

New Method of Transmitting Heat which Takes Advantage of the Thermal and Optical Properties of Infrared Rays

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Near infrared ray have the property of generating heat, irradiating the object. The optical characteristic is about the same as a visible ray of light. However, it is a little known fact that near infrared rays have thermal energy which is possible to optically transmit like optical fibre that can transmit optical information. This does not belong in any category of thermal transmission such as radiation, conduction and convection, which is designated as “total reflection transmission”.

In this paper I would like to describe the mechanism of my Infrared Guide Heating Device which has utilized and developed the above properties of infrared rays.

1. Introduction

During the research and development of new material such as silicon, silicon carbide, graphene, and thin-film materials, it is often necessary to heat-treat them under a wide variety of conditions. Especially for the samples obtained through the R&D phase, it is extremely important to heat-treat them in a clean ambient environment, with no risk of contamination. Furthermore, during observation tests conducted in an ultra-high vacuum or various kinds of gas environments, conditions, pinpoint heating of samples is also essential to protect the measurement instruments placed near the samples.

2. About Infrared Ray

In 1800, a British astronomer Herschel (1738-1822), during his observation of the sun's rays, discovered infrared ray, which was outside the visible spectrum and possessed an invisible heating effect(Photo 1). When a rainbow can be seen in a sunny sky after a rain, it is because the sunlight strikes the water droplets falling through the sky, and the visible



Photo 1 William Herschel (Origin by Wikipedia)

wavelength range is spectrally separated based on the prism principle into the seven colors of red, orange, yellow, green, blue, indigo, and violet, which are visible to the human eye. The light beyond the red color in a rainbow is the infrared ray (thermal ray), which is not visible (Fig. 1). The reason we feel warm when sunlight hits us is also due to infrared ray, which generates heat when it strikes our body.

Infrared ray with this heating characteristic can be divided into near-, middle- and far-infrared rays depending on the wavelength.

Infrared rays can also be generated artificially. Near-infrared rays are utilized primarily for heat-treating new materials; middle-infrared rays, for taking measurements; and far-infrared rays, for heating, cooking, drying food and other materials, and medical applications, etc.

The wavelength of visible rays range from 0.4 to 0.76 mm, while those of near-infrared rays range from 0.76 to 2.0mm. Due to the proximity of their wavelengths, visible rays and near-infrared rays share some physical characteristics. For example, they both possess such optical characteristics as radiation, transmission, condensation, reflection, and refraction. Near-infrared rays differ in the

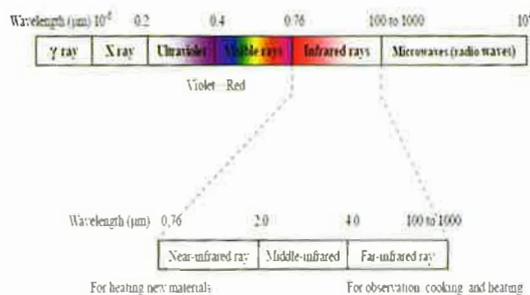


Fig. 1 Electromagnetic wave spectrum and infrared rays

heating effect they possess in addition. When near-infrared rays are radiated onto an opaque object, the object absorbs their thermal energy and its temperature rises. However, when near-infrared rays are radiated onto a transparent object, no thermal energy is absorbed. The near-infrared rays pass through the transparent object like ordinary light and are totally reflected when they reach a boundary between two substances having different refractive indexes. In other words, near-infrared rays do not generate any heat inside transparent objects.

For example, near-infrared rays can transmit heat from one end of a long, transparent circular rod to the other end, just as optical fibers can transmit light. Although this property is not widely known, it has been empirically proven, and infrared guide heating systems that utilize an infrared lamp as the heat source have been commercialized and are in wide use for clean heating in an ultra-high vacuum.

3. New Heat Transmission Method

Fig. 2 shows a cross-sectional diagram of a commercially available infrared guide heating system that uses a new heat transmission method. An infrared lamp, which serves as the heat source, is positioned at the first focus point F1 of a rotating spheroid mirror. Infrared rays emitted from the energized lamp are reflected in the mirror and collected at the second focus point F2. One end of a long transparent circular rod is placed at focus point F2 to guide the collected near-infrared rays into the rod. Some components of the incident near-infrared rays travel straight

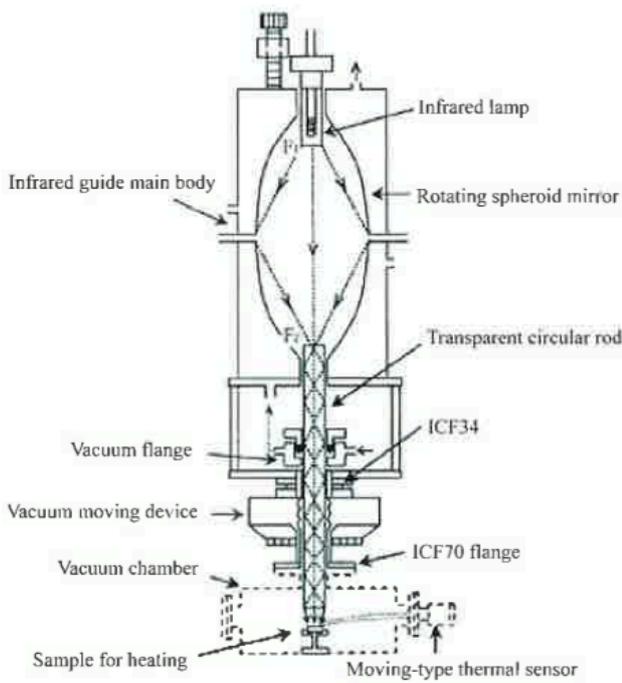


Fig. 2 Structure of an infrared guide heating system

through the transparent circular rod while others are totally reflected off the internal surface of the rod repeatedly until they reach the other end.

As shown in Fig. 3, using θ to represent the incident angle of the near-infrared rays entering the transparent circular rod, and \varnothing to represent the refractive angle with respect to the internal surface of the transparent circular rod having a refractive index of n , the total reflection condition of the incident angle $90^\circ - \varnothing$ on the rod internal surface R can be expressed using the following equations:

$$n \sin \varnothing = \sin \theta$$

$$n-1 = \sin(90^\circ - \varnothing) \varnothing \leq \varnothing c$$

In other words,

$$\sin \theta \cdot \sin(90^\circ - \varnothing) \varnothing \leq \varnothing c$$

where “ $90^\circ - \varnothing c$ ” indicates the critical angle.

Near-infrared rays that enter at the incident angle that satisfies the above

conditional expression are totally reflected optically off the internal surface R of the transparent circular rod repeatedly, without traveling outside the rod, and are finally emitted from the tip. When a sample is placed near this position, it absorbs the thermal energy of the near-infrared rays and rises temperature.

Until recently, it was thought that heat could only be transferred using one of the following methods: “conduction”, “radiation”, and “convection”. Transferring heat using near-infrared rays, which possess optical characteristics, is considered an entirely different heat transfer mode. “Thermal conduction” occurs when heat flows from a higher-temperature object to a lower-temperature object, at speeds as slow as several to dozens of seconds, even with objects possessing excellent thermal conductivity, such as metals. The lower the thermal conductivity, the slower the conduction speed, and thermally insulating materials conduct no heat at all.

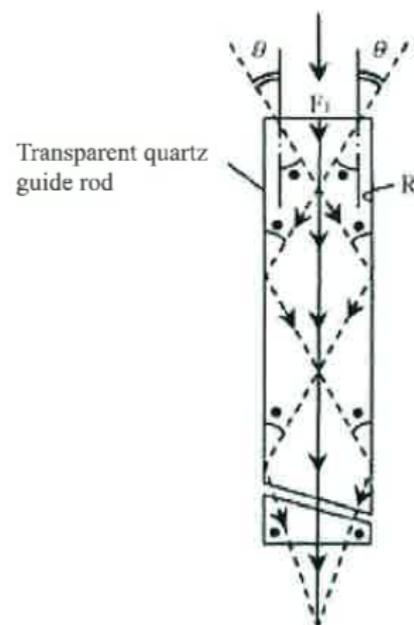


Fig. 3 Principle of the total-reflection heat transmission.

However, in the different heat transmission mode mentioned above, heat is transferred and transmitted quickly, regardless of the thermal conductivity of the object, provided that it is transparent. Inside the long transparent circular rod shown in Fig. 2, heat is transferred and transmitted from one end and emitted from the other end. Furthermore, shutting down the heat source instantly stops the heat supply. During the entire operation, the temperature of the transparent circular rod does not rise. In other words, the only role the rod plays is high-speed heat transfer, which differs from thermal conduction.

“Thermal radiation,” the second heat-transfer method, is a phenomenon in which heat is radiated in all directions from the heat source. In contrast, in the different heat transmission mode mentioned above, heat is transferred and transmitted linearly inside the transparent circular rod and is not radiated to the outside. Additionally, little attenuation occurs. “thermal convection,” the third method, is a phenomenon in which heat is transferred by the continuous movement of a fluid that is in contact with a heat source; the fluid receives heat through conduction or radiation from the heat source, which decreases its specific gravity. As explained above, the aforementioned different heat transfer mode possessed different characteristics from the three types of thermal transfer methods, and can be considered a new method of transferring and transmitting heat. Because of its similarities to the way light is transferred through optical fibers, the new method has been named the “total-reflection heat transmission.”

4. About Total-reflection transmission

4.1 Features of the infrared guide heating system

(1) Ultra high-speed heating: Near-infrared rays, which possess a heating characteristic, travel through a transparent circular rod at high speed, instantly striking the sample to drop rapidly.

(2) Heating only the sample without heating the surrounding area: Near-infrared rays do not leak outside the transparent circular rod, do not attenuate, and are transmitted to the sample instantly.

(3) Transmitting heat from a distance: With resistive heating methods, the sample must be placed near the heat source. In contrast, the new heating method transmits heat to a sample placed at a distance to raise its temperature.

(4) Clean and non-contact heating: the new heating method provides clean, non-contact heating because it emits no gas, thus eliminating concerns about pollution. It can even heat objects in a vacuum, in the ambient atmosphere, or in an oxygen gas atmosphere, etc.

(5) Free of induction or electrical noise: Because the heat source for the new heating method can be positioned away from the sample, there are no effects from induction or electrical noise, making it possible to obtain even faint electrical information from the sample.

4.2 Main specifications and performance

THERMO RIKO developed two infrared guide heating systems: the GVL298⁽²⁾ an ultra high-speed heating model, and the GVH298⁽¹⁾, an ultra high-vacuum model. Table 1 shows their main specifications, performance levels, and application examples.

Table 1

Model	GVL298 Ultra high-speed heating model	GVH298 Ultra high-vacuum model
Infrared guide section	Water-cooling system gold spheroid mirror	
Max. attainable temperature	1500°C	1400°C
Heating area	10-20 dia.	
Max. attainable vacuum degree	$5 \cdot 10^{-7}$ Pa (10^{-9} Torr)	$5 \cdot 10^{-9}$ Pa (10^{-11} Torr)
Max. heating rate	100-150°C/sec	1°C/sec
Application examples	Thin-film crystal growth Temperature-programmed desorption (TPD) analysis, etc.	X-ray photoelectron spectroscopy Heating samples under electron microscopy

5. Application Examples of the Infrared Guide heating system

5.1 Cleaning a sample in an ultra-high vacuum

Photo 2 shows an example in which the infrared guide heating system has been installed in an X-ray photoelectron spectroscopy. The long component in the top center of the photo is the GVH-model infrared guide heating system, which acts as a clean heating source. In the clean heating of samples, the sample receives infrared rays inside a pre-chamber under the infrared guide heating system, rising in temperature and discharging impurities. The cleaned sample is transferred in the ultra-high vacuum to the analysis chamber on the right side by means of a conveying mechanism, without being exposed to the atmosphere. This system prevents the contamination that can occur from exposure to



Photo 2 Example, GVH298 installed with JPS-9010 (X-ray Photoelectron Spectrometer: XPS) made in JEOL and supplied to Fuel Cell Nanomaterials Center, University of Yamanashi in 2011. (provided by Prof. Toshihiro Miyao) Max. attainable temperature: 1400°C

the ambient atmosphere, allowing high-precision analysis of a lean sample.

5.2 Heating a sample being irradiated with X-ray

Photo 3 shows system in use at Spring-8 in Hyogo prefecture. This system heats a sample being irradiated with X-rays in a high vacuum to an ultra-high temperature, and can move the sample around the X-, Y-, and Z-axes. It can also analyze the crystalline structure of the sample while raising, lowering, or maintaining its temperature. In this system, infrared rays are directed at both the top and bottom surfaces of the sample to raise its temperature, and do not interfere with the passage of the incident X-rays being directed at the sample or diffract rays.



Photo 3 X-ray topography heat treatment system (provided by Prof. Yoshinori Chikaura of Kyushu Institute of Technology)

- Max. attainable temperature: 1,500°C
- Sample rotation: Around X- and Y-axes
- Attainable vacuum degree: 5×10^{-4} Pa

5.3 Rapid Annealing Device



Photo 4: GVL298 Ultra high-speed heating model (supplied to National Cheng Kung University in 2010) which was a infrared

Guide Heating Device installed spherical vacuum chamber

5.4 Thermal Desorption Spectroscopy Device



Photo 5: TDS1200 Thermal Desorption Spectroscopy Device (commenced in 2008) (provided by Messrs. ESCO Ltd)

- Max. attainable temperature: 1,200°C

6. Summary

This article has described heat treatments applied in an ultra-high vacuum, an oxidizing atmosphere, and during X-ray radiation as application examples of the clean heating technology that uses the new heat transmission method in an ultra-high vacuum. In addition to these applications, the new technology is also coming into wide use as a clean heat treatment method effective during plasma generation, temperature-programmed desorption analysis, and inside a magnetic field.

The most notable characteristic of this heating method is the fact that it can transmit heat directly to the target object in a range from dozens of centimeters to more than several meters with almost no attenuation. This means that this new method can be applied to

the high-speed and clean heating of only the targeted material inside equipment for which making an electrical connection is difficult, inside a large structure, or in a liquid. We expect the new method to become more widely used in these applications as well.

Reference

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