Theoretical and Experimental Investigation of Solar Heat Potential at Low Temperatures: Towards Large Scale Integration in the Agro Food Sector

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Received: 21.11.2015 Accepted:01.03.2016

Abstract- Several applications in the agro food sub-sector have been classified as suitable to be supplied by solar heating systems. The present work deals with the potential use of solar thermal energy and its evaluation under climatic conditions in Algeria. In the first part, an experimental investigation conducted on small scale solar water heating system is presented followed by simulation. The experimental tests gave a better understanding of the thermal behavior of the system as well as the outlet temperature levels which can be reached by locally manufactured flat plat collectors. The second part presents the potential use of solar heat for industrial applications, particularly those consisting of heating make-up water and water feedback from heat recovery which exists almost in all agro food industries. Thus, water inlet temperature through the secondary circuit varied between 20 and 90°C. The results obtained show that the annual specific energy yield delivered by the solar system decreased by increasing water feedback temperature.

Keywords- Flat Plat Collectors; Solar process heat; System monitoring; TRNSYS simulation.

1. Introduction

Nowadays, the use of solar thermal energy is becoming more attractive in many applications (residential, agricultural and industrial sectors). Swimming pools and domestic sectors are mostly targeted by the water solar heating system technologies, either in direct or indirect configurations, followed by large scale residential and commercial buildings. However, the introduction of these systems in industrial applications remains insignificant (25 MW_{th} from 195.8 GW_{th} of the total installed capacity by the end of 2010) [1]. Some of the recent integrated installations were reported in literature, they provided consistent analysis of the system [2] and led to, experimental validation [2, 3], and fault analysis [4]. Several studies aiming at evaluating the potential use of solar heating for industrial applications, both in some targeted countries and remote regions were reported in literature [5–11]. Thus, many applications have proved to be efficient in integrating in solar heating systems according to the temperature levels required by these applications and their continuous profile of using thermal energy [12]. Also, different collector's technologies were considered in modeling work in order to estimate the annual specific energy gain by temperature levels [13], as well as the hydraulic integration concept [14].

Furthermore, the agro food sector seems to be one of the most promising application fields of solar heating systems since various tasks are performed often at low temperatures (bellow 100°C). The optimization of flat plat collector technology allowed adequate range of temperatures to be achieved [16]. It is clear that economic assessment plays a major role in decision making related to the integration of such a system in the industrial plant and the assessment of its beneficial role. However, there are some issues to be addressed prior to this integration knowing that this can differ from one process to another [17, 18]. Thus, two different levels of integration can be distinguished: supply level and process level [19, 20].

The Algerian agro-food sector is growing steadily and, consequently, the demand for thermal energy will increase. As a result the substitution of fossil resources, mainly the natural gas, becomes more than necessary. Moreover, temperature levels which are required for the tasks heating in the agro food processes are often low temperatures; this makes the integration of solar heating systems suitable. At the moment, there is no data available in literature that allows the assessment of solar heat for industrial processes in Algeria. The present work is dedicated mainly to the supply level integration, taking into consideration two options for fluid heating: make-up water and feedback water from the heat recovery.

2. Experimental investigation on small scale solar water heating system

2.1. Theoretical analysis

The useful energy gain from the collector is expressed, according to Eq. (1) [21], as follow:

$$Q_u = \dot{m} \, . \, C_p \, . \, (T1-T2) \qquad (1)$$

Where Q_u is useful energy gain in (W), $\dot{m}$ is the mass flow rate in the solar loop in (kg/s), C_p is the specific heat capacity of the working fluid in (J/(kg .°C)) , T1 and T2 are the collector inlet and outlet temperatures in (°C).

The instantaneous efficiency of a solar thermal collector is defined as the ratio between the useful energy gain (Q_u) and the solar energy received on the collector plane (A_c.I). It is expressed by Eq. (2).

$$\eta_{coll} = (Q_u)/((A_c.I)) = (\dot{m}_{pc} \, . \, C_p \, . \, (T1-T2)) \, / \, ((A_c.I)) \qquad (2)$$

Where η is the efficiency, A_c is the area of the solar collector in (m²) and I is the solar irradiance intensity in (W/m²)

Also, the collector efficiency can be expressed following Eq. (3).

$$\eta_{coll} = F_R[(\tau\alpha)_e - U_L \, (T1 - Ta)/I \,] \qquad (3)$$

where, F_R . $(\tau\alpha)_e$ and F_R. U_L are the optical and thermal losses characteristics of the collector respectively. Ta is the ambient temperature.

The system efficiency (η_{sys}) is defined as the ratio of total produced useful energy to the total received solar energy on the collector field during the same periode.

$$\eta_{sys} = \frac{\text{total produced useful energy by the system}}{\text{total received solar energy on collector field}} \qquad (4)$$

2.2. System description

The flat plat collectors are exposed to the incident solar radiations which are converted into heat via the absorber plates. The heat is transferred to the working fluid and is transported to the plat heat exchanger using the circulating pump. The cold water supplied by the tank 1 is heated by the heat transferred from the working fluid and gets stored into tank 2 (Fig. 1). Four locally manufactured flat plat collectors, of 2 m² area for each collector, were used in this experiment (Fig.2).

2.3. Instrumentation and control strategy

Thermocouples (KTY Types) were used in order to measure the outlet, inlet and the produced water temperatures. Two electro-magnetic flow meters (Fisher & Porter MAG-XM and MAG-XE Types) were installed to measure the flow rate of both the fluid in the solar loop (primary circuit) and the produced hot water (secondary circuit). The measurement of incident solar irradiance on the collector's plane was carried out using a pyranometer (KIPP & ZONEN CM11 Type) equipped with a solar integrator (KIPP & ZONNEN) to record the daily incident energy. All these instruments were connected to the data acquisition unit monitored by the PC via a serial port (RS232) (Fig. 3). The data acquisition is done with time interval of 10 seconds. A software program was developed, using Delphi, for the data processing. The climatic parameters (global horizontal radiation, ambient temperature, wind speed etc.) were measured using a weather station (MWS9). The control strategy applied to the system is based on the well known "on-off controller". The pump is turned on if the temperature difference between the collector outlet (T1) and the heat exchanger outlet (T4) is higher than 10 °C, otherwise, the pump is turned off. The heat exchanger outlet temperature (T4) in the secondary circuit is set to 45 °C; if this value is reached the PC sends a command signal to the data acquisition unit to switch on the electro valve, otherwise, the electro valve is switched off.

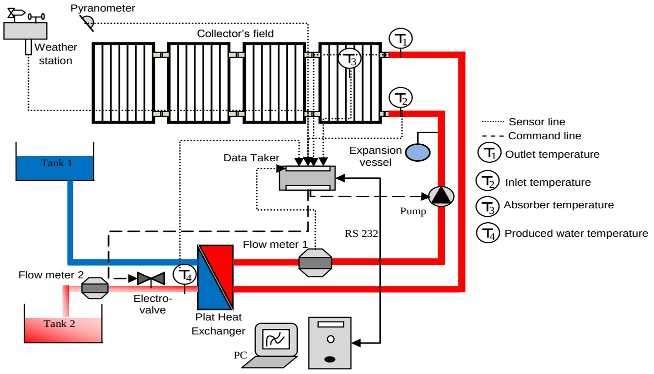

Fig. 1. Hydraulic and command scheme of the solar water heating system in forced circulation using plat heat exchanger.

Fig. 2. View of the collector’s field.

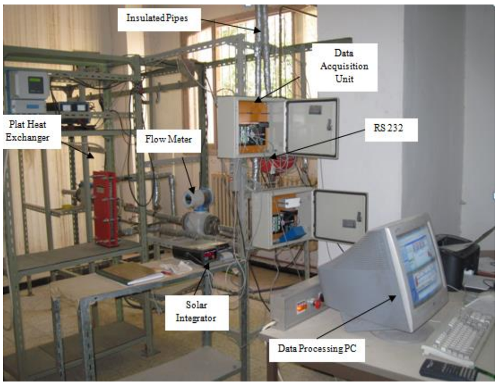

Fig. 3. View of the experimental set-up.

3. System behaviour under the applied control strategy

3.1. *Thermal behaviour*

The experimental test conducted during the typical day of April, 14, 2013 shows the influence of solar irradiance on the thermal parameters of the system. The test period started at 07:45 and finished at 18:00. The average values of ambient temperature and wind speed during this period were 25.5 °C and 0.3 km/h respectively. As it can be seen in Fig. 4, the solar irradiance reached its maximum intensity at noon (950 W/m²) and some fluctuations were recorded due to some passing clouds. The production of hot water at 45 °C started at 10:45 and ended at 16:45, during this time interval the outlet collector temperature was approximately 70 °C. The start up of the electro valve was recorded approximately at 10:45 a.m and the fluctuations seen on the temperatures graphs were due to the on-off switching of the electro valve. The tapped volume of the hot water was 164 liters, with 6.839 kWh/m².d of daily incident solar irradiance.

3.2. *Outlet temperatures*

The fluid outlet temperature from the collectors is closely dependent on the solar radiation intensity (Fig. 5). However, solar radiation is not the only parameter that can be involved. Ambient temperature (Ta) and mass flow rate (ṁ) have also a significant influence on the thermal behaviour of the system. It should be noticed that experimental tests were conducted at several days through the year and averaged values each month for the selected tests were presented. The ambient temperature during the test days ranged between 3.7 and 25.6 °C. The system operated with variable mass flow rate which ranged between 0.026 and 0.044 kg/s. The solar thermal system showed high outlet temperature of about 77.45 °C, this the fact that ambient temperatures during the selected test day reached higher values than those of the other days.

3.3. *Influence of solar irradiance and mass flow rate on collector efficiency*

An experimental analysis was performed in order to investigate the influence of irradiance intensity on the collectors efficiency (Fig. 6). The test was conducted in the day of April 11, 2013 from 09:30 to 17:30, the sky was clear throughout the test period and the ambient temperature ranged between 17.3 to 24.2 °C with an average wind speed of 0.453 km/h. The efficiency of the collectors field decreases with the increasing irradiance, which reveals a significant heat and optical losses. The average efficiency was found to be 29.61%.

Fig. 7 shows the efficiency as a function of mass flow rate. As it can be seen, the efficiency increases with increasing flow rate from 0.028 to 0.037 kg/s.

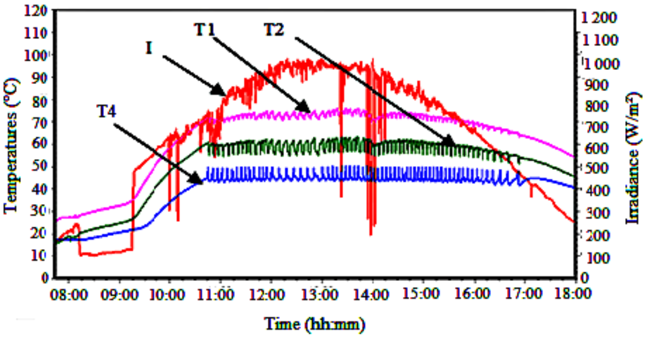

Fig. 4. Daily evolution of solar irradiance (I), outlet, inlet and hot water temperatures (T1, T2, T4) during clear sky.

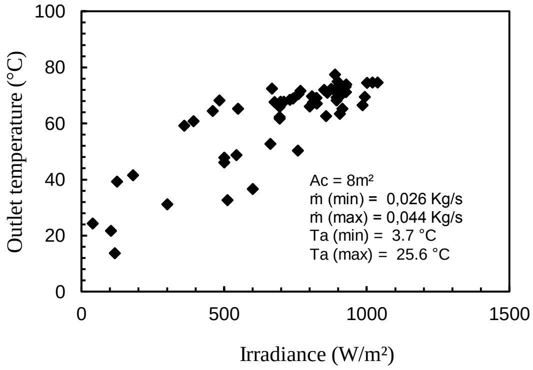

Fig. 5. Comparison of collectors outlet temperatures at different irradiance levels.

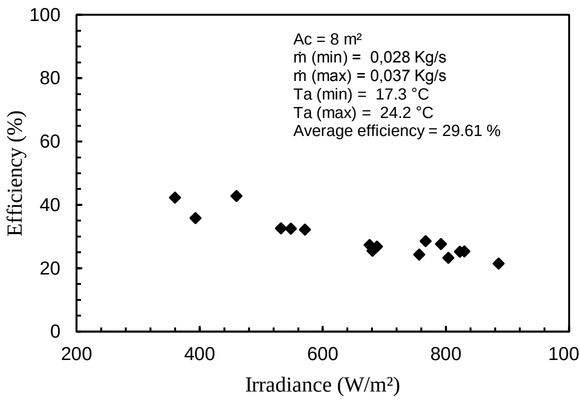

Fig. 6. Influence of solar irradiance on collector's efficiency.

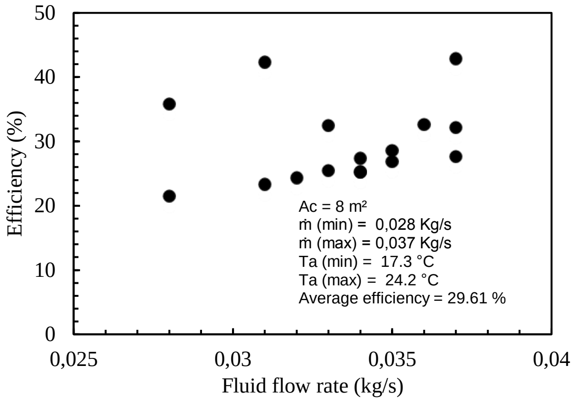

Fig. 7. Influence of mass flow rate on the collector's efficiency.

3.4. Comparison of the computed and measured results

A Trnsys 16.1(transient simulation program) was used in order to simulate the annual energy yield of the system [22]. Experimental parameters values were used for modelling. The main parameters are shown in Table.1. Meteonorm database was used in order to estimate the climatic conditions of Batna city. As it is shown in Fig. 8, the simulated and measured amount of solar irradiation led to certain deviations ranging from 0.52% to 14.28%.

The annual total amounts of simulated and measured solar irradiation received per unit area were found to be in very good agreement (1778.34 and 1778.56 kWh/m².a respectively, so a deviation of 0.012 %). Moreover, the measured and simulated average values of ambient temperatures showed significant differences especially in October where the deviation is about 34.6%.

Regular measurements were carried out in 2013 in order to determine the potential use of solar heat delivered by the system, followed by simulation to confirm the results of the different parameters especially those related to the flat plat collectors. Fig. 9 shows the monthly measured and simulated specific energy yields delivered by the system and efficiencies. The measured energy yields per month were less than those predicted by the simulation model during the year. The highest monthly specific energy yield both for the simulation and the measurement was in July. Also, the measured annual specific energy yield of the system was 253.97 kWh/m².a, giving a system efficiency of 14.28 %, however, the predicted value by modelling was 272.44 kWh/m².a with a system efficiency of 15.32%.

Table1. Simulation parameters.

Parameter	Value	Unit
Location latitude (Batna)	35.55	°
Total area of the collectors (A_c)	8	m²
Optical efficiency	0.42	-
Linear loss coefficient (a_1)	4.01	W/m².K
Square loss coefficient (a_2)	0.017	W/m².K²
Collector slope	45	°
Primary circuit flow rate ($\dot{m}_p$)	0.037	kg/s
Secondary circuit flow rate ($\dot{m}_s$)	0.0337	kg/s
Primary fluid specific heat (C_P)	3.819	kJ/kg.K
Secondary fluid specific heat (C_S)	4.19	kJ/kg.K
UA of heat exchanger (UA_{hx})	40	W/ (m^2_{ap}.K)
Primary circuit pipes length (L)	22.3	m
Piping loss coefficient (U_{pipe})	5	W/(m².K)

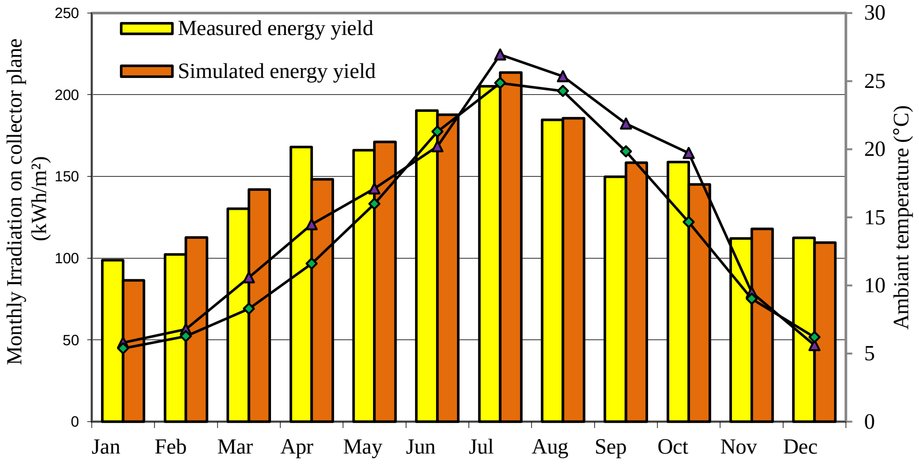

Fig. 8. Measured and computed irradiation on collectors plane and average ambient temperature.

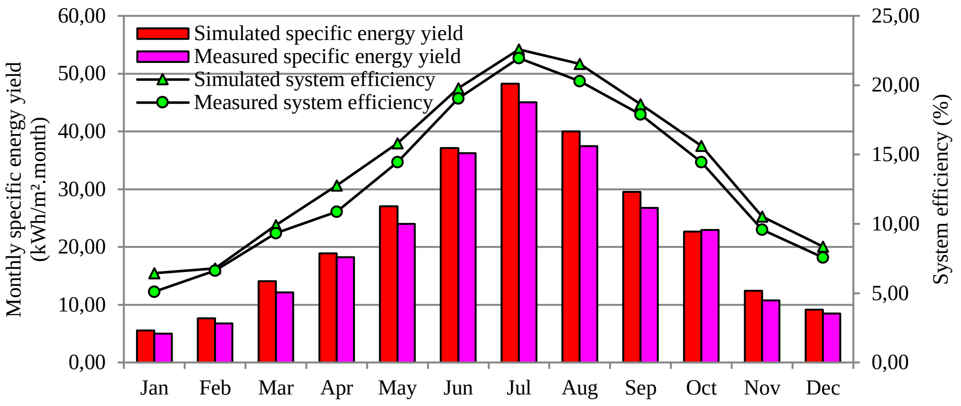

Fig. 9. Measured and computed specific energy yield and system efficiency.

4. Large scale solar water preheating system

4.1. Description of the integration concept

Fig. 10 shows schema layout of the solar system integration. The solar thermal system uses flat plat collectors and external plat heat exchanger. In the case of this configuration, the solar heating system can be operate for preheating makeup water coming from the water feed tank which exists almost in all agro food companies. However, in this case the water temperature leaving the tank is of great importance as the inlet temperature of the secondary circuit of the solar system. So, the higher the feedback-water temperature can be the smaller is the energy yields delivered by the solar system. Also, there is a possibility for heating directly the fresh water coming from the source.

4.2. System simulation and assumptions

Trnsys simulations were carried out to assess the potential of solar process heat in Batna city, Algeria. The climatic conditions (Solar irradiance and ambient temperature) are mentioned in section 3.4. The working fluid in the primary circuit is made of water and glycol. The control strategies of the two pumps are the same as used in [23]. It is assumed that the thermal requirement of the process are higher than the heat generated by the solar system. Furthermore, the heated water is generally supplied to the boiler but it can be also supplied directly to the process if the temperature wanted of a given process task is reached. The UA-value of the plat heat exchanger was 100 W/(m^2_{col}.K) as it is recommended in [24]. The parameters used for the simulation are given in Table.2.

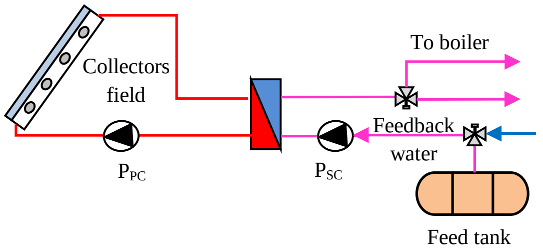

Fig. 10. Concept of solar thermal system integration into industrial process (supply level).

Table 2. Large scale simulation parameters.

Parameter	Unit	Value
Collector area	m²	1000, 1500, 2000
Specific heat of the collector fluid	kJ/kg.°C	3.819
Specific heat of the process fluid	kJ/kg.°C	4.19
Solar loop fluid flow rate	kg/s	1.536 – 4.388
Secondary circuit fluid flow rate	kg/s	1.4 - 4
Optical efficiency (η_0)	-	0.848
Heat loss coefficient (a_1)	W/(m².K)	3.460
Heat loss coefficient (a_2)	W/(m².K²)	0.017
Pipe length (solar loop)	m	40
Pipe U-value	W/(m².K)	40

4.3. System simulation and assumptions

Figure 11 shows the results of various simulations performed for three different large areas of collector's field. The present parametric analysis was conducted in order to determine the annual energy yield of the solar heating system under different values of the secondary circuit fluid flow rate, which varied between 1.4 and 4 kg/s. Also, it must be noticed that the heated fluid in this case was the fresh water (T_{inlet} = 20°C) which was the first option. It is obvious that the system achieved higher energy yields at high flow rates. Moreover, the system energy yield per square meter area was affected by increasing flow rate depending on the area of collectors. The choice of the flow rate depends on the working process fluid rate. However, it is to emphasize that in this kind of dilemma in which the produced fluid temperature decreases with increasing fluid flow rate, the energy yield keeps increasing.

The second option consists of heating the water leaving the feed tank. As this water is recovered from the process after having performed the several heating tasks, it goes back to the feed tank with at a given temperature. Fig. 12 shows the annual energy yield that can be delivered by the solar system depending on the feedback water temperature. It becomes clear that the annual energy yield decreases with increasing feedback water temperature, leading to a decrease in the overall system efficiency. A typical example, an increase of water temperature coming from the feed tank from 50 to 90 °C causes a decrease of 40.3% in terms of annual energy yield under a flow rate of 4 kg/s.

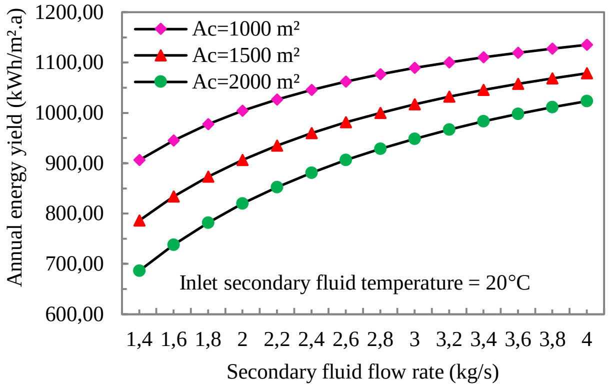

Fig. 11. Annual specific energy yield depending on collector area and process flow rate.

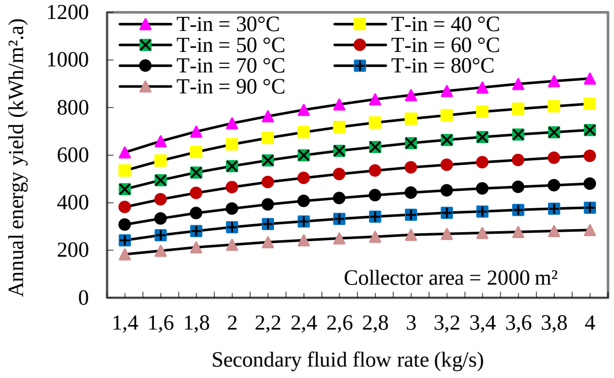

Fig. 12. Annual specific energy yield depending on process flow rate and water feedback temperature.

5. Conclusion

The main objective of this work was to assess the potential use of solar thermal energy using flat plat collectors.

In the first part of the work, a thorough analysis of a solar water heating system was carried out which allowed to determine the thermal behavior of the system. It was found that the collector outlet temperature exceeded 70°C in some tests due to better conditions of temperature. It was also found that the variation in energy yields during the year was caused by the incident solar energy irradiance on the surface of the collectors and the ambient temperature. The high level of losses recorded was linked to high level of solar irradiance.

In the following step, several simulations of large scale solar thermal system were performed in order to evaluate the potential use of solar thermal energy. The system design was mainly dedicated to preheating make-up water and feedback water from heat recoveries. Thus, for a collector area of 1000 m², an annual specific energy yield of 1135.06 kWh/m².a can be achieved when heating make-up water.

Finally, this investigation suggests that flat plat collectors are adequate for application of solar thermal systems both in residential and industrial sectors, since the range of temperature needed is made possible by the use of this type of collectors leading to the ultimate goal of saving natural gas and minimizing CO_2 emissions.

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