Current Optics and Photonics
Vol. 1, No. 5, October 2017, pp. 500-504
ISSN: 2508-7266(Print) / ISSN: 2508-7274(Online)
DOI: https://doi.org/10.3807/COPP.2017.1.5.500

Investigation of an Infrared Temperature Measurement System for Thermal Safety Verification of Plasma Skin Treatment Devices

Jong-ryul Choi[1†], Wookeun Kim[1†], Bongkeun Kang[1], Tae-Ha Song[1], Hee Gyu Baek[1], Yeong Gil Han[2], Jungmoon Park[2], and Soowon Seo[1]*

[1]Medical Device Development Center, Daegu-Gyeongbuk Medical Innovation Foundation (DGMIF), Daegu 41061, Korea
[2]R&D Team, Innovac Technology, Inc., Daegu 41059, Korea

(Received March 23, 2017 : revised September 2, 2017 : accepted September 12, 2017)

In this paper, we developed a temperature measurement system based on an infrared temperature imaging module for thermal safety verification of a plasma skin treatment device (PSTD). We tested a pilot product of the low-temperature PSTD using the system, and the temperature increase of each plasma torch was well-monitored in real-time. Additionally, through the approximation of the temperature increase of the plasma torches, a certain limitation of the plasma treatment time on skin was established with the International Electrotechnical Commission (IEC) guideline. We determined an appropriate plasma treatment time (T_{Safe} < 24 minutes) using the configured temperature measurement system. We believe that the temperature measurement system has a potential to be employed for testing thermal safety and suitability of various medical devices and industrial instruments.

Keywords : Infrared thermography, Plasma skin treatment device (PSTD), Temperature imaging, Thermal safety verification
OCIS codes : (110.3080) Infrared imaging; (110.6820) Thermal imaging; (120.4290) Nondestructive testing; (120.4800) Optical standards and testing

I. INTRODUCTION

Plasma, one of the fundamental states of matter, is defined as an ionized gas-like state that consists of excited ions and electrons in almost equal numbers. [1]. Usually, plasma is generated by heating a material using strong heat sources or electromagnetic fields [2, 3]. To be specific, strong heat sources or electromagnetic fields can separate electrons, neutrons, and ions from the atoms of the material. Plasma is categorized as high-temperature or low-temperature according to the temperature ratio of electrons and gases. On the other hand, plasma can be classified as high-pressure or low-pressure based on the pressure condition while generating the plasma. Since the first identification using experimental discharge tubes, such as a Crookes tube, plasma has been utilized in various necessary and industrial components because temperatures, sizes, and densities of plasma emissions are easily controllable. [4-9]. For instance, fluorescent lamps can emit a visible fluorescent light from plasma of mercury gas in the lamps [10]. The exposure of plasma generated from nitrogen (N_2), oxygen (O_2), or argon (Ar) gas and a thermal oxidation can be applied to bond glasses and polydimethylsiloxane (PDMS)-based microfluidic channels for the development of *in vitro* microfluidic devices [11-15].

In addition, the possibility of biomedical applications of low-temperature plasma has been studied by various research groups [16-20]. X. Zu *et al.* introduced argon plasma treatments for the enhancement of human-skin-derived fibroblast migrations in *in vitro* chitosan substrates

[†]The authors contributed equally to this work.
*Corresponding author: soowon@dgmif.re.kr
Color versions of one or more of the figures in this paper are available online.

[21]. O. Lademann *et al.* studied the improvement of drug permeation through skin barriers using tissue-tolerable plasma (TTP), then suggested the feasibility of efficient cosmetics and drugs delivery based on plasma [22]. S. Rupf *et al.* investigated a cool plasma jet to eliminate oral microbes and applied the device in their study for dental treatments [23]. The most striking medical application using plasma is a plasma skin treatment. The plasma skin treatment is defined as one of the medical treatments in dermatology for direct exposure of radicals to eliminate skin lesions or efficient drug releases to deep regions of skins. With practical applications and bridge developments to commercialize, several low-temperature plasma medical devices have been commercialized [24-26].

In investigations and the commercialization of medical devices, a thermal safety is important to protect patients using the medical devices. For this reason, the International Electrotechnical Commission (IEC), the international standards and conformity assessment institute for all regions in electro-technology such as electrical and communication items, established technical standards of medical electrical equipment (IEC 60601-1), including the temperature requirements of components or surfaces that can be touched to patients [27]. Therefore, the thermal characteristics of every plasma skin treatment device (PSTD) must be tested and a safe range of applications should be specified to prevent heat injuries. In previous temperature tests in various industrial plasma torches, one-dimensional sensors such as a thermocouple, a thermochron and a fiber-optic temperature measurement device were employed to acquire averaged temperatures during the operation [28, 29]. On the other hand, thermal imaging by infrared (IR) thermography has been well established for non-contact measurements of temperatures in specific regions [30-32].

In this paper, we developed the temperature measurement system based on an infrared temperature imaging module for thermal safety verification of each torch in the PSTD consisting of multiple plasma generating torches. We tested a pilot product of the low-temperature PSTD using the system, and the temperature increase of each plasma generating torch was well-monitored in real-time. Additionally, through the approximation of the temperature increase of the plasma torches, a certain limitation of the plasma treatment time on skin was established with the IEC guideline. Through the pilot study to test the PSTD consisting of multiple plasma generating torches, we were convinced that the temperature measurement system has a potential to be employed for two-dimensional, multi-component tests of thermal safety and compensating to observe the regulation in medical devices and industrial instruments.

II. METHODS

A schematic of the infrared temperature measurement system for thermal safety verification of PSTDs is illustrated in Fig. 1. For the two-dimensional measurement of temperatures varying in time, an infrared temperature imaging module (FLIR C2, FLIR® Systems, Inc., Wilsonville, Oregon, United States) was installed in front of the PSTD at an appropriate distance to retain a tight focus. Lens holders (ALH-2, Namil Optical Instruments, Co., Incheon, Republic of Korea), metallic support posts (PHS, Namil Optical Instruments, Co.), and post holders (PH, Namil Optical Instruments, Co.) were employed to stand and fasten the PSTD and the temperature imaging module on rail carriers (RC-1, Namil Optical Instruments, Co.). To determine the appropriate distance between the PSTD and the module, all components were installed on a precision optical rail (POR-12, Namil Optical Instruments, Co.). Since performances in the configured temperature measurement system depend on specifications of the temperature imaging module, a measurable temperature range is from -10 to 150°C and a resolution is 0.10°C. In comparison with other temperature measurement devices which have been generally employed in thermal safety tests in various industrial plasma treatment torches, the temperature imaging sensor employed in the system has similar or somewhat lacking performances, especially the measurable range. On the other hand, this system configured in the study has an exclusive merit, a feasibility of two-dimensional and multi-point temperature measurements. Also, the main objective in developing the temperature measurement system is the

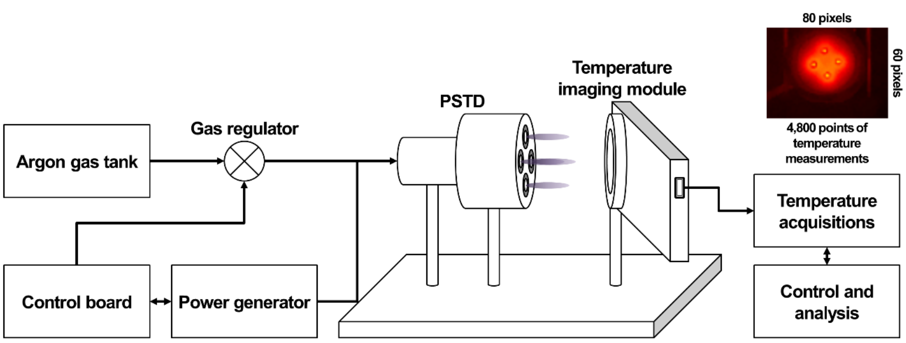

FIG. 1. A schematic of an infrared temperature measurement system for thermal safety verification of the PSTD.

confirmation whether a temperature on the PSTD is over 41°C, so we selected the temperature imaging module as an appropriate temperature sensor in the configured system.

In a preliminary test of temperature measurement, we applied a pilot product (PST-DM-03, Innovac Technology, Anyang, Republic of Korea) consisting of four plasma-generation torches. The radio-frequency electrical power generated by the power generator and Ar gas adjusted by the gas regulator were supplied to the pilot product of the PSTD. The control board in the pilot product monitored supplied power and Ar gas for confirming efficient supplements and prohibiting a sudden increasing of them. A brief sketch map of PSTD operations is illustrated in the left side of Fig. 1.

For transient acquisitions (thermal image acquisition time variance = 1 second) and the storage of the thermal images when the PSTD was operated, control and analysis software (FLIR ResearchIR, FLIR® Systems, Inc.) was employed. Post-processing to establish multi-pixel temperature distributions, color mapping and quantitative analysis of transient temperature changes on each plasma generating torch in the PSTD were achieved by the control and analysis software.

III. RESULTS

Figure 2 illustrates temperature distribution images of the PSTD during the operation with the emission of Ar gas-based low-temperature plasma. As described in each temperature distribution image of Fig. 2, the configured temperature measurement system provided two-dimensional distributions and transient temperature changes. From temperature distribution images in multiple temporal points, the temperature of the PSTD during the operation was proportionally increased over time. The temperature of the centers in each plasma torch was higher than that of the surroundings. From this point, the heat traveled from the center of the plasma torches to the surroundings.

To confirm the pattern in increasing temperatures during the operation and determine an appropriate plasma treatment time for a compliance of the safety standard specification, quantitative analysis of transient temperature variations at the center of each plasma torch was conducted as illustrated in Fig. 3. In the qualitative interpretation based on thermal images in Fig. 2, the quantitatively induced temperatures at the center of the four plasma torches in the PSTD were proportionally increased over time. Temporal temperature changes in four plasma torches had a similar pattern with fluctuations as described in Fig. 3. The pilot product of the PSTD used the single power generator and electrical power was equally shared by a 1 × 4 radio-frequency electrical power divider and supplied to each plasma generating torch. For this reason, patterns in temperature increase of the four plasma generating torches is similar.

Derived from the data in Fig. 3, we induced linear approximations to acquire a temperature-time relation model of the center of each plasma torch, as shown in Fig. 4. The linear approximation ($T_{Torch\ \#N}(t) = A*t + B$) was employed to estimate temperature-time relation models of four plasma

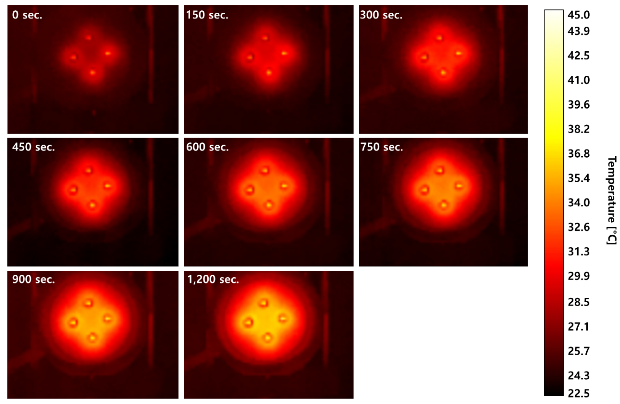

FIG. 2. Transient temperature images of the PSTD during the operation with the emission of Ar gas based low-temperature plasma.

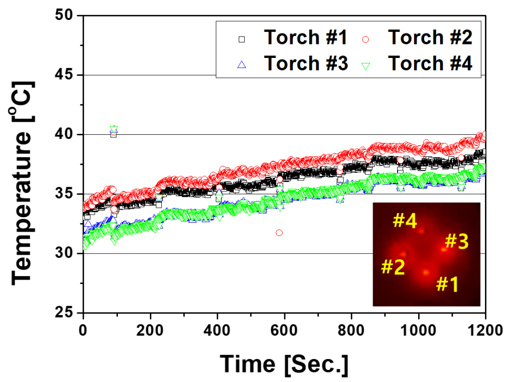

FIG. 3. Transient temperature changes on the center of four plasma torches in the PSTD. An inlet figure indicates where each plasma generating torch corresponds to the number in the graph.

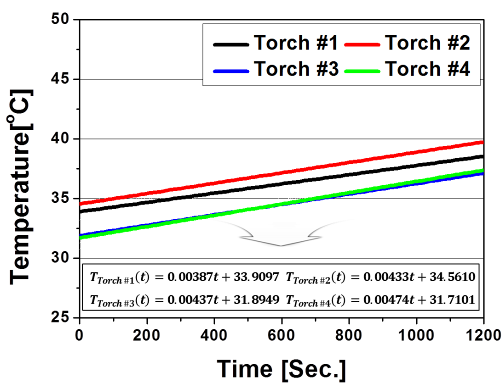

FIG. 4. Linear approximations of transient temperature changes on the center of four plasma torches in the PSTD. Equations in an inlet box indicates a temperature-time relationship of each plasma generating torch during the operation.

TABLE 1. Gradients and constants of linear approximations in central temperatures of four plasma torches

(t: treatment time, second)		
Torch No. (N)	Gradients (A)	Constants (B)
1	0.00387	33.9097
2	0.00433	34.5610
3	0.00437	31.8949
4	0.00474	31.7101

TABLE 2. Expected time when the temperature on the center of each plasma torch reaches regulated temperature for thermal safety assessments (T_{Safe} = 41°C)

Torch No. (N)	t [sec.] at $T_{Torch\ \#N} = T_{Safe}$
1	1832.12
2	1487.07
3	2083.55
4	1959.89

generating torches although there were a few fluctuations in temperature changes. Gradients and constants of linear approximations in central temperatures of the four plasma torches are suggested in Table 1.

The averaged R-square, a parameter that can represent a statistical accuracy of approximations, was 0.91144. Based on the approximated temperature-time relations of each plasma torch and the standard of the thermal safety (T_{Safe} = 41°C) in the technical standards of the medical electrical equipment, we could establish the appropriate plasma treatment time for the prevention of thermal damages to patients using the PSTD, as shown in Table 2.

Table 2 shows that the minimum expected time for the temperature at the center of the plasma torch to reach the regulated temperature for the thermal safety (T_{Safe} = 41°C) was 1487.07 seconds (approximately 24 minutes). From transient thermal images and quantitative approximations, the appropriate plasma treatment time to satisfy the guideline of the thermal safety has been determined to be under 24 minutes. Also, additional cooling modalities or designs to reduce heat accumulation are needed for the extension of plasma treatment time.

IV. CONCLUSION

In this study, we investigated the infrared temperature measurement system to verify the thermal safety of PSTDs. According to the result in the pilot study of temperature monitoring, temperature changes of each plasma-generating torch in the PSTD were well perceived in order to establish temperature increasing patterns and confirm whether or not the safety regulations are exceeded. The temperature measurement system can be applied for thermal safety tests with two-dimensional temperature distributions, so the inspector can easily find parts with a problem in thermal safety assessments.

Since a series of tests, for instance, the confirmation of individual standard specifications of a selected medical device and common standard specifications of electro-mechanical and electromagnetic safety are needed to secure safety and validity, a temperature test using the temperature measurement system configured in this study does not fully guarantee that a medical device can be used and commercialized. The thermal safety test of non-contact parts in medical devices is one part of various tests in confirming the satisfaction of standard specifications. From the investigation of the temperature measurement system, a well-established safety verification platform should be required to test various medical devices and confirm that standard specifications are regulated. Especially, the need to develop customized safety verification instruments for novel medical devices based on advanced technologies is expected to increase.

On the other hand, we faced the problem of irregular disconnections in thermal image storage through a mismatch between the triggers in the personal control computer and shutter reconfigurations in a temperature imaging module. The problem can be resolved by the employment of a high-speed and large-data-capable data acquisition (DAQ) board and a deliberate trigger platform. Through the improvement of slight issues confirmed in the pilot study, the temperature measurement system, which can acquire two-dimensional temperature distributions during the operation, can be employed for thermal safety tests on various medical devices and industrial instruments.

ACKNOWLEDGMENT

This work is supported by the Daegu-Gyeongbuk Medical Cluster Settled Company R&D Support Project (DG1D001, Project title: Electrode device and power module development for plasma skin therapy) funded by Daegu Metropolitan City.

REFERENCES

1. P. A. Sturrock, *Plasma physics: an introduction to the theory of astrophysical, geophysical and laboratory plasmas* (Cambridge University Press, Cambridge, UK, 1994).
2. Q. Z. Luo, N. D'angelo, and R. L. Merlino, "Shock formation in a negative ion plasma," Phys. Plasmas **5**, 2868-2870 (1998).
3. F. F. Chen, "Plasma ionization by helicon waves," Plasma Phys. Contr. F. **33**, 339 (1991).
4. A. Schutze, J. Y. Jeong, S. E. Babayan, J. Park, G. S. Selwyn, and R. F. Hicks, "The atmospheric-pressure plasma jet: a review and comparison to other plasma sources," IEEE T. Plasma Sci. **26**, 1685-1694 (1998).

5. L. Martinu and D. Poitras, "Plasma deposition of optical films and coatings: a review," J. Vac. Sci. Technol. A **18**, 2619-2645 (2000).
6. H. H. Kim, "Nonthermal plasma processing for air-pollution control: a historical review, current issues, and future prospects," Plasma Process. Polym. **1**, 91-110 (2004).
7. E. Gomez, D. A. Rani, C. R. Cheeseman, D, Deegan, M. Wise, and A. R. Boccaccini, "Thermal plasma technology for the treatment of wastes: a critical review," J. Hazard. Mater. **161**, 614-626 (2009).
8. S. Gopi, A. Sarma, A. Patel, and G. Ravi, "Non-thermal plasma at atmospheric pressure: system design and development," Instrument. Sci. Technol. **41**, 651-665 (2013).
9. B. Jiang, J. Zheng, S. Qiu, M. Wu, Q. Zhang, Z. Yan, and Q. Xue, "Review on electrical discharge plasma technology for wastewater remediation," Chem. Eng. J. **236**, 348-368 (2014).
10. J. F. Waymouth and F. Bitter, "Analysis of the plasma of fluorescent lamps," J. Appl. Phys. **27**, 122-131 (1956).
11. F. Reymond, J. S. Rossier and H. H. Girault, "Polymer microchips bonded by O2-plasma activation," Electrophor. **23**, 782-790 (2002).
12. K. Haubert, T. Drier and D. Beebe, "PDMS bonding by means of a portable, low-cost corona system," Lab Chip **6**, 1548-1549 (2006).
13. N. Ferrell, R. R. Desai, A. J. Fleischman, S. Roy, H. D. Humes, and W. H. Fissell, "A microfluidic bioreactor with integrated transepithelial electrical resistance (TEER) measurement electrodes for evaluation of renal epithelial cells," Biotechnol. Bioeng. **107**, 707-716 (2010).
14. M. Kamruzzaman, A.-M. Alam, K. M. Kim, S. H. Lee, Y. H. Kim, G.-M. Kim, and T. D. Dang, "Microfluidic chip based chemiluminescence detection of L-phenylalanine in pharmaceutical and soft drinks," Food Chem. **135**, 57-62 (2012).
15. H. N. Chan, Y. Chen, Y. Shu, Y. Chen, Q. Tian, and H. Wu, "Direct, one-step molding of 3D-printed structures for convenient fabrication of truly 3D PDMS microfluidic chips," Microfluid. Nanofluid. **19**, 9-18 (2015).
16. T. Shimizu, B. Steffes, R. Pompl, F. Jamitzky, W. Bunk, K. Ramrath, M. Georgi, W. Stolz, H.-U. Schmidt, T. Urayama, S. Fujii, and G. E. Morfill, "Characterization of microwave plasma torch for decontamination," Plasma Process. Polym. **5**, 577-582 (2008).
17. A. Popelka, I. Novák, M. Lehocký, I. Chodák, J. Sedliačik, M. Gajtanska, M. Sedliačiková, A. Vesel, I. Junkar, A. Kleinová, M. Špírková, and F. Bílek, "Anti-bacterial treatment of polyethylene by cold plasma for medical purposes," Molecules **17**, 762-785 (2012).
18. J. Schlegel, J. Köritzer, and V. Boxhammer, "Plasma in cancer treatment," Clin. Plasma Med. **1**, 2-7 (2013).
19. G. Isbary, T. Shimizu, Y. F. Li, W. Stolz, H. M. Thomas, G. E. Morfill, and J. L. Zimmermann, "Cold atmospheric plasma devices for medical issues," Expert Rev. Med. Devices **10**, 367-377 (2013).
20. T. Von Woedtke, H. R. Metelmann, and K. D. Weltmann, "Clinical plasma medicine: state and perspectives of in vivo application of cold atmospheric plasma," Contrib. Plasm. Phys. **54**, 104-117 (2014).
21. X. Zhu, K. S. Chian, M. B. E. Chan-Park, and S. T. Lee, "Effect of argon-plasma treatment on proliferation of human-skin-derived fibroblast on chitosan membrane in vitro," J. Biomed. Mater. Res. A **73**, 264-274 (2005).
22. O. Lademann, H. Richter, M. C. Meinke, A. Patzelt, A. Kramer, P. Hinz, K.-D. Weltmann, B. Hartmann, and S. Koch, "Drug delivery through the skin barrier enhanced by treatment with tissue-tolerable plasma," Exp. Dermatol. **20**, 488-490 (2011).
23. S. Rupf, A. Lehmann, M. Hanning, B. Schäfer, A. Schubert, U. Feldmann, and A. Schindler, "Killing of adherent oral microbes by a non-thermal atmospheric plasma jet," J. Med. Microbiol. **59**, 206-212 (2010).
24. M. A. Bogle, K. A. Arndt, and J. S. Dover, "Evaluation of plasma skin regeneration technology in low-energy full-facial rejuvenation," Arch. Dermatol. **143**, 168-174 (2007).
25. K. D. Weltmann, E. Kindel, T. von Woedtke, M. Hähnel, M. Stieber, and R. Brandenburg, "Atmospheric-pressure plasma sources: prospective tools for plasma medicine," Pure Appl. Chem. **82**, 1223-1237 (2010).
26. J. Heinlin, G. Morfill, M. Landthaler, W. Stolz, G. Isbary, J. Zimmermann, T. Shimizu, and S. Karrer, "Plasma medicine: possible applications in dermatology," J. Dtsch. Dermatol. Ges. **8**, 968-976 (2010).
27. IEC 60601-1: changes from 2nd to 3rd edition, Intertek, 2008.
28. D. Dobrynin, A. Wu, S. Kalghatgi, S. Park, N. Shainsky, K. Wasko, E. Dumani, R. Ownbey, S. Joshi, R. Sensnig, and A. D. Brooks, "Live pig skin tissue and wound toxicity of cold plasma treatment," Plasma Med. **1**, 93-108 (2011).
29. K. Knoerzer, A. B. Murphy, M. Fresewinkel, P. Sanguansri, and J. Coventry, "Evaluation of methods for determining food surface temperature in the presence of low-pressure cool plasma," Inno. Food Sci. Emerg. Technol. **15**, 23-30 (2012).
30. C. A. Balaras and A. A. Argiriou, "Infrared thermography for building diagnostics," Energy Build. **34**, 171-183 (2002).
31. A. M. Ovechkin and G. Yoon, "Infrared imaging for screening breast cancer metastasis based on abnormal temperature distribution," J. Opt. Soc. Korea **9**, 157-161 (2005).
32. H. G. Jones, "Application of thermal imaging and infrared sensing in plant physiology and ecophysiology," Adv. Bot. Res. **41**, 107-163 (2004).