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DESIGN AND EXPERIMENTAL STUDY OF SOLAR LIGHTING-HEATING SYSTEM BASED ON SPECTRAL SELECTIVITY OF NANOFLUIDS

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ABSTRACT

Solar lighting is considered as a promising technique, which has huge potential to energy conservation and help to relax the mood of residents in the building. However, existing solar lighting systems used a filter to allow only visible light (shortwave) entering buildings and all the other energy contained in the longwave of the solar was released into the surrounding air, which caused the low efficiency of solar energy utilization and the high costs due to such a filter. It is not beneficial for promoting the market application of solar lighting technology. In this paper, a solar lighting-heating dual-effect system was developed which uses a hollow filter that filled by nanofluids to separate the longwave and shortwave of the solar. Based on the spectral selectivity of nanofluids, this system can utilize solar energy in different wavelengths separately. A series of tests were conducted and results suggested that the solar energy utilization efficiency of this system was much higher than traditional solar lighting systems.

Keywords: Solar lighting, Nanofluids, Spectral selectivity, Experimental investigation

NONMENCLATURE

Abbreviations	
Q	Quantity of Heat
G	Radiation Intensity
c	Specific Heat Capacity
t	Temperature
A	Cross-sectional Area
E	Illumination
ϕ	Luminous Flux
η	System Efficiency

Symbols	
in	Inlet
out	Outlet
R	Solar Radiation

1. INTRODUCTION

Energy and environment are the focus of global attention. Energy and environment are the foundation and key to ensure the sustainable development of human cities and society [1]. In recent years, the developed countries in the world attached great importance to the smart use of energy, vigorously embark on research and development of new energy, clean energy and low-cost energy. Globally, they are also advocating low-carbon, environmental protection, energy conservation and emission reduction [2].

Meanwhile, more than four quarts of energy are used annually to provide artificial lighting for buildings in the US, at a cost of about $40 billion [3]. China's lighting power consumption accounts for about 12% of the country's total power generation. In 2013, for example, the annual power generation was 5245.1 billion kWh, and the annual lighting power consumption reached 629.4 billion kWh. Although some lighting needs to be done in the morning or late at night, most electric lighting is done in the daytime. Due to the influence of structural design and geographical location, underground space, large-span space, north and single-facing housing space and other places also need to provide lighting in the day to meet the normal life and production. For buildings with larger perimeter ratios and more than one floor, skylights and windows are not suitable for most lighting in buildings because many rooms are too far from the outside walls or roofs. When

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the sky is clear, turning on the lights to supplement lighting has become a habit of people, but also a helpless move. Therefore, solar lighting could greatly save the energy consumption of artificial lighting

Moreover, as a vital part of the physical environment of the whole building, the light environment of the building directly affects the physical and mental health of the people in the building and the quality of their life and work. The introduction of natural light is conducive to alleviating visual fatigue, relaxing the mood of the people in the building and effectively avoiding negative emotions. In office buildings, people spend most of their time under artificial light. As a result, 15% of office workers complain of eye strain [4]. The invisible wavelength required for vitamin D3 synthesis is absorbed by the eyes and skin. Sunlight can be used to reduce the effects of diseases, such as seasonal affective disorders [5]. Sunlight irradiation is helpful to improve the recovery rate of patients and productivity of workers.

As early as the 1980s, Himawari developed an optical fiber solar lighting system, but due to its high cost, it didactive any market penetration [6]. Then the hybrid solar lighting (HSL) technology (based on parabolic collector) was developed at Oak Ridge National Laboratory. The technology has been licensed to Sunlight Direct LLC, but the company has no commercial products [6].

After years of research and development, photoconductive lighting technology has been put into practical application. But there are still many problems to be solved, among which the most prominent one is the optical fiber thermal protection, which will not only affect the normal operation of the system, but also increase the investment of the system. Many scholars have carried out research on this issue. Tekelioglu and Wood [7] were the first companies to solve the burning problem of plastic optical fibers in optical fiber lighting systems using large diameter (100 cm) parabolic concentrators. Their thermal analysis showed that fused silica glass accessories were added to plastic fibers. Parans system [8] uses 6.5 cm x 6.5 cm small Fresnel lens as the main concentrator plastic optical fiber. In a recent study, a parabolic reflector (36.0 cm in diameter) with a collimating lens for optical fiber sunlight illumination was analyzed [9]. In a pre-emptive effort to alleviate heat problems, they use silicon fibers at the beginning and plastic fibers for optical transmission. The above research promotes the practical application of photoconductive lighting system. However, the problem of optical fiber thermal protection has not been well solved, especially in the case of high power focusing.

Based on the above problems, this paper presents a dual-effect system of building lighting and thermal transmission using nanofluids spectroscopic solar optical fiber, and carries out actual experimental tests for the system. The experimental results showed that from the perspective of full spectrum utilization of sunlight, the hollow liquid-carrying lens with unique design can use the spectral selectivity of nanofluids to make use of the sunlight (absorbing the energy of infrared part and transmitting visible light). In addition, the input end of the optical fiber is close to the bottom of the lens, and the liquid in the lens can be used to cooling the optical fiber. The unique design of the system can effectively alleviate the thermal effect of optical fibers and improve the overall utilization efficiency of solar energy. Different kinds of nanofluids can be filled into the lens in different seasons, so that the system is suitable for the seasonal energy demand characteristics of the building.

2. DESIGN OF DUAL-EFFECT SYSTEM

Usually, an efficient daylighting system are preferred that have a minimum number of modules with an effective output while remaining cost effective. A daylighting system with a single concentrator is preferred instead of installing a system with many concentrators giving the same output as that of the single concentrator [5]. The thermal protection of optical fibers becomes more serious when concentrators with a single high concentration factor are used. The dual-effect system proposed in this paper can effectively alleviate this problem.

2.1 Two-stage optics for collecting solar energy

The system uses secondary optical elements to collect and utilize solar energy. As shown in Figure 1, the light is first converged through the Fresnel lens, and the convergent light are injected into the conical part of the secondary lens. The design of the conical part is helpful to reduce the accuracy requirement of the solar tracking element (the principle is explained in detail in 2.2). The secondary lens is a hollow liquid-filled lens filled with nanofluids, which can selectively absorb and transmit sunlight. The absorbed solar energy (long wave) can be used for building heat, and the transmitted solar energy (short wave) can be transmitted to indoor lighting through optical fiber bundles. The optical fiber bundle is close to the bottom of the second-order lens. The second-order lens not only diverts the energy of the optical fiber bundle, but also water-cooled the optical fiber bundle.

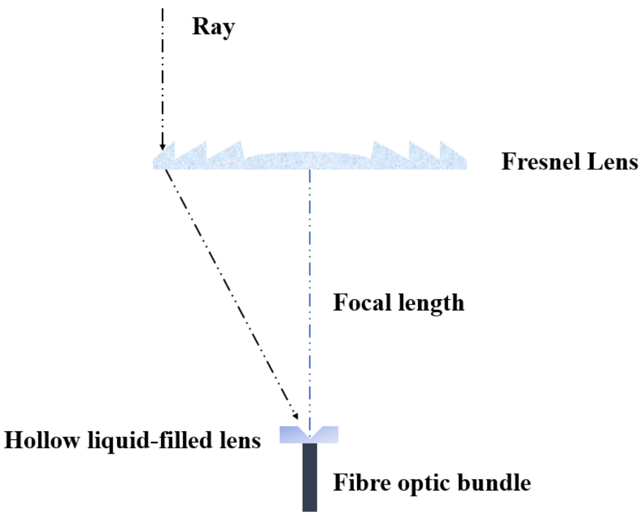

Fig 1 Schematic diagram of Two-stage optics element.

2.2 Design of hollow liquid-filled lens

As shown in Fig. 2, the hollow lens designed by this system is different from the transitional lens. There is a large space cavity inside the lens, and water inlet and water outlet are respectively opened on both sides. It can inject various nanofluids into the cavity to realize the function of light splitting. The cone design at the bottom of the hollow lens is beneficial to the secondary focusing and the coupling of the light beam and the optical fiber bundle.

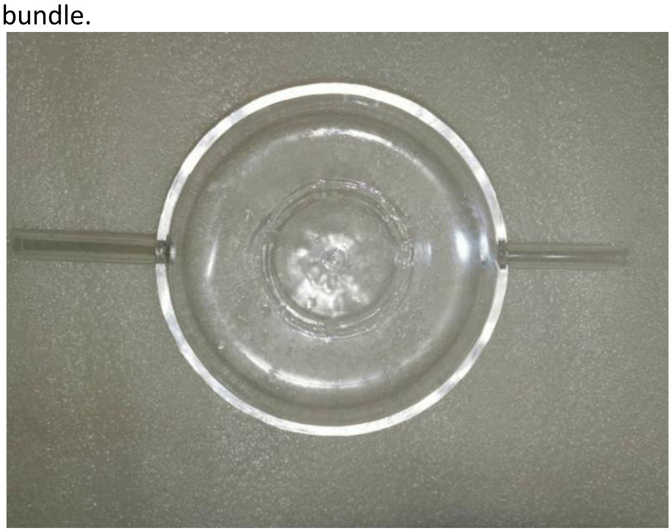

Fig 2 Photographs of Hollow Lens.

Compared with the traditional convex lens, the advantage of this element lies in that it cannot only concentrate light but also split sunlight, to make use of sunlight in different spectra and improve the utilization rate of sunlight. As shown in Fig. 3, by filling the nanocrystal fluid in the hollow lens, visible light can almost completely pass through the lens and enter the optical fiber for illumination. Some infrared rays provide heat through the lens and some are absorbed by the liquid in the cavity. When the liquid filled into the lens is different, the components of the transmitted light are also different, so it can be used in different conditions.

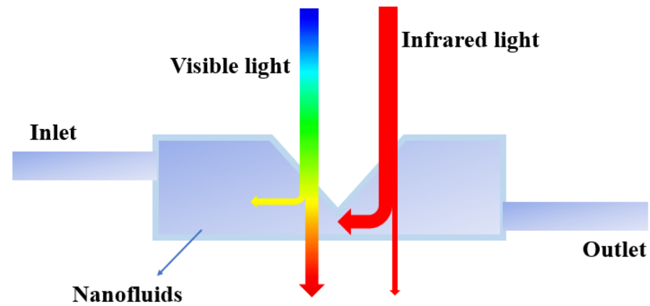

Fig 3 Schematic diagram of working principle of hollow lens.

3. EXPERIMENTAL SETUP

3.1 Experimental apparatus

As shown in Fig. 4, a portion of solar energy entered the optical fiber bundle after collecting and distributing the two-stage optical lens. A solar photometer was placed at the output end of optical fiber bundle to monitor the illuminance in real time. Another part of the solar energy was absorbed by the nanofluids inside the hollow lens. Nano-fluid was driven by water pump in the water tank and sent into the lens. A rotameter was set on the water supply pipe to measure the loop flow. Temperature collection points were set on the supply and back pipes. In addition, a PT100 platinum resistor was placed at the input end of bundle for optical fiber thermal protection monitoring. The solar radiation intensity is monitored by the solar power meter. Specific test equipment model parameters are shown in table 1.

Table 1 Experimental test apparatus and accuracy.

Test object	Test equipment	Accuracy
Temperature	four-wire system Pt100	±0.05℃
Flow	LZB-10 Rotor flowmeter	±0.1%
Illumination	MOLUX5032C	±3.0%
Radiation	SM206	±5 W/m^2

3.2 Test procedure

As shown in Fig. 5, after the sunlight passes through the secondary optical collector, one part of the sunlight is absorbed by nanofluids in the hollow lens and transformed into heat Q_{out}, while the other part is transmitted through the lens to a distant place for illumination through optical fiber bundle.

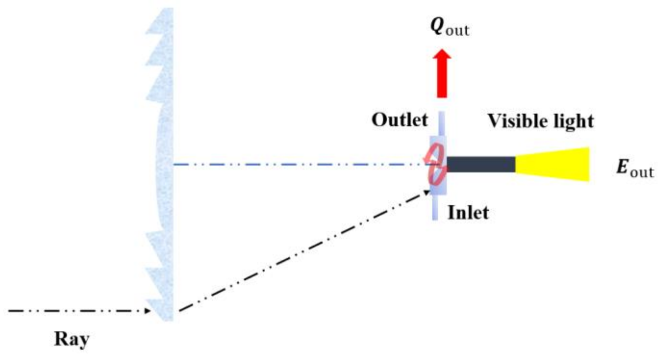

Fig 4 Schematic diagram of energy diversion for Two-stage optics element.

Data acquisition instruments and physical quantities have been introduced in Section 3.1. The total solar energy injected into the system can be calculated by formula (1).

$$Q_{in} = G_R A_{lens} \tag{1}$$

Among them, A_{lens} is the area of Fresnel lens and G_R solar direct radiation intensity.

As shown in Formula 2, the heat absorption Q_{out} can be calculated by the temperature difference and flow rate of the supply and return water in the nanofluid loop.

$$Q_{out} = cm(t_{out} - t_{in}) \tag{2}$$

The heat absorption efficiency η_1 of the dual-effect system can be obtained by dividing the heat absorption Q_{out} by the total incident energy Q_{in} of the solar energy.

$$\eta_1 = \frac{Q_{out}}{Q_{in}} \tag{3}$$

Likewise, the illumination efficiency η_2 of a dual-effect system can be calculated by formula (4) -(6).

$$\phi_{in} = E_R A_{\text{lens}} \tag{4}$$

$$\phi_{out} = E_{out} A_{fibre} \tag{5}$$

$$\eta_2 = \frac{\phi_{out}}{\phi_{in}} \tag{6}$$

Among them, E_R direct sun illumination, E_{out} is the output illumination of the optical fiber, A_{fibre} is the cross-sectional area of the output of the optical fiber.

4. RESULTS

In this paper, the system efficiency of dual-effect system was tested. The test time was 8:30-11:35 a.m. on August 2, 2019, in Harbin. The experimental conditions are shown in Table 2.

Table 2 Experimental condition.

Parameter	value
Fiber length	8m
Fresnel lens area	0.25 m^2(50cm×50cm)
Rate of flow	100 L/h
Graphite nanofluids	Size 50nm Volume concentration 0.05%

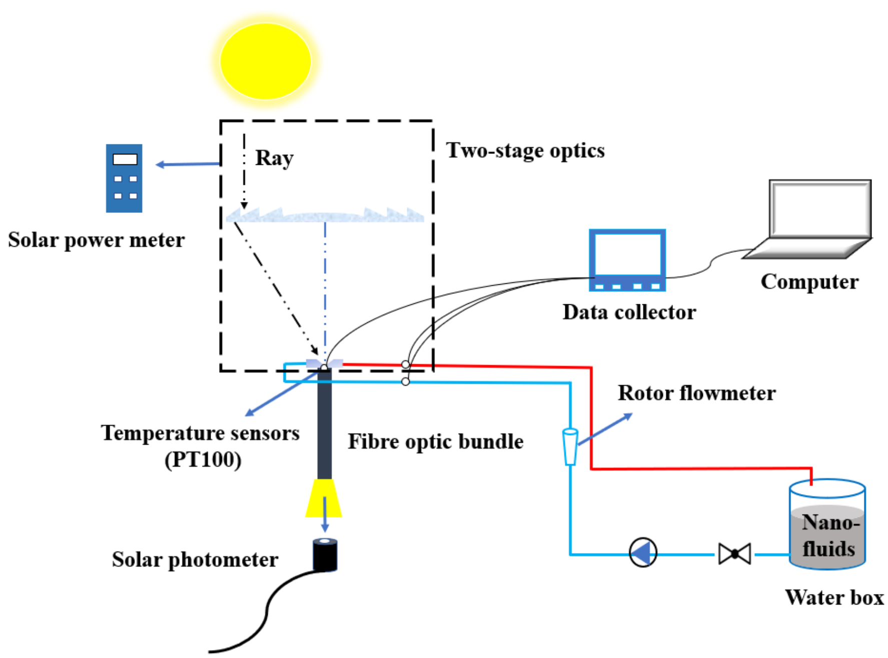

Fig 5 System Data Acquisition Diagram.

Fig. 6 shows the direct solar radiation intensity data collected during the experiment (8:30-11:35). The solar radiation intensity increased gradually from 926 to 1100 W/m^2 during the experiment period. The intensity of direct solar radiation drops to 437 W/m^2 and 560 W/m^2 at 9:55 and 10:10 respectively, because of clouds passing by to block out the sun. As shown in Fig. 4, part of the solar energy was absorbed by nanofluids flowing through the hollow lens and converted into heat. Fig. 7 shows the variation of the supply and return temperature of nanofluids during the experimental phase. The temperature of liquid supply increased from 33.6℃ to 45.1℃ during the period of 8:30-11:35. The water temperature is lower and the fluid temperature rises faster at the beginning of the experiment. The heating rate of the fluid decreases with the increase of the temperature of the fluid. During the whole experiment, the temperature of the input end of the optical fiber bundle is not higher than 100℃, which indicates that the design can deal with the thermal protection of optical fiber well under the condition of high concentration.

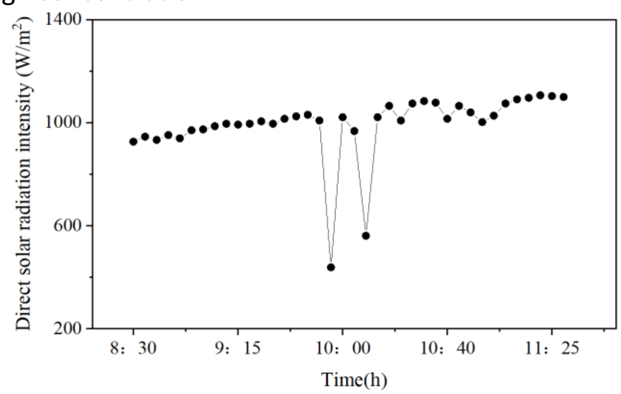

Fig 6 Experimental data of direct solar radiation intensity.

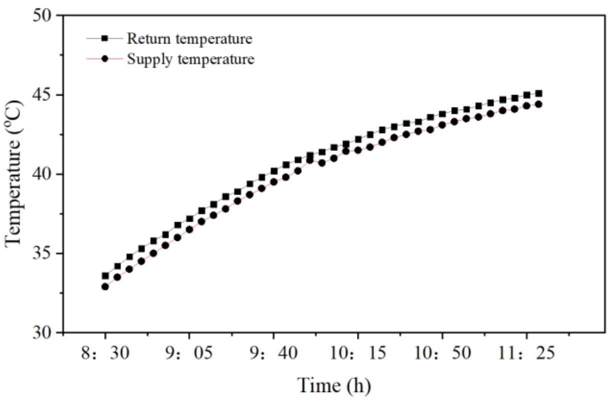

Fig 7 Experimental data of supply and return temperature of nanofluids.

The heat absorption efficiency of dual-effect system can be calculated through the efficiency calculation formula introduced in section 3.2, and the results are shown in Fig. 8. The heat absorption efficiency η_1 of the system decreases gradually with the passage of time. The efficiency was maintained between 35% and 40% at the beginning of the experiment, while at the later stage, it was only about 30%. The main reason is that with the increase of liquid temperature, the heat loss increases gradually, which makes the heat absorption efficiency of the system decrease gradually.

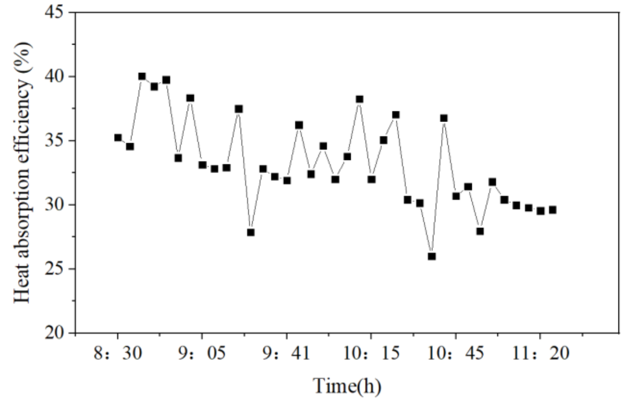

Fig 8 Heat absorption efficiency of dual-effect system.

Fig. 9 shows the experimental data of direct sun illumination. The trend of the data is approximately the same as that of direct solar radiation intensity. It increased slowly over time, and dropped sharply twice during the period because of cloud cover. Fig. 10 shows the experimental data of the illumination output of the optical fiber bundle, which trend of change is like that of direct solar illumination data, with the value rising from 429600 lux to 577300 lux.

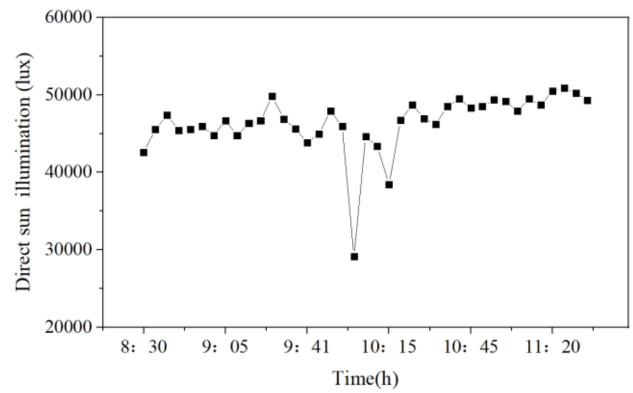

Fig 7 Experimental data of direct sun illumination.

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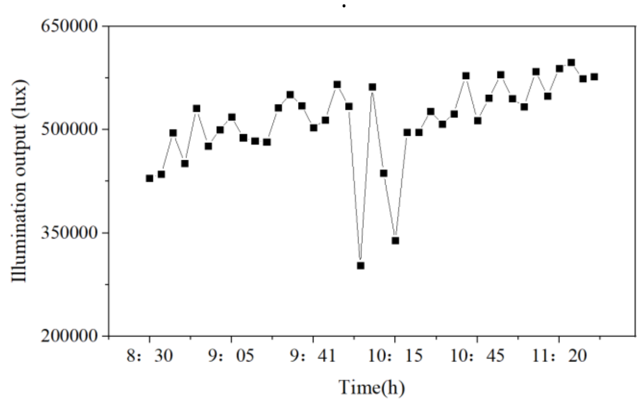

Fig 10 Experimental data of the illumination output of the optical fiber bundle.

Similarly, the Illumination output efficiency η_2 can be calculated by the formula described in section 3.2. Fig. 11 shows the calculation result of light transmission efficiency. The efficiency of light transmission is almost constant (fluctuating between 10-12%).

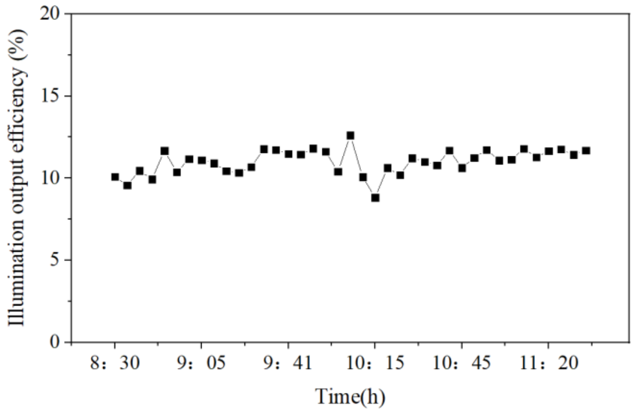

Fig 11 Illumination output efficiency of dual-effect system.

Thus, the dual-effect system proposed in this paper can not only guarantee the efficiency of the current optical fiber-based daylighting systems [10], but also effectively additional utilize the solar energy of 30%-35%. The use of large concentrator can reduce the number of tracking and collecting components in the optical guide system and reduce the cost of the optical fiber-based daylighting systems [5]. However, high-power focusing also aggravates the thermal protection problem of optical fiber-based daylighting systems. The experimental results show that the secondary optical element (hollow lens) designed in this paper can effectively avoid the thermal damage at the input end of the optical fiber bundle, which provides a new idea for the development of daylighting technology.

5. CONCLUSION

Daylighting is a technology with energy saving potential, but there are still many problems in its application. The dual-effect system proposed in this paper, from the perspective of solar spectrum utilization, can guarantee the light transmission efficiency of 10%-12% of the conventional optical fiber-based daylighting systems and provide the additional photothermal utilization efficiency of 30%-35%. The design and proposal of this system not only improves the applicability and flexibility of the optical guide lighting system, but also provides new ideas for solving the existing problems of the optical fiber-based.

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