FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 9 No. 3, March, 2025, pp 373 - 378
DOI: https://doi.org/10.33003/fjs-2025-0903-3251

DEVELOPMENT AND TESTING OF A SOLAR ADSORPTION REFRIGERATOR UNDER HAZY CONDITION

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ABSTRACT

Preservation of foods, drinks, fruits, fish, and perishables using cleaner form of energy at low financial cost has necessitated the adoption of solar powered refrigeration system most especially in locations with known viable solar resources. A 0.36m^2 solar-powered adsorption refrigeration system utilizing an activated carbon/methanol pair was developed, tested, and evaluated under a cloudy sky condition of harmattan haze of Bauchi weather condition in January. A single 4mm plane glass forms the collector employing the location latitude as the inclination angle. Copper tubes arranged in parallel and connected to two headers are embedded underneath the absorber and, then coated with black paint. Collector air tightness is improved by the use of glazing rubber. Five liters of water in the cooling cabinet attained 13°C after 56 hours of experiment achieving a 41% temperature reduction and, 0.56 cooling coefficient of performance. This work indicates the practicability of solar adsorption refrigeration in the tropics amidst cloudy sky conditions. For improved performance under unfavorable weather conditions, provision should be made for auxiliary heating. The applications of this form of refrigeration will curb the use of conventional energy, minimize grid dependence, reduce household recurrent bills, and ozone layer-depleting chlorofluorocarbons (CFCs).

Keywords: Activated carbon/methanol, Adsorption, Cooling, Development, Solar energy

INTRODUCTION

The increasing use of conventional energy and its adverse environmental impact have searched for alternatives that are renewable and non-ozone depleting more intensely. Solar energy like all other renewable energies, is safe, has no adverse effect on the environment, and is readily available, especially in the tropics (Emmanuel *et al.,* 2020). Solar energy has widespread applications in space and water heating, power generation, space cooling and refrigeration, solar distillation, direct electricity generation, and solar thermal energy storage (Benjamin, 2023; Likta, 2023). Solar refrigeration is used to preserve food, drinks, fruits, fish, vegetables, and other forms of perishables. Solar cooling or refrigeration is more valuable in countries located in the tropics where received solar radiation is relatively high throughout the year and, could meet the system load energy demand with minimal auxiliary heat obligation for effective cooling. The conventional refrigeration system is energy intensive as well as results in environmental degradation, unlike the use of solar adsorption refrigeration system which is cost-effective and environmentally friendly as this refrigeration system does not use any of the ozone layer depleting chlorofluorocarbon (CFCs) (Mena and Nibal, 2024). Researches in solar-powered refrigeration are found in literature and, have demonstrated certain potential for cooling for preservations and, ice making. An experimented adsorptive solar refrigerator in Yverdon-les-Bains, Switzerland with adsorption pair of silica gel and water by Hildbrand *et al.* (2002) had a gross solar cooling COPSR mean value of 0.16. Evaluation of prototype solar adsorption refrigeration based on an intermittent thermodynamic cycle by Miguel *et al.* (2003) in Peru ensured better performance compared to previous versions. A novel solar-powered adsorption refrigeration system by Khattab (2004) operating with activated carbon/methanol with arrangements of plane reflectors for heating the generator indicated a net solar COP of 0.136 and, 0.159 for cold and hot-climate respectively. Buchter *et al.* (2004) tested a single 2m^2 glazed collector adsorptive solar refrigerator with a natural air-cooled condenser in Ouagadougou, Burkina-Faso. Experimental performance in terms of the gross solar coefficient of performance indicated a range of 0.09 and 0.13 at irradiance between 19 and 25 MJ/m^2 and, averaged ambient temperature of 27.4 °C. A transient simulated performance of a solar-powered adsorption refrigeration system by Rekiyat *et al.* (2012) using a flat plate solar collector, with activated carbon/methanol as the adsorbent/adsorbate pair in Kano, Nigeria achieved a cold room temperature of about 1 °C. Rifat *et al.* (2014) in their study, investigated analytically, a solar heat-driven basic adsorption cooling system with silica-gel-water pair for different versions under the climatic conditions of Dhaka, Bangladesh. The study reveals that a solar-driven adsorption chiller with heat-storage unit could work beyond the sunset time. The thermal COP of a solar prototype adsorption refrigerator with activated carbon and methanol developed by Mohand *et al.* (2014) was found to be dependent on the refrigerating effect and the solar radiation. Norhafizah and Tohru (2016) presented a study on combinations of solar-powered adsorption refrigeration systems and thermal storage. Analytical calculation results for activated carbon-ammonia and activated carbon-methanol as working pairs for the adsorption reaction indicate a higher coefficient of performance, COP for activated carbon-methanol than activated carbon-ammonia pair while, adsorption chiller system with hot water thermal storage has higher COP than the system with ice thermal storage. The performance evaluation of a solar-powered solid adsorption refrigerator under Akure environmental climatic conditions by Anjorin and Bello (2016) reported higher C.O.P and, daily ice production compared to those reported in literature for systems with solar collector plates. The COP of the implementation results of a solar adsorption refrigerator based on CPC by Du *et al.* (2017) was found to be 0.166 and 0.143 when the system received irradiance of 600 W/m2 and 400 W/m2 respectively, and could overcome the challenge faced by the conventional adsorption bed.

Despite various research found in literature concerning solar-powered adsorption refrigeration, there is a need for the development of these systems to attest to the commercial sustainability of solar absorption refrigeration technology using available materials which can contend favourable with the ozone layer depleting chlorofluorocarbon (CFCs) refrigeration systems. Besides, previous works concentrate on testing the performances of solar-powered adsorption systems under clear sky conditions. However, due to the fluctuating nature of solar radiation received across the seasons and time of the day, there is a need to establish the practicability of solar adsorption refrigeration under unfavourable weather conditions most especially in the tropics. This will aid in forming the guideline for searching for auxiliary heating sources for solar adsorption refrigeration systems. This research work designed, constructed, and preliminary tested the performance of solar-powered adsorption refrigerating with activated carbon/methanol pair under cloudy sky conditions.

MATERIALS AND METHODS

The system design analysis is carried out for its major prototype components of solar collector, adsorber bed, evaporator, condenser, hot water storage tank and the cooling cabinet.

Solar collector

Collector useful heat gained Q_u is expressed in Equation 1 as presented by Amritpal (2012).

where;

$$Q_u = \eta Q_s = A_c F_R[I_T(\tau\alpha) - U_L(T_i - T_a)] \quad (1)$$

where;

$$Q_s = A_c I_T \quad (2)$$

F_R is collector heat removal factor; A_c is the collector area, m^2; I_T is the intensity of radiation on a horizontal surface; τ is the cover glazing transmittance; α is the absorber absorptance; U_L is the overall heat loss coefficient of solar collector; T_i is the heat transfer fluid input temperature; T_a is the ambient temperature.

Heat losses of the collector

The overall heat loss from the collector is represented in Equation 3 as expressed by Amritpal (2012).

$$Q_{loss} = U_L A_c(T_i - T_a) \quad (3)$$

Where the overall heat loss coefficient U_L is given by the sum of the top, back and edge losses of the collector as reported by Benjamin (2019)

$$U_L = U_t + U_b + U_e \quad (5)$$

Collector efficiency η

The flat plate collector efficiency as given by Duffie and Beckman (2006) is expressed in Equation 6.

$$\eta = \frac{Q_u}{A_c I_T} \quad (6)$$

Refrigeration effect

The useful cooling produced otherwise known as the refrigeration effect is expressed in Equation 7 as reported by Akinbisoye and Odesola (2013).

$$Q_e = h_{fg} - C_{pmv}(t_c - t_{ev}) \quad (7)$$

where; h_{fg} is the latent heat of vaporization; $C_{pmv}$is the specific heat capacity of methanol vapour; t_c is the condenser temperature; t_{ev} is the evaporator temperature.

Adsorber bed

The amount of useful heat required to desorb methanol from activated carbon as given by Mena and Nibal (2024) is expressed in Equation 8

$$Q_{ad} = M_{ac}(C_{p,ac} + xC_{p_{ml}})\Delta T + M_m H_m \quad (8)$$

where;

M_{ac} is the mass of activated carbon; $C_{p,ac}$ is the specific heat capacity of activated carbon; x is the quantity of methanol adsorbed per kg of activated carbon; $C_{p_{ml}}$ is the specific heat capacity of methanol at constant volume; M_m is the total mass of methanol adsorbed; H_m is the latent heat of desorption of M_m methanol

The volume of the methanol required is:

$$V_m = \frac{M_m}{\rho_m} \quad (9)$$

where;

ρ_m is the density of methanol

Coefficient of performance, COP

The ratio of the cooling effect to the heat input known as the coefficient of performance is calculated in Equation 10 (Manahil, 2009).

$$COP = \frac{Q_e}{Q_{ad}} \quad (10)$$

Adsorption capacity of activated carbon-methanol

The adsorption capacity of activated carbon to methanol is estimated from Equation 11 (Mena and Nibal, 2024).

$$x = x_o exp\left[-k\left(\frac{T}{T_s} - 1\right)^n\right] \quad (11)$$

where;

x *is the adsorption capacity*; k *and* n are the characteristic parameters of adsorption refrigeration pair; x_o is the adsorption capacity at saturation temperature and pressure; T_s and T_s is the adsorption temperature and saturation temperature respectively.

Mass and volume of activated carbon

The mass and volume of the activated carbon required are expressed in Equations 12 and 13 respectively (Manahil, 2009).

$$M_{ac} = \frac{M_m}{x} \quad (12)$$

$$V_{ac} = \frac{M_{ac}}{\rho_{ac}} \quad (13)$$

where;

ρ_{ac} is the density of activated carbon

Evaporator

The amount of heat (cooling load) to be removed from the cooling compartment by the refrigerant in the evaporator Q_{ev} is given by Anthony *et al.*, (2024) in Equation 14.

$$Q_T = Q_{ev} = U_{ev} A_{ev} \Delta T \quad (14)$$

where;

A_{ev} is the evaporator surface area; ΔT is the temperature difference of the evaporator; U_{ev} is the overall heat transfer coefficient for the evaporator.

Condenser

The heat given up by the refrigerant vapour Q_c to the surrounding air is given in Equation 15 (Manahil, 2009).

$$Q_c = U_c A_c \Delta T = \dot{m} h_{fg} * \quad (15)$$

where;

$h_{fg} *$ is the latent heat of vaporization (modified); A_c is the area of condenser pipe; $\Delta T = (T_{sat} - T_{ci})$; T_{sat} is the methanol saturation temperature; T_{ci} is the condensing temperature; U_c is the condenser overall heat transfer coefficient.

Water tank

The tank volume for the water is estimated from Equation 16 (Gideon, 2016).

$$V_{wt} = \pi r^2 h_t \quad (16)$$

where; h_t is the height of the water tank

The heat gained by water from the collector is given in Equation 17 (Emmanuel *et al.*, 2020).

$$Q_w = M_w C_{pw} \Delta T \quad (17)$$

where;
M_w is the mass of water; C_{pw} is the specific heat capacity of water
The mass of the water in the tank is a function of the volume of water in the tank and is expressed in Equation 18:

$$M_w = V_{wt} \times p_w \quad (18)$$

Wall transmission load
The amount of heat leakage through the walls Q_{wall} is given by Equation 19 (Anthony *et al.*, (2024)

$$Q_{wall} = AU\Delta T \quad (19)$$

Where;
Q_{wall} is the amount of heat transfer through the wall; A is the surface area of the cooling cabinet, m^2; ΔT is the change in temperature between the inside and the outside of the cabinet; U is the overall heat transfer coefficient.
Product load
The total amount of sensible heat and latent heat to be removed in cooling and freezing a product is given by Manahil (2009) in Equation 20:

$$Q_p = M_p C_p (t_p - t_i) + M_p L_p \quad (20)$$

where;
M_p is the mass of product; C_p is the specific heat capacity of product; t_p is the temperature of the product; t_i is the cooling temperature inside the cabinet; L_p is the latent heat of freezing of product.

Heat loss due to air infiltration
Gosney and Olama () reported the formula for computing air infiltration as stated in Equation 21.

$$Q_u = C_{inf} A\sqrt{H} \left(\frac{p_i - p_0}{p_i}\right)^{1/2} \left[\frac{2}{1 + (p_i/p_0)}\right]^{3/2} \quad (21)$$

where;
Q is the volume rate of flow; C_{inf} is the infiltration coefficient; A is the area of doorway or lid; H is the height of doorway; ρ_i and ρ_o are air densities of the cold and warm air respectively.
Refrigeration load
The system sensible and latent heat which is the mass rate of flow multiplied by the difference in enthalpies as show in Equations 22

$$q = \dot{m}(h_{c,o} - h_{c,i}) \quad (22)$$

$$q = \dot{m}c_{p(T_o - T_i)}$$

where;
q is the refrigeration load; $h_{c,o}$ and $h_{c,I}$ are enthalpies of warm air and cold air respectively; C_p is the specific heat capacity of air.
The total cooling load is the sum of all the components of the cooling load, and thus expressed in Equation 23.

$$Q_T = Q_u + Q_p + q \quad (23)$$

Table 1: Design characteristics of the solar powered adsorption refrigeration

Parameter	Value
Collector useful heat gain, kW	0.285
Cooling cabinet area, m^2	0.66
Wall transmission load, KJ	429.7
Product load, kJ	837.4
Air filtration load, kJ	11.24
Total cooling load, kJ	1406.174
Refrigerating capacity, kW	0.033
Heat rejected by refrigerant, kJ/kg	1164
Mass of methanol, kg	1.28
Volume of methanol, m^3	0.00162
Mass flow rate of methanol, kg/s	0.0000296
Mass of activated carbon, kg	4.6
Volume of activated carbon, m^3	0.002
Water storage tank volume, m^3	0.034
Condenser heat, W/m^{2}K	3.43
Mass of water in tank, kg	26
Collector overall heat loss coefficient, W/m^{2}K	7.3
Collector area, m^2	0.36
Collector efficiency, %	50

System Development
The hybrid adsorption refrigeration system consisted of a solar collector, adsorber bed, evaporator, condenser, hot water storage tank, and a cooling cabinet. Methanol served as the working fluid and activated carbon as the adsorber. The collector is made of an insulated metal box with a 4mm glass cover serving as the glazing and, dark-coloured absorber plate for greater energy absorptivity. The absorber plate contains copper pipes arranged in parallel and connected to two headers, one at the top and the other at the base of the parallel pipes and this arrangement is brazed onto a hollow metal pipe. The absorber plate is coated with black paint for better heat absorption. A sheet metal formed into the shape of a rectangular box of the required dimensions and insulated with fiber glass on both sides and at the base to house the absorber plate arrangement, while a 4mm thick transparent glass is used for glazing and glazing rubber used to improve the unit air tightness. The adsorber bed is made of two concentric copper pipes, an outer copper pipe sealed at one end by brazing and an inner copper pipe a little longer than the outer pipe. The perforated pipe was then made to fit at the center of the sealed outer pipe. The space in-between the concentric pipes was then filled properly with the mixture of activated carbon and methanol to ensure that it is tightly packed after which the copper pipes were sealed at the other open end. Each of the extended inner pipes was then connected to form a single channel. Copper pipe was cut into length as required and then rolled into the desired S shape to form the evaporator. It was then placed on one side of the aluminum surface in the box. A suitable condenser that satisfies the design requirement was selected from the market and fixed to the system. The water storage tank is of cylindrical cross-

section. Steel sheet was used as the material for forming the tank and painted to prevent rusting. The tank is double concentric cylinders sandwiched with a fiberglass insulation to minimize heat loss. A drain was provided at the bottom of the tank by fitting a pipe that runs through from the surface of the inner cylinder to the outer cylinder. Another pipe was fitted to one side of the tank to allow the return of water back to the tank. The cooling cabinet outer wall was produced from galvanized steel sheet and the cooling chamber was produced from aluminium sheet to specified dimensions.

Experimentation

The collector was inclined at location latitude which serves as the system tilt angle. The hot water tank was placed on a stand 9500 mm high close to the collector and the cooling box just below the tank. The Rubber hose connects both the inlet and outlet of the collector to the tank to enhance the thermo siphoning effect. With the adsorber placed mid-way in the hot water tank, control valves were used to connect the adsorber to the condenser and evaporator. Test performance is conducted on three consecutive days in January. A digital thermometer capable of measuring temperature in the range of -5 to 1350 °C and, monitoring measurement at four different points at the same time was deployed. However, ambient temperature was obtained from a weather station less than 500 m from the test bed rig. On all test days, control valves were kept closed from the hours of 8:30 am to 13:30 am for regeneration temperature to be attained at the adsorber. As desorption of methanol starts, the valve that connects the adsorber to the condenser is opened while that connecting the evaporator is kept closed. The condenser cools the desorbed methanol vapour to the ambient temperature and, then flows into the evaporator in the cooling cabinet. At reduced solar radiation for heating, hot water is drained from the tank and replaced with cold water and, the valve connecting the condenser to the adsorber is closed and that connecting the evaporator to the adsorber is opened. This is to enable the absorption of methanol to effect the cooling in the refrigerator cabinet.

Plate 1: The system assembly of the solar adsorption refrigerator

RESULTS AND DISCUSSION

In the preliminary test, the initial and maximum water recorded temperatures were 22 and 35°C while, that of evaporator minimum and maximum were observed to be 21 and 28 °C respectively. The preliminary experimentation noticed no significant cooling in the cabinet. However, drops of methanol were detected from the valve connecting the adsorber to the condenser signifying that the desorption process had occurred. The leakages were then amended and similar readings were recorded on the next three consecutive test days. Figures 1 to 3 are the graphs showing the relationships of the temperatures for various units of the system and the time of the day. The obtained maximum condenser and water tank temperatures were 30 and 31 °C on the first and third day respectively. To obtain higher condenser temperatures, it is evident that the solar collector needs to be heated to a higher adsorbent temperature. Though, it should be lower than 100°C. There is noticeable progressive cooling from day one to three (figures 1-3). The system cooling cabinet containing 5 litres of water attained a temperature of 13 °C after 56 hours of the experiment from an initial temperature of 22 °C indicating a temperature reduction of about 41 % indicating a 0.47 system cooling coefficient of performance. The computed coefficient of performance from observed data varies slightly lower than that of the estimated theoretical which was put at 0.51. The low cooling coefficient of performance achieved is ascribed to the cloudy sky condition during the test period which was characterized by harmattan haze, low effectiveness of activated carbon adsorption due to the brazed temperature of copper tubes, and heat losses during temperature measurement. The experimental trend of this work agrees with that of Akinbisoye and Odesola (2013) who obtained 15 °C for evaporator pipes for a solar-powered adsorption ice maker using activated carbon/methanol pair for received peak solar radiation of 926 W/m^2 at 14:00 hours in Ibadan. Umar and Aliyu (2008) simulated work of a single glazed collector/absorber/generator unit revealed the possibility of ice-making under climatic conditions of Kano with an average solar coefficient of performance of 0.78 and, in agreement with values found in the literature.

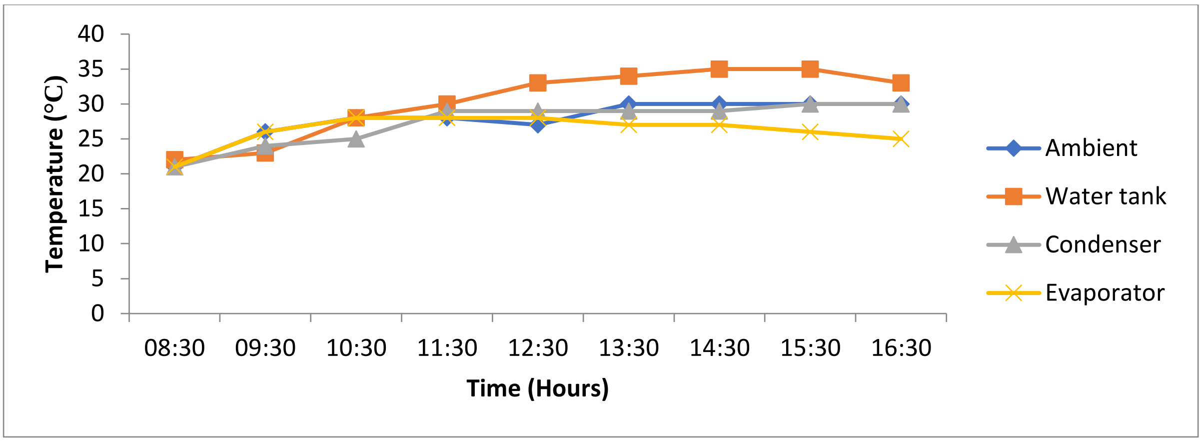

Figure 1: Variation in temperature at various units of the system for day one

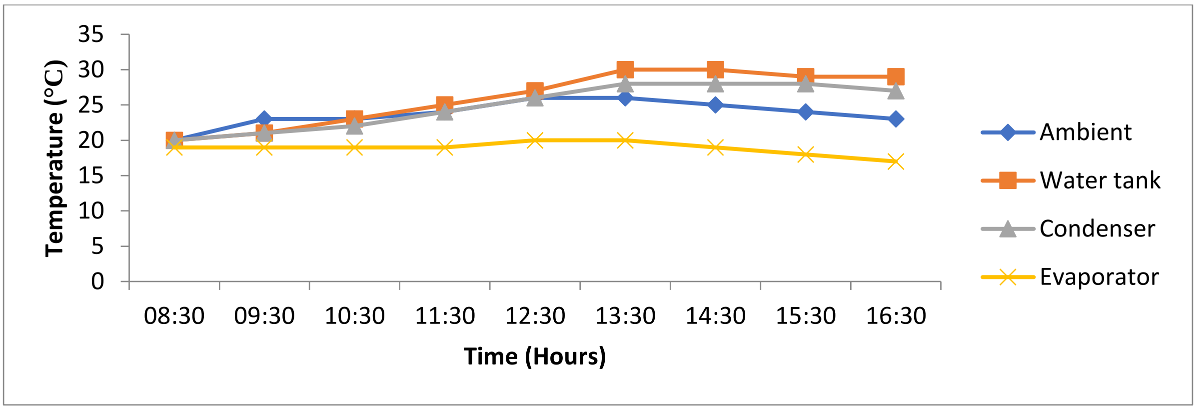

Figure 2: Variation in temperature at various units of the system for day two

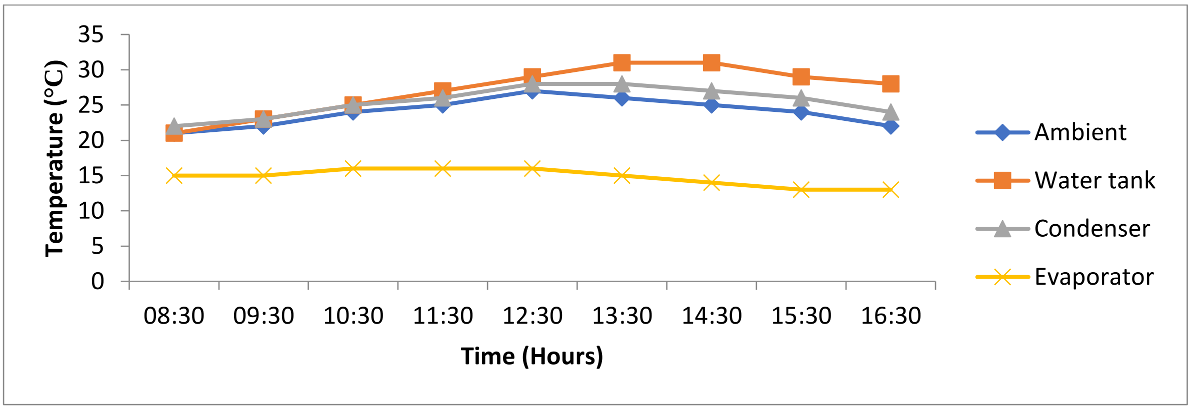

Figure 3: Variation in temperature at various units of the system for day three

CONCLUSION

The obtained results indicate the feasibility of solar adsorption refrigeration in the tropics amidst poor weather conditions. The solar- powered adsorption would have performed maximal under sunny sky conditions or with an auxiliary heating source. Besides, the brazed temperature of copper tubes rendered partially ineffective the activated carbon adsorption capability in addition to heat losses during periods of temperature measurement. The variation in the computed cooling coefficient of performance to that found from the theoretical estimate is due to differences in experimental data and values used for design analysis. The implementation of solar adsorption refrigeration will curb the use of conventional refrigeration, save energy; reduce recurrent bills, and ozone layer depleting chlorofluorocarbons (CFCs).

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