



Performance of a novel solar assisted Bian stone thermal therapy



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ABSTRACT

In this paper, a novel Bian stone thermal therapy assisted by using solar radiation is proposed for safe thermal therapy on patients. A mathematical model is developed based on heat balance, and the performance of heat transfer from the novel Bian stone thermal therapy system to human body is studied. Sensitivity analysis is also performed. Fluid heated by solar radiation is channeled through a pipe to heat the Bian stone. For stronger solar radiation, or smaller or shorter pipe, the Bian stone attains the initial body temperature faster, and the novel thermal therapy system shows better performance and can therefore be used on patients earlier during the day. Early use of the thermal therapy system is a very important factor because the lowest ambient temperature is normally obtained early in the morning. Moderate water flow velocity is suitable by considering good mixing effect and power savings. The stone-body contact surface area has little influence on the critical heating time for the Bian stone to reach the initial body temperature after sunrise. This work lays a solid foundation for safe use of the solar assisted Bian stone thermal therapy.

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1. Introduction

In recent years, fossil fuels have been depleting and air pollution worsening. Fossil fuels are also environmentally unfriendly hence there is need to look for alternative energy sources for various domestic and commercial use. Like wind power, biomass, and gravitational potential energy of water for use [1–3], solar radiation energy has been considered as a reliable and widely available energy source for sustainable use in the near future [4,5]. Additionally, solar radiation energy is safe and environmentally friendly.

Bian stone also called bianshi or stone needle is one of the earliest known instruments of therapy in Traditional Chinese Medicine [6]. The Bian stone is used for performing massage, heating, and other physiotherapies (Fig. 1a). Bian stone can be used to help relaxing muscle, relieving pain, promoting blood circulation and so on [7]. The Bian stone therapy has obvious therapeutic effect on many diseases, such as shoulder peri-arthritis [8], cervical spondylosis [9] and osteoarthritis [10]. Nowadays, the Bian stone's function of nursing health in daily life is attracting great interest of more and more people [6].

Thermal therapy helps in generating heat in the human body and leads to higher tissue temperature. This rise in temperature produces vasodilation, thus promoting better blood circulation. It also can improve the metabolism of human tissues and organs. Thermal therapy has good effect on some diseases such as, some pains [11], blood vessels [12], nerves [12], myalgia [13], fibromyalgia [13], contracture [13], bursitis [13] and muscle spasms [13]. Electricity is usually used to heat the Bian stone in order to enhance the thermal therapy on patients [14]. However, like for electrothermal blanket [15], there is potential safety risk for the electrothermal Bian stone attached to human bodies when it is used many times.

Safety is always one of the most important factors during treatment. Therefore, a major question of how to improve safety during treatment must always be asked using any form of treatment. Previous studies on Bian stone have focused on analyses of the chemical constitute of the materials [16,17]. However, to date, little work on safety of electrothermal Bian stone therapy has been reported. In order to solve the safety problem, this paper explores a new way of using solar radiation to assist in the application of Bian stone thermal therapy. A mathematical model is developed, the heat transfer performance is studied, and the sensitivity analysis is performed.

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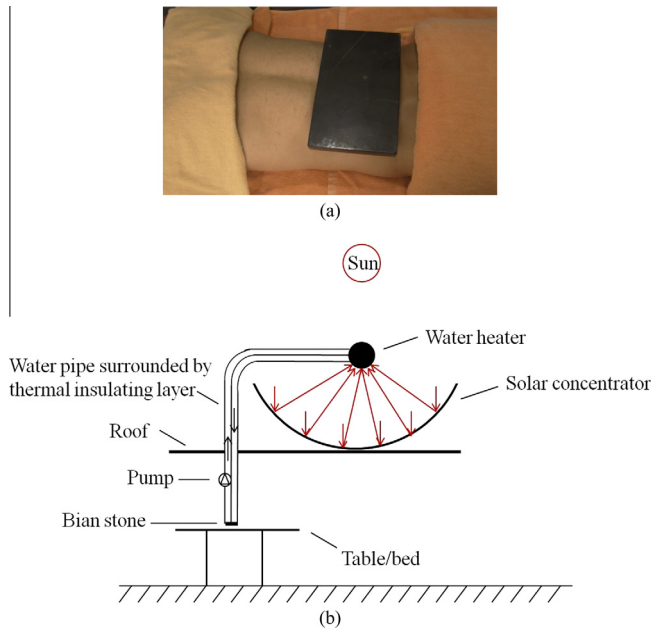


Fig. 1. (a) Picture of a traditional Bian stone therapy (which is from the Traditional Therapy Center of the Second Affiliated Hospital of GUCM); (b) schematic of solar assisted Bian stone thermal therapy system.

2. Description of Bian stone therapy and novel solar assisted system

2.1. Characteristics of Bian stone therapy

Use of Bian stone as an instrument of therapy can be traced back to the New Stone Age about 4000 years ago [6,18]. The Bian stone in the earliest form used for therapy is a piece of polished sharpened flat stone or stone needle used for treating illness by pricking certain parts of the body [19]. The acupuncture originated from the Bian stone therapy [20]. With the development of Traditional Chinese Medicine, stone needles were gradually replaced by needles made of metal used for acupuncture [19,21]. Whatever the case, Bian stone played an important role in ancient therapy and works well in modern therapy.

Use of Bian stone for physiotherapy is determined by the material characteristics of Bian stone. Bian stone is composed of numerous calcite microcrystallines [17]. The stone has good capability of heat conduction, storage and radiation due to its high-content microcrystalline calcite with good thermal properties [17,22]. Specifically, Bian stone has high infrared emission rate. Infrared radiation energy can easily be absorbed by human body and is more useful in heating the human body than visible radiation which is strongly reflected by the human body. The good thermal property of Bian stone determines its very good physiotherapeutic effect on the human body. In this case, Bian stone can improve the energy metabolism of human cells and promote microcirculation, thus being very beneficial to alleviating diseases and improving health conditions [22,23].

2.2. Description of a novel solar assisted Bian stone thermal therapy system

A novel Bian stone thermal therapy assisted by using solar radiation is proposed (Fig. 1b). In the solar assisted Bian stone thermal therapy system, a concentrating solar collector, i.e., a parabolic dish concentrator tracking the sun's beams is installed on the roof of a house to heat the water heater at its center. Two water pipes

are used to link the water heater and the upper surface of Bian stone. A pump is used to force the circulation of water in the two pipes. In order to accelerate the heating rate of water in the pipe and reduce the heat loss through the pipe wall, the water pipe should be as short as possible. Therefore, the pipe can reach the heater through the dish concentrator center, and the table/bed of therapy can be located below the concentrator center. The heat transfer principle used in the system is: flowing water obtains heat from the water heater and releases heat to Bian stone. The continuously heated Bian stone can be used for therapy on patients' bodies when the stone temperature is over the initial body temperature. One factor that must be considered is that the rate at which Bian stone heats up is slow, therefore, modeling the heating process of Bian stone and body and studying the performance are very important processes. Once the body is heated to a target temperature, any available heat control technology to keep the body at the target temperature can be employed in releasing the redundant heat to other materials or systems. This aspect is not studied in this work.

3. Mathematical model

A mathematical model based on heat balance is developed for the solar assisted Bian stone thermal therapy system. The following assumptions are made:

- (1) The power of the pump is enough to force the water to mix fully and quickly. Therefore, the temperature of the working fluid is taken to be constant and uniform to some extent.
- (2) The heat loss through the body is not considered because the heat penetration depth is assumed to be far smaller than the thickness of the studied part of the body.
- (3) The heat is transferred from the stone to the body perpendicularly to the stone-body contact surface.

By assuming the maximum irradiance of a day to occur at the noon (12:00), solar radiation intensity G at any time t for daylight hours in a day is calculated by [24]

$$G = G_{\max} \cdot \cos((t/3600 - 12)\pi/\Delta) \quad (1)$$

where G_{\max} is the maximum solar radiation in the day and Δ is the total daylight hours in the day, while for non-daylight hours $G = 0$.

The ambient temperature in the day can be taken as [24]

$$T_{\infty} = T_{\infty avg} + \Delta T_{\infty} \cdot \cos((t/3600 - 14)\pi/12) \quad (2)$$

where $T_{\infty avg}$ is the average temperature of the day, and ΔT_{∞} is the diurnal temperature range, which is equal to the maximum temperature variation in the day, and is assumed to occur at 14:00 p.m.

The equation to describe the heat transfer from the solar radiation absorbed by the solar concentrator to the working fluid is given by

$$\alpha G A_{coll} - U_{loss}(T_f - T_{\infty})A_p - h_f(T_f - T_{st})A_{st} = m_f c_{pf} \frac{dT_f}{dt} \quad (3)$$

where α is the effective absorptivity of solar radiation G , A_{coll} is the effective collecting area of solar radiation, A_p is the average heat transfer area of the pipe conveying fluid and the thermal insulating layer, A_{st} is the area of the stone-body contact surface, m_f is the total mass of working fluid in the pipe, c_{pf} is the specific heat capacity of working fluid, T_f is the temperature of working fluid, and U_{loss} is the effective heat loss coefficient of the working fluid.

The heat transferred from the working fluid to the Bian stone is assumed to be stored in the stone and the studied part of the body. The structure of the body including skins, muscles, bones, blood, vessels and so on is very complex. In addition, the Bian stone is assumed to be thin. In order to study the heat transfer in the body

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