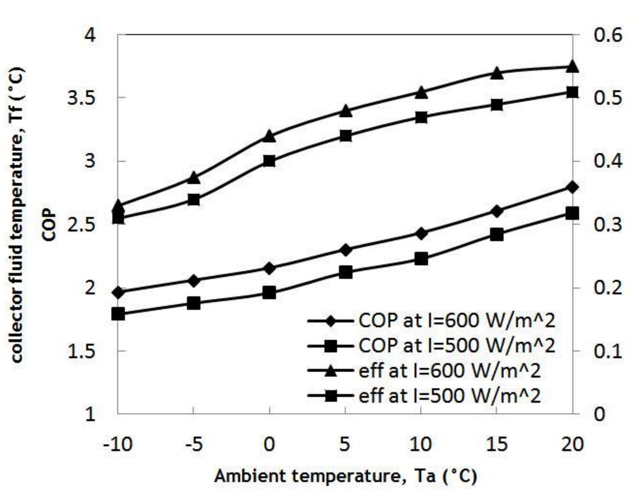
Effect of compressor speed on COP



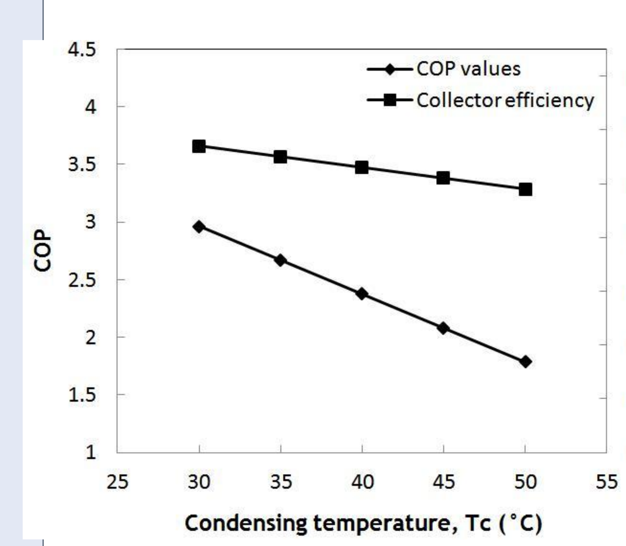
Heat output at various compressor speed



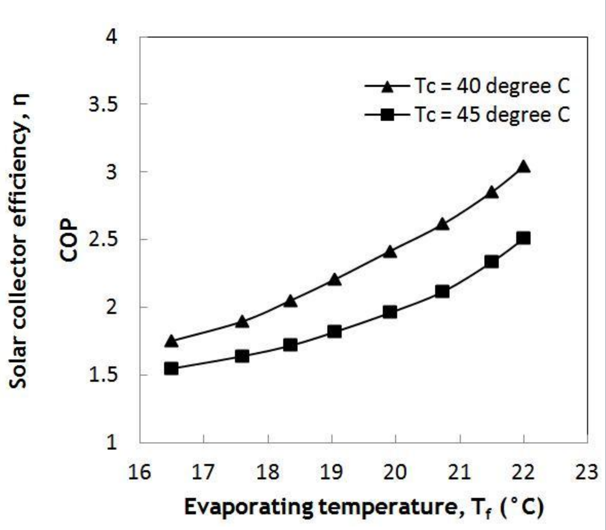
Effect of collector fluid temp. and collector efficiency at various compressor speed



Effect of ambient temp. on COP and solar collector efficiency



Variation of COP and collector efficiency with condensing temperature



Relation between COP and evaporating temperature

CONCLUSION

Thermal performance of SA-DXHP water heater by using CO_2 as a refrigerant for the moderate weather conditions of North Dakota has been simulated and is discussed in this paper. The results were then optimized for varying compressor speed. Results revealed that by decreasing compressor speed from 1500 to 900, the COP can be improved by an average of 57%. The efficiencies of the solar collector were also predicted (50–55%) and found a good agreement with the experimental values. Even though U-pipe assisted evacuated tube solar heat pump systems pertain higher initial cost, the environmentally friendly and economically cheap CO_2 have better prospect in solar thermal applications.

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