

# Development of a Simulation Model for the Hybrid Solar Dryers as Alternative Sustainable Drying System for Herbal and Medicinal Plants

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**Abstract.** *A simulation model of hybrid solar drying as alternative sustainable drying system for herbal and medicinal plants was developed. Heat absorbed from the solar radiation, heat gained by the collector and supplemented by the burner, heat gained or lost by the product, heat gained or lost through the drying bin wall, heat gained or lost with the drying air and the latent heat of the moisture evaporation from the product were the main components of the equations describing the drying system. The model was able to predict the moisture loss from the product at a wide range of temperatures and air recirculation percentages (70, 80 and 90%). The energy consumption for drying herbs was investigated by using of different energy sources including solar energy, diesel and propane fuels. Experiments were conducted to validate the simulated model results. The results indicated that the solar collector could raise the temperature by 5-13 °C. The mint moisture content was dried from 80% to MC ranged from 10.99 to 13.09% when it was dried at 60°C and the drying air was re-circulated at 70 to 90% during the month of January, meanwhile, it reached from 5.27-8.6% at the same percentages for air re-circulation during July. The energy consumption was 31.81 MJ/kg dried mint at 90% of fresh air recirculation while it was 42.91 and 53.95 MJ/kg for 80 and 70% of air recirculation percentages, respectively during January. During July, the energy consumption for water evaporation was 24.18 MJ/kg dried mint at 90% of fresh air recirculation while it was 30.56 and 36.89 MJ/kg for 80 and 70% of air recirculation percentages, respectively. On the other hand, using the solar collector contributes by 45% of the total energy required for drying the mint at 60°C and 90% air recirculation percentage during January, while it was 52% contribution during July at the same conditions. One kg dried mint costs LE 1.32 and 1.00 under the hybrid system during Jan. and July months, while it was LE 2.39/kg and 2.08 under the artificial drying system during the same months using propane fuel. In case of using diesel fuel; it costs 2.43 and 4.4 LE/kg and 1.84 and 3.82 LE/kg for the hybrid and the artificial systems, during January and July, respectively, when 90% of the drying air was re-circulated. The model results were validated at 90% of air recirculation and showed reasonable agreement with the experimental ones in temperature, moisture content of mint and energy consumption.*

**Keywords.** *Simulation model, hybrid solar dryer, herbal and medicinal plants, air recirculation, energy consumption.*

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## Introduction

Generally, drying can be done either naturally, by sun drying or industrially through the use of solar dryers or hot air drying. Solar dryers could be used as an alternative to the hot air and open sun drying methods, especially in locations with good sunshine during the harvest season like in Egypt, which the solar energy incident on Egyptian land ranges from 5-8 kW.h/m<sup>2</sup>/day (Sayigh, 1977). Solar energy is an important alternative source of energy and preferred to other energy sources because it is abundant, inexhaustible and non-pollutant. Also, it is renewable, cheap and environmental friendly (Basunia & Abe, 2001). However, large scale production limits the use of open sun drying. Drying of herbs and medicinal plants is one of the oldest forms of food preservation methods known to man and is the most important process for preserving food since it has a great effect on the quality of the dried products. The major objective in drying agricultural products is the reduction of the moisture content to a level which allows safe storage over an extended period. Also, it brings about substantial reduction in weight and volume, minimizing packaging, storage and transportation costs (Okos, et al., 1992).

Many researches on the mathematical modelling and experimental studies have been conducted on the thin layer drying processes of various vegetables, fruits and agro-based products such as bay leaves (Gu'nhan et al., 2005), hazelnut (O'zdemir & Devres, 1999), green pepper, green bean and squash (Yaldiz & Ertekin, 2001), apricot (Sarsilmaz, et al., 2000; Togrul & Pehlivan, 2003), green chilli (Hossain & Bala, 2002), pistachio (Midilli & Kucuk, 2003), potato (Akpinar, et al., 2003a), apple and red pepper (Akpinar, et al., 2003), pumpkin (Akpinar, et al., 2003b), eggplant (Ertekin & Yaldiz, 2004), carrot (Doymaz, 2004), fig (Doymaz, 2005), Citrus aurantium leaves (Ait Mohamed et al., 2005), rosehip (Erenturk, et al., 2004), kiwi (Simal, et al., 2005), mint (Akpinar, 2006), .

Solar drying systems became an important method of drying agricultural products. Solar conversion technologies differ from region to another, because of the variation in the solar intensities and some economical and industrial factors. The total power requirement of all fans is 3 kW. The resulting energy consumption is dependent on the species being dried. For mint 0.27 kWh per kg evaporated water and 0.93 kWh per kg crude drug are calculated. For hops the energy consumption amounts to 0.1 kWh per kg evaporated water and 0.3 kWh per kg crude drug (Moller et al., 1989).

The whole industry of exporting dried herbs and medicinal plants are at risk. The drying cost of dried herbs using fossil energy with the governmental policy of liberalizing energy cost will become very crucial. With the expected rising of energy cost, the total exporting cost will be critical compared to competitors from other producers from other countries and elsewhere. This is beside the environmental hazards of using fuel as the source of energy. Therefore, the main objective of this study is to develop an appropriate model for the hybrid drying system to study the feasibility of using the solar radiation as an alternative, pure and cheap source of energy. The effect drying temperature and air recirculation percentages on the drying time, final moisture content and energy consumption for some herbal plants was studied. Testing and verifying of some results of the model with the experimental results was carried out. Applying the model results to design and construct an appropriate hybrid solar dryer for some herbal and medicinal plants was conducted.

### Simulation Model

Heat and mass balances were carried out in order to describe the drying system. The temperature rise and moisture loss during the drying are described by means of the transient energy conservation equation, combined with an equation for the rate of moisture loss. However, the following assumptions were made in developing the model:

- The product is uniformly distributed in the drying space.
- Product leaves are characterized as homogenous objects and have a uniform temperature.
- A steady state condition is achieved.
- The coefficient of evaporation remains constant.

The heat balance equation is based on the concept that the algebraic summation of the rate of sensible energy gain, the absorbed solar heat, heat gain or heat loss from the dryer room, and the heat loss due to the moisture evaporation. These could be include: Heat absorbed from the solar radiation, heat gained by the collector and supplemented by the burner, heat gained or lost by the product, heat gained or lost through the drying bin wall, and the latent heat of the moisture evaporation from the product. The total solar radiation incident on a surface is the combination of the direct, diffuse and ground-reflected irradiance of the surface, which were given in the ASHRE, 2009. The solar calculations of the solar collector were determined according to Duffe and Bechmman, (1991), Bala and Woods (1994), and Turhan Koyuncu, (2006) and Sukhatme (1993). Psychometric air properties were calculated according to ASAE (1998). The modified Henderson equilibrium equation and its constants for mint were applied as used by Akpinar (2006). The model was used to predict the ambient temperature, inlet and outlet temperatures of the solar collector, temperature leaving the drying room, mixture temperature, RH at the pervious locations, and moisture content of mint and the energy consumption at different drying temperatures and air recirculation percentages. The model development equations, flowchart and the other input data are in the Appendix.

All computational procedures of the simulation model were carried out using Excel Spreadsheet.

#### Model inputs:

Climatic conditions: the ambient temperature and RH were fed to the model and the rest of psychrometric properties of the drying air were calculated. For the solar calculations, the location longitude is  $33^\circ$  and latitude is  $28.4^\circ$ . collector area is  $48\text{m}^2$  ( $4 \times 12\text{m}$ ), air specific heat is  $1009\text{ J/kg.K}$ , efficiency factor of solar collector, 0.77, air flow rate,  $2\text{ kg/s}$ , wind speed,  $2.4\text{ m/s}$ , wind convection coefficient,  $10\text{ W/(m}^2\text{K)}$ .

#### Materials and Methods:

According to the model results, a hybrid solar dryer was designed and constructed.

#### Experimental setup:

The hybrid solar dryer consists of cabinet dryer, solar collector, and supplementary power source (burner). The burner incorporates a switch which has a sparking mechanism when turned clockwise. This spark produced by the clockwise rotation of the switch ignites the gas and produces a light blue flame which heats up the drying chamber.

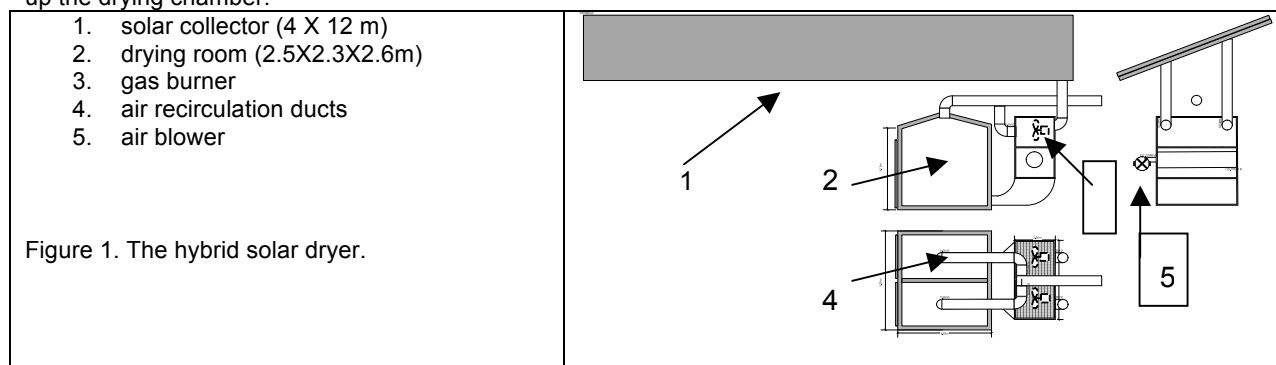


Figure 1. The hybrid solar dryer.

The drying chamber has a length of 2.5 m, width of 2.3 m and height of 2.6 m. It is made of galvanized steel (5 mm thickness). The trolley is made from stainless steel and has a length of 2.3 m, width of 1.1 m and height of 2.4 m. It is designed in such a way that it allows easy insertion of individual trays at a distance of 0.2 m apart and has tires for easy movement of trays. The trays are made of stainless steel and have a length 1.1 m, width 0.74 m and depth of 0.03 m. They have perforated bottom which allows heated air to pass through products. The air blower was used to force and re-circulate the drying air to the drying chamber. A proper blower has to be selected for appropriate distribution of heated air to be achieved.

**Experimental procedures:** Mint was used as an example for most herbal plants which was brought from the local market with an initial moisture content of 80%. The fresh mint was washed and prepared for drying. The solar drying experiments were carried during both January and July months, 2010 from 8:00 am to 8:00 pm in Sharkia Governorate, Egypt which is located at  $33^\circ$  longitude and  $28.4^\circ$  latitude. Mint was placed and distributed on the trays with total initial weight of 250 kg for the whole drying bin. Ambient temperature, inlet, outlet temperatures of air in the solar collector, temperature inside the drying room and temperature leaving the drying room. relative humidity, solar radiation, wind speed and mint weight loss were recorded each 60 min intervals. Data-loggers were used to measure the temperatures and RH. Solar radiation was measured using a Pyrhemeter (measuring range of  $0\text{--}2000\text{ W/m}^2$ , with spectral range of  $200\text{--}3000\text{nm}$ , Netherlands). Wind speed was measured using an anemometer. Moisture content of mint was determined using a Sartorius Moisture Analyzer model MA45, Germany. Drying was carried out at  $60^\circ\text{C}$  temperature, with three percentages (90, 80 and 70%) of air recirculation of the air leaving the drying room at a constant air flow rate ( $2\text{ m}^3/\text{s}$ ). Energy consumption for drying with and without solar collector was recorded during both January and July months as the lowest and highest solar radiation incident months.

#### The Simulated Model Results and Discussions:

Figs 2 and 3 show the diurnal variation in different temperatures (ambient, inlet and outlet of the collector, and drying bin, solar radiation during the months of January and July as the most lowest and highest temperatures and solar radiation values during the year. The model was tested by drying mint during two months of the year, January and July, where, the drying temperature was maintained at  $60^\circ\text{C}$ . The ambient temperature ranged from  $11.5$  to  $14.9^\circ\text{C}$  during the month of January; meanwhile it ranged from  $27.9$  to  $34.9^\circ\text{C}$  during the month of July. The outlet temperatures of the solar collector ranged  $11.7$  to  $28.7^\circ\text{C}$  during Jan. whereas it was from  $28.1\text{--}26.8^\circ\text{C}$  during July. It could be seen that the solar collector could raise the temperature by  $5\text{--}13^\circ\text{C}$ . The solar radiation was fluctuating from  $230.8$  to  $732.3\text{ W/m}^2$  during Jan., while it varied from  $131.6$  to  $1029.8\text{ W/m}^2$  during July.

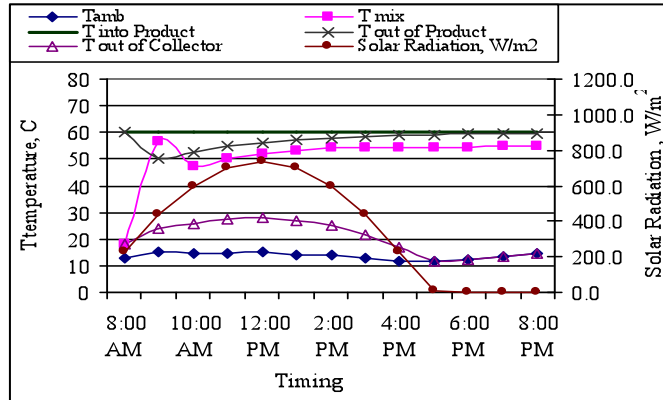


Fig. 2. The diurnal variations of temp and solar radiation during January.

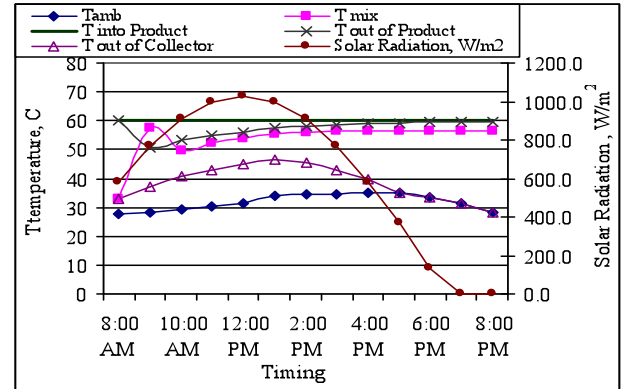


Fig. 3. The diurnal variations of temp and solar radiation during July.

**Moisture content (MC)** as influenced by drying temperature at different air recirculation percentages. Figs 4 and 5 show the effect of drying air recirculation on the moisture content of mint. It could be seen that increasing the air recirculation percentage increased the moisture loss and decreased the time required from drying mint to 11%. The figure shows that the mint moisture content reached from 10.99 to 13.09% when the drying air was re-circulated at 70 to 90% during the month of January, meanwhile, it reached from 5.27-8.6% at the same percentages for air re-circulation during July. The figures showed that the predicted values of MC were in a good agreement with the experimental one, which was a little lower than the predicted ones.

#### Energy consumption:

Figs. 6 and 7 and table 1 show the energy consumption for drying mint using hybrid solar dryer with different percentages of air recirculation during two months of the year. With using the solar collector (hybrid solar drying), energy consumption for water evaporation increased with increasing the percentage of air recirculation, where it was 31.81 MJ/kg dried mint at 90% of fresh air recirculation while it was 42.91 and 53.95 MJ/kg for 80 and 70% of air recirculation percentages, respectively during January.

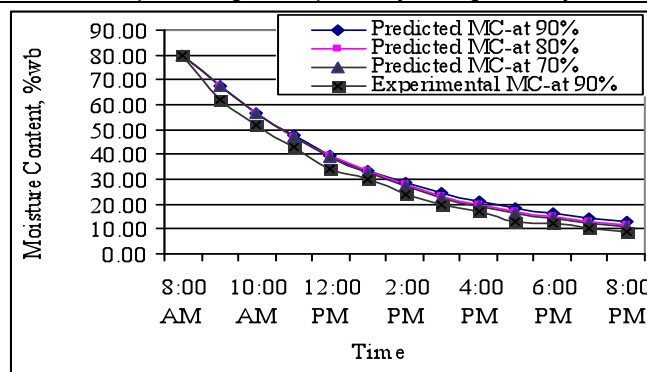


Fig. 4. The predicted and experimental moisture content (MC) of mint during January at different percentages of air recirculation.

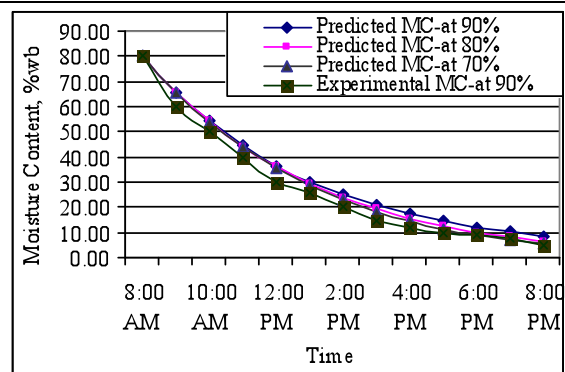


Fig. 5. The predicted and experimental moisture content of mint during July at different percentages of air recirculation.

Meanwhile, energy consumption without using collector (artificial drying), for water evaporation increased with increasing the percentage of air recirculation, where it was 57.63 MJ/kg dried mint at 90% of fresh air recirculation while it was 68.73 and 79.76 MJ/kg for 80 and 70% of air recirculation percentages, respectively during the same month. Meanwhile, energy consumption without using collector, for water evaporation increased with increasing the percentage of air recirculation, where it was 49.99 MJ/kg dried mint at 90% of fresh air recirculation while it was 56.38 and 62.71 MJ/kg for 80 and 70% of air recirculation percentages, respectively during the same month. It is worthy to mention that using the solar collector contributes by 45% of the total energy required for drying the mint at 60°C and 90% air recirculation percentage during January, while it was 52% contribution during July at the same conditions. During July, the energy consumption for water evaporation was 24.18 MJ/kg dried mint at 90% of fresh air recirculation while it was 30.56 and 36.89 MJ/kg for 80 and 70% of air recirculation percentages, respectively.

Table 2 shows the energy cost for drying mint at different air recirculation percentages using different kinds of fuel with and without using solar radiation as alternative source of energy during two months of the year. It could be seen that to obtain one kg dried mint costs LE 1.32 under the hybrid system, while it was LE 2.39/kg under the artificial

drying system using propane fuel, in case of using diesel fuel; it costs 2.43 and 4.4 LE/kg for the hybrid and the artificial systems, respectively during January.

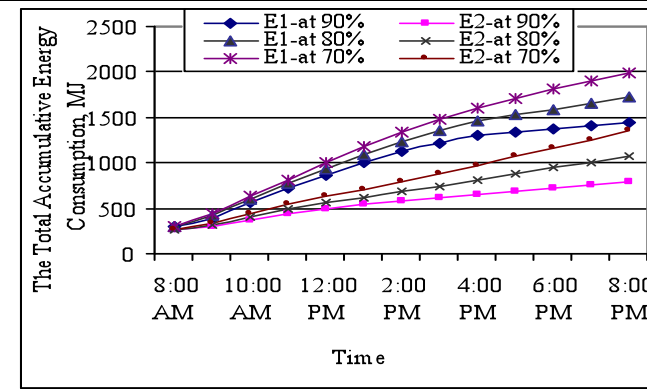


Fig. 6. Energy consumption for drying mint using hybrid solar dryer with and without solar collector at different percentages of air recirculation during January. (E1 refers to artificial drying; E2 refers to hybrid solar drying).

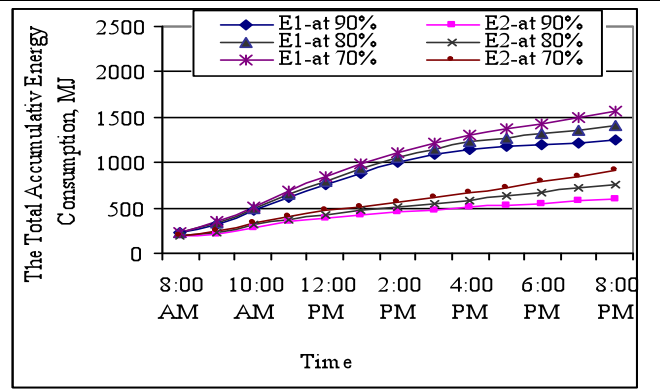


Fig. 7. Energy consumption for drying mint using hybrid solar dryer with and without solar collector at different percentages of air recirculation during July.

During July, to obtain one kg dried mint costs LE 1.00 under the hybrid system, while it was LE 2.08/kg under the artificial drying system using propane fuel, in case of using diesel fuel; it costs 1.84 and 3.82 LE/kg for the hybrid and the artificial systems, respectively at 90% of air recirculation of the drying air.

Table 1. Energy consumption for drying mint using hybrid solar dryer with different percentages of air recirculation during two months of the year

|                                                          | Energy at 90% air recirculation |             | Energy at 80% air recirculation |       | Energy at 70% air recirculation |       |
|----------------------------------------------------------|---------------------------------|-------------|---------------------------------|-------|---------------------------------|-------|
|                                                          | January                         | July        | January                         | July  | January                         | July  |
| Energy consumption for hybrid solar drying system, MJ/kg | <b>31.81</b> (45)*              | 24.18 (37)* | <b>42.91</b>                    | 30.56 | <b>53.94</b>                    | 36.89 |
| Energy consumption for artificial drying, MJ/kg          | <b>57.63</b> (65)*              | 49.99 (60)* | <b>68.73</b>                    | 56.38 | <b>79.76</b>                    | 62.71 |

\* the experimental values

Table 2. Energy cost for drying mint using hybrid solar dryer with different percentages of air recirculation during two months of the year.

|                    |                     | Energy cost at 90% air recirculation, LE/kg |      | Energy cost at 80% air recirculation, LE/kg |      | Energy cost at 70% air recirculation, LE/kg |      |
|--------------------|---------------------|---------------------------------------------|------|---------------------------------------------|------|---------------------------------------------|------|
|                    |                     | January                                     | July | January                                     | July | January                                     | July |
| Using propane fuel | Hybrid solar drying | 1.32                                        | 1.0  | 1.79                                        | 1.27 | 2.24                                        | 1.54 |
|                    | Artificial drying   | 2.39                                        | 2.08 | 2.86                                        | 2.35 | 3.32                                        | 2.61 |
| Using diesel fuel  | Hybrid solar drying | 2.43                                        | 1.84 | 3.30                                        | 2.33 | 4.11                                        | 2.81 |
|                    | Artificial drying   | 4.40                                        | 3.82 | 5.24                                        | 4.30 | 6.08                                        | 4.78 |

1 LE (the Egyptian pound) = 0.1333 EUR

## Conclusions

A simulation model of hybrid solar drying as alternative sustainable drying system for herbal and medicinal plants was developed. The most important results could be summarized as follows: the model was able to predict the air properties that used in drying and the solar radiation during the whole year at different drying temperatures and air

recirculation percentages. It could be seen that the solar collector could raise the temperature by 5-13 °C. The solar radiation was fluctuating from 230.8 to 732.3 W/m<sup>2</sup> during Jan., while it varied from 131.6 to 1029.8 W/m<sup>2</sup> during July. The mint moisture content was dried from 80% to MC ranged from 10.99 to 13.09% when it was dried at 60°C and the drying air was re-circulated at 70 to 90% during the month of January, meanwhile, it reached from 5.27-8.6% at the same percentages for air re-circulation during July.

The energy consumption was 31.81 MJ/kg dried mint at 90% of fresh air recirculation while it was 42.91 and 53.95 MJ/kg for 80 and 70% of air recirculation percentages, respectively during January. During July, the energy consumption for water evaporation was 24.18 MJ/kg dried mint at 90% of fresh air recirculation while it was 30.56 and 36.89 MJ/kg for 80 and 70% of air recirculation percentages, respectively. On the other hand, using the solar collector contributes by 45% of the total energy required for drying the mint at 60°C and 90% air recirculation percentage during January, while it was 52% contribution during July at the same conditions.

One kg dried mint costs LE 1.32 and 1.00 under the hybrid system during Jan. and July months, while it was LE 2.39/kg and 2.08 under the artificial drying system during the same months using propane fuel. In case of using diesel fuel; it costs 2.43 and 4.4 LE/kg and 1.84 and 3.82 LE/kg for the hybrid and the artificial systems, during January and July, respectively, when 90% of the drying air was re-circulated.

The model results were validated at 90% of air recirculation and showed reasonable agreement with the experimental ones in temperature, moisture content of mint and energy consumption.

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