(54) Title: METHOD OF PREDICTING ULTRAVIOLET IRRADIANCE

(57) Abstract: A method of predicting ultraviolet irradiance on at least indirectly-illuminated surfaces of interior rooms of complex shape and containing complexly reflecting surfaces, using computer simulation of sufficiently similar rooms and surfaces and simulated ultraviolet emission sources sufficiently calibrated to real sources, and adjusting an ultraviolet device until desired targeted surfaces in the room have achieved a predicted accumulation of ultraviolet irradiance.
Published:

— with international search report (Art. 21(3))
METHOD OF PREDICTING ULTRAVIOLET IRRADIANCE

CLAIM OF PRIORITY


TECHNICAL FIELD

[0002] The present invention relates generally to predicting and optimizing the application of ultraviolet light in an enclosed space, including ultraviolet-C (UVC), more particularly, a method of predicting UV irradiance.

BACKGROUND

[0003] Ultraviolet light is used in many applications including disinfection of surfaces, water and air, curing of coatings, photocatalysis, and other uses. Ultraviolet light is often used in at least partially enclosed spaces often with multiple surfaces such as walls, barriers, and other objects. The surfaces in these spaces often interact with ultraviolet light much differently than the same surfaces interact with visible light.

[0004] U.S. Patent 8,841,634 teaches an Ultraviolet Germicidal Irradiation (UVGI) disinfection process utilizing a ring of cylinder-shaped housings containing UVC lamps. U.S. Patent 8,841,634 also teaches a configurable UVC emission field by increasing or decreasing individual lamps based on information from corresponding UVC radiometric sensors.

[0005] U.S. Patents 6,656,424 and 6,911,177 teach a plurality of vertical UVC lamps in a ring with a plurality of UVC radiometric sensors on the top of the lamp assembly. The device continues to power all lamps until all of the sensors have received a desired amount of only reflected UVC light.

[0006] U.S. Patent 8,816,301 teaches a ring of slanted lamps with and without reflectors, and a mechanism to move lamps and reflectors in order to focus UVC within a vertical band.
U.S. Patent 8,105,532 teaches a UVC light sterilizing wand utilizing a distance sensor to calculate accumulated direct UVC light irradiance, including an indicator to the user when said accumulated irradiance, or dosage of UVC light, has been achieved.

**SUMMARY OF THE INVENTION**

In accordance with the invention, a method of predicting UV irradiance on at least indirectly-illuminated surfaces of interior rooms of complex shape and complexly reflecting surfaces, using computer simulation of sufficiently similar rooms and surfaces and simulated UV emission sources sufficiently calibrated to real sources, and adjusting a UV device until desired targeted surfaces in the room have achieved a predicted accumulation of UV irradiance.

The present inventors have recognized, among other things, that a problem to be solved includes actively predicting the level of UVC disinfection for surfaces in enclosed spaces. Mobile UVC devices in the prior art ineffectively disinfect an enclosed space, especially surfaces not in direct light of the device. Operators of mobile UVC devices are not able to predict which surfaces, external to the device, and not in the direct light of the device will achieve the desired level of disinfection. It can be desirable that a mobile UVC disinfection device be placed in a location and be activated for sufficient length of time with a sufficient UVC intensity to effectively disinfect nearly all surfaces in an enclosed space that are desired to be disinfected, but present methods only predict surfaces in direct light of the device or surfaces corresponding to UVC radiometric sensor measurements. Operators of fixed-mount, immobile, UVC lighting systems are not able to predict which surfaces, external to the system, and not in the direct light of the system’s UVC lights, will achieve a desired level of disinfection.

One approach to predicting the amount of UVC that is incident on a surface in an enclosed space is to determine the light fall-off from the emissive area of the UVC device from the UVC device emitter to the targeted surface. This calculation using fall off is for direct light only. Furthermore, simply measuring direct distance does not account for reduced UVC irradiance caused by objects that occlude at least part of the emissive area of the UVC lamps, such as a bed in a hospital room which can block some of the UVC light from targeted surfaces beyond the bed. In this instance where objects occlude a portion of the UVC lamps, a calculation of UVC irradiance based on distance would not properly reduce said calculated irradiance by the amount of total UVC blocked by the occlusion, thus overestimated the UVC irradiance at the surface. Approaches to UVC disinfection of water can incorporate computer simulation but these approaches uses measurements and calculations for fixed mount lamps inside unchanging
metal reactors of simple form, typically without occlusions. This approach does not solve the problem of achieving a desired accumulated UVC irradiance, corresponding to a predicted UVC surface disinfection dose, on target surfaces in interior rooms because it cannot account for the complex objects which can occlude, reflect, refract, scatter or absorb UVC light in interior rooms.

[0011] One approach to predict both direct and indirect UVC that is incident on a surface in an enclosed space is to use computational fluid dynamics (CFD) mathematics with a computer simulation. This CFD approach is a costly and complex approach that does not reliably predict complex surfaces or multiple surfaces of varying levels of UVC light scattering, reflection and absorption. CFD is utilized for highly reflective metal vessels of simple and consistent form, with direct UVC illumination used in UV water treatment. Approaches to try to utilize CFD to predict UV irradiance on multiple surfaces within complex interior rooms with complex objects and complexly reflective surfaces resulted in undesirable ray effects contaminating the data on many modeled surfaces. Moreover attempts to use CFD for complex rooms such as modeling hospitals rooms for UVC disinfection studies required greatly simplified model geometries, and did not produce the level of predictive accuracy across the intensity ranges (orders of magnitude of irradiance) needed for UVC disinfection prediction.

[0012] Approaches to try to predict both direct and indirect human visible light that is incident on surfaces in an enclosed space using ray tracing algorithms in render engines of 3D modelling programs do not predict ultraviolet light interactions with complex surfaces or multiple surfaces of varying levels of UVC light scattering, reflection, and absorption. Another approach is use UVC radiometric sensors in the enclosed space but this does not accurately predict UVC irradiance on an incident surface that is not precisely where the sensor is located, nor does it predict UVC irradiance, and therefore UVC disinfection, in another surface location or another enclosed space. In an example, the present subject matter can provide a solution to this problem, such as by a functional method which predicts the amount of UVC light that is incident on surfaces in an enclosed space containing occlusions and diffuse reflections.

[0013] The present inventors have recognized, among other things, that a problem to be solved includes determining the best location to place a mobile UVC device in an enclosed space. One approach to determine UVC device placement within an enclosed space is simply to advocate that it be centered in the room, or placed central between a wall of the space and an object such as a bed in a hospital patient room. This center placement, and similar rule-of-thumb general
guidelines, do not allow an operator to target specific surfaces in the room. In an example, the present subject matter can provide a solution to this problem, such as by a functional method which determines the effects of placement of a mobile UVC device on the disinfection level of multiple surfaces.

[0014] The present inventors have recognized, among other things, that a problem to be solved includes determining the appropriate amount of time that a mobile UVC device in an enclosed space should illuminate the enclosed space for a given device location. One approach to determine UVC device illumination time in an enclosed space is to use sensors and a microprocessor control system which keeps the UVC device lamps powered on until one or all sensors have accumulated a desired UVC irradiance deemed equivalent to a predicted UVC disinfection dose. This approach only determines UVC irradiance, and therefore predicts UVC disinfection, only on the small detectors of the sensors used to measure said predicted dose. This approach doesn’t determine UVC irradiance, or dose, on any other surface in the room. Other approaches to treatment time are based on predicted direct light irradiance on surfaces at certain distances from the device. This approach does not determine UVC irradiance on indirectly illuminated surfaces that require the UVC light to reflect or scatter from at least one other surface before becoming incident on the targeted surface. In an example, the present subject matter can provide a solution to this problem, such as by a functional method which determines the effects of time of UVC illumination of a mobile UVC device in a location in an enclosed space, on the predicted disinfection level of multiple surfaces.

BRIEF DESCRIPTION OF DRAWINGS

[0015] Figure 1 shows an embodiment of the invention.

[0016] Figure 2 shows the results of prior art methods of simulation for direct and indirect UV light.

[0017] Figure 3 shows the results of simulation of direct and indirect UV light using the teachings of this invention.

[0018] Figure 4 shows the results of prior art methods of simulation for indirect and partially occluded direct UV light.

[0019] Figure 5 shows the results of simulation of indirect and partially occluded UV light using the teachings of this invention.
DETAILED DESCRIPTION

[0020] References will now be made in detail to certain claims of the invention, examples of which are illustrated in the accompanying drawing. While the invention will be described in conjunction with the enumerated claims, it will be understood that they are not intended to limit those claims. On the contrary, the invention is intended to cover all alternatives, modifications, and equivalents, which can be included within the scope of the invention as defined by the claims.

[0021] References in the specification to “one embodiment”, “an embodiment”, “an example”, “another embodiment”, “a further embodiment”, “another further embodiment,” and the like, indicate that the embodiment described can include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one of ordinary skill in the art to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described.

[0022] In this document, the terms “a,” “an,” or “the” are used to include one or more than one unless the context clearly dictates otherwise. The term “or” is used to refer to a nonexclusive “or” unless otherwise indicated. In addition, it is to be understood that the phraseology or terminology employed herein, and not otherwise defined, is for the purpose of description only and not of limitation. Any use of section headings is intended to aid reading of the document and is not to be interpreted as limiting; information that is relevant to a section heading may occur within or outside of that particular section. Furthermore, all publications, patents, and patent documents referred to in this document are incorporated by reference herein in their entirety, as though individually incorporated by reference. In the event of inconsistent usages between this document and those documents so incorporated by reference, the usage in the incorporated reference should be considered supplementary to that of this document; for irreconcilable inconsistencies, the usage in this document controls.

[0023] The term “interior room” as used herein can include hospital patient, operating, or exam rooms, or hotel rooms, or cruise ship rooms, or rooms inside houses or apartments, or school rooms, or rooms within offices building, or interior spaces within a factory, processing plant,
kitchen or restaurant, or interior spaces in public buildings, or any space containing complex surfaces and objects.

[0024] The term “substantially” as used herein refers to a majority of, or mostly, as in at least about 50%, 60%, 70%, 80%, 90%, 95%, 96%, 97%, 98%, 99%, 99.5%, 99.9%, 99.99%, or at least about 99.999% or more.

[0025] The term “multiple” refers to two or more (e.g., 2, 3, 4, 5, 6, etc.)

[0026] The term “ultraviolet light” refers to electromagnetic radiation with a wavelength shorter than human-visible light, such as about 10 nm to about 400 nm.

[0027] The term “UVC” (e.g., ultraviolet C, short-wave ultraviolet, FAR-UV, deep UV) refers to the band of UV light between about 100 nm and about 300 nm. Further, a subset of UVC includes, UV light lying between the wavelengths of about 200 and about 300 nm, commonly referred to as the “germicidal region” because UV light in this region can inactivate microorganisms including, but not limited to, bacteria, protozoa, viruses, molds, yeasts, fungi, nematode eggs, or algae. An especially destructive wavelength of UV light is about 260 nm.

Germicidal UV lamps typically emit light with a wavelength that is substantially close to 260 nm for its destructive purposes, such as around typically around 254 nm.

[0028] The term “absorbing” refers to the process by which a photon is prevented from transmitting through, refracting, or reflecting from a material.

[0029] The term “visible” refers to optical properties of an object or process that occurs within the range of human vision, typically from about 400 to about 700 nanometers in wavelength.

[0030] The term “transparent” refers to a photon traveling through a material without being absorbed.

[0031] The term “light” refers to any form of electromagnetic radiation.

[0032] The term “specular reflection” refers to mirror-like reflection of light from a surface, in which light from a single incoming direction is reflected into a single outgoing direction.

[0033] The term “light scattering”, “diffusively reflect”, or “diffuse reflection” refers to reflection of light from a surface or sub-surface such that an incident ray is reflected or scattered at unpredictable angles.
[0034] The term “complex shape” refers to the shape of objects or interior spaces that are not uniform or easily predicted. Examples of complex shapes include interior rooms of human occupied dwellings, human utilized objects of specific of generalized function with multiple surfaces such as hospital beds, chairs, desks and other shapes.

[0035] The term “complexly reflective” refers to objects with ultraviolet reflection characteristics that are diffuse, or involve sub-surface scattering, or that involve wavelength dependent absorption in the ultraviolet ranges. Examples of complexly reflective surfaces include latex wall paints, plastic surfaces, fabrics, metals and other surfaces with diffuse reflection and some absorption in ultraviolet ranges. The term can refer to a complex nature of a given surface, such as a surface with a combination of specular and diffuse and absorption, or it can refer to objects with surfaces of varying reflection.

[0036] The term “render file” or “HDR file” or “file” used in context of a render engine output refers to the computational output of a brightness level for rendered surfaces. The computational output can take the form of an “*.HDR” file format but it can also refer to other high dynamic range file formats, or other file formats, or to the computed value within the program (and not a true file) which can be used by software code to execute steps of embodiments in an automated process.

[0037] Figure 1 shows an embodiment of the invention consisting of steps in the functional method. In the first step 10, radiometric sensor measurements of the UV light source is taken to produce a UV radiance map which accounts for the three-dimensional (3D) emission field complexity and UV light intensity fall off from the UV light source. The process can be performed in a generally absorbing space and by a space of known geometry and UV reflection. The sensor is placed in locations in direct light and can be placed in location of indirect light where UV light reflects from a surface of reflection. In the second step 20, a computer 3D model of the UV light sources, the sensor and any reflecting surfaces used in step 10 is created. In the third step 30, a render engine is used to generate a render file in preferably high dynamic range of the surfaces in the model corresponding to the sensor’s detection area. In the fourth step 40, the rendered brightness of the modeled surface of the modeled sensor is quantified. In step 50, the quantified brightness of the render in step 40 is mathematically transformed, by a transfer function including a multiplier containing a linear coefficient that can also contain a non-linear multiplier. In step 60, the numerical output of step 50 is compared to the specific sensor measure corresponding to the modeled conditions. In step 70, changes are made to the
transfer function or the model or the model’s materials or the render engine settings and steps 30-70 can be repeated as required. This iteration can continue until the step 60 demonstrates a predictive accuracy within a desired level. Steps 10 through 70 are referred to as the “calibration” steps. In the calibration steps, the light sources, the computer modeling settings, the render engine settings and the transfer function are established and locked down and “calibrated” for the predictive simulation described in the next steps. The adjustable settings that are locked down during calibration are not changed except for re-calibration.

[0038] In step 80, a 3D computer model calibrated under steps 10-70 is created containing a calibrated model of UV light sources in a modeled enclosed space and modeled target surfaces corresponding to real surfaces desired to have UV irradiance prediction with enclosed spaces sufficiently similar to the modeled enclosed spaces. In step 90, the target surfaces are selected within the 3D modeling program and render engine as designated for rendering, preferably in high dynamic range. In step 100 the surfaces are rendered. In step 110, the rendered surface’s brightness is quantified. In step 120, the quantified brightness is mathematically transferred to predicted UV irradiance via the transfer function derived in the calibration steps. In step 130, the 3D model is modified for at least one parameter, as just one example, the location of the UV light source, and the targeted surfaces are re-rendered, or optionally new targeted surfaces can be designated. In step 140, the outputs from the changed parameters in the model are compared. In step 150, the preferred output of the changes to the model parameter is identified. Steps 80-150 are referred to as the “simulation and optimization” steps.

[0039] Figures 2, 3, 4, and 5 shows the differences between prior art simulation methods and the teachings of this invention. In all Figures the Y axis is UV irradiance in W/m2, and the X axis represents surfaces in a real hospital room and the respective modeled surface. The numbers on the X axis of Figures 2 and 3 (numbered 1-14) correspond to like surfaces, as do the numbers of Figures 4 and 5 (numbered 1-6), but while Figures 4 and 5 are a subset of data of Figures 2 and 3, respectively, the numbering has been changed for illustration purposes. Figures 2 and 4 were created from data published in Improved the Effectiveness of Ultraviolet Germicidal Irradiation through Reflective Wall Coatings: Experimental and Modeling Based Assessments, published in Indoor and Built Environment, July 26, 2014. This paper represents the best attempt using the prior art to predict UV irradiance on surfaces in complex enclosed spaces with diffusely reflecting walls. This paper also describes the drawbacks of non-CFD simulation methods in the prior art. The data from Figures 2 and 4 was created using CFD methods, comparing simulation results to radiometric sensor measurements. Figures 3 and 5 were created using the same
hospital patient room for sensor measurement, and to create the 3D model, as described in the paper, but using the teachings of the present invention. In Figures 3 and 5, the term “LumaSim” refers a name of a software program created using the teachings of this invention. Comparing Figure 2 to Figure 3 shows the dramatic improvement in predicted accuracy from the prior art (CFD) to the teachings of this invention. Note that following the teachings of the present invention, in this example, provides predictive accuracy for five orders of magnitude of UV irradiance intensity, compared to predictive accuracy of 2 or less orders of magnitude of UV irradiance intensity using CFD. Furthermore, the irradiance range over which CFD was predictive was high levels of irradiance on surfaces in full direct “line of sight” UV light from the mobile UVC device used in the paper’s study. Predicting direct light can be calculated using the physics of light fall-off mitigated by the emissive area of the light source, so it is debatable what utility is gained from the time and expense of performing CFD for direct light prediction. Removing the directly lit surfaces further illustrates the dramatic improvement in predictive accuracy using the teachings of the invention. Figures 4 and 5 shows sensor measurements versus the prior art (Figure 4) and versus the teachings of this invention (Figure 5) for surfaces indirectly lit by reflections or surfaces partially occluded from a portion of the direct UV light by objects in the room. It should be apparent in Figure 4 that CFD methods are not suitable for accurately predicting irradiance on surfaces illuminated by indirect or partially occluded UV light in enclosed spaces such as described in the paper. Figure 5 shows the excellent predictive accuracy of UV irradiance on surfaces illuminated by indirect or partially occluded UV light using the teachings of this invention.

Measurement

[0040] UV light sources are specialty devices. Radiometric sensor measurement of the output of the desired UV light sources should account for the UV light, at the targeted UV wavelengths desired, emitting in all directions from the sources. Measurement of individual UV lamps can be measured with models of individual lamps of the form factor of the real lamp created during the calibration steps, or assemblies of lamps and reflectors can be measured, and a composite model with a combined equivalent emissive area created in the calibration steps. Alternatively, the manufacturer of the UV light sources can provide quantified measurements suitable to replace the first step 10. Multiple measurements of the UV intensity fall-off over distance can be taken and multiple rendering can be performed of corresponding distances within the model should be performed during the calibration steps, and iteration and adjustments within calibration until the predicted UV irradiance coming out of the transfer function sufficiently matches, with the
desired accuracy, across a broad range of intensities, preferably several orders of magnitude of intensity differences corresponding to different measured intensities. Inclusion of reflective surfaces, inclusion of specular, diffuse and combinations therein, and indirect sensor measurements and the corresponding models and rendering are steps in calibration to reduce the overall subsequent amount of iteration and adjustment needed. The calibration should be performed for direct light to account for the spatial irregularity of the UV light sources and the particular UV intensity fall-off, and the calibration steps should be performed for indirect light to determine other appropriate modeling and render engine settings.

Modeling

[0041] The inventors have found that many 3D modeling computer programs are sufficient to create the models in the steps of the invention. During the calibration steps, the model form and relative dimensions should correspond to the form and dimensions of the UV light sources, the sensor detector dimensions, form, and field of view, and the dimensions of any reflective surfaces present during measurement. The “materials” or surfaces on the mesh of the objects in the models must be adjusted to fit the surface finish and reflective characteristics of real surfaces used in the measurements. Real world measurement of the UV reflective characteristics of the surfaces to be modeled can be performed with UV-Vis spectrophotometry. A scaling factor, including whether non-linearity exits, is derived for the “materials” or modeled surfaces within the modeling program or the render engine which scales the adjustable value for absorption, diffuse component of reflection, specular component of reflection, and other adjustable settings as part of the iteration during calibration. Once this scaling factor is known, it is part of the settings that are locked down during calibration and are not changed during simulation and optimization unless re-calibration is needed.

Calibration

[0042] Calibration can be a performed many times, with small and large adjustments made during each cycle though some or all of the steps. The order of the steps of calibration in Figure 1 are the order of one embodiment but other embodiments are possible. In one embodiment, the measurement step 10 could be derived from manufacturer’s data. In another embodiment, an already calibrated simulation system of the invention could be used to create a UV light source and the output of the transfer function used to build a field and fall-off mapping of the new UV light source. In another embodiment several parallel simulations, each with changes to various adjustable settings of the model, render engine or transfer function could be performed, as an
example as a multi-factorial experiment design, to reduce the amount of iteration to achieve predictive accuracy. In another embodiment, the calibration steps could be partially or fully incorporated into the simulation and optimization steps, though this approach can dramatically increase the necessary iteration and should be anchored to external measurements for validation that desired accuracy was eventually achieved.

Rendering

[0043] Render engines can be unbiased tracing algorithms, including physics-based stochastic path tracing. Computationally efficient approximations or compositing techniques, such as irradiance caching, and other techniques, can be used provided that care is taken to understand the effects of these techniques on accuracy and fidelity of the simulation. Modeled material surfaces should accurately simulate the interaction with the surface and the desired UV wavelengths. A modeled surface, such as a glass window for example, can have different render engine surface settings for UVA then for UVC. In many cases, real world measurements of reflection and scattering may be performed on the surface materials desired to be modeled.

[0044] Rendering can be in high dynamic range to allow for the teachings of the invention to account for the potentially many orders of magnitude of irradiance on surfaces in complex spaces with complexly reflective surfaces. In one embodiment, the rendering creates HRD files of a target region of a surface on an object in the model corresponding to a specific location in the real world, as an example on a specific part of a doorknob of a hospital patient room. In another embodiment, the target surfaces are chosen as an array with sizes as small as the pixels of the render engine settings and the render engine is modified or additional programming is created to render irradiance of each target as a rendered gradient on desired surfaces as a grayscale gradient or false color grid, preferably overlaying the render such that it is clearly understood by the user what UV irradiance is being achieved on the surfaces in the enclosed space. In this embodiment, the transfer function is applied to each pixel and the false color or gray scaling is scaled to predictive UV irradiance numbers.

Transfer Function

[0045] The transfer function is a means to covert the pixel brightness measured from the rendered target surfaces to the units of measure for the predictive irradiance. In one embodiment, floating point decimal average brightness of an HDR render file is calculated. This average brightness is multiplied by a linear coefficient with an optional non-linear factor to
convert the number corresponding to average pixel brightness of the HRD file to microwatts per second per square centimeter, a unit of measure of irradiance. Several methods exist to quantify rendered brightness that can be suitable for the invention. Irradiance is energy within a time over an area and can be expressed in many units. The inventors have determined that using the teachings of this invention, with render engines using unbiased tracing algorithms, preferably physics-based stochastic path tracing, that strictly linear coefficients for transfer functions are possible. Small errors in the scaling function relating real surface diffuse or specular reflection to the adjustable settings in the modeling program or render engine can require derived non-linear correction factors to maintain simulation prediction across the desired orders of magnitude of high dynamic range intensity within the desired accuracy.

Simulation and Optimization

[0046] The thirteenth step 130 of an embodiment shows that model parameters can be adjusted for subsequent comparison 140 and optimization 150. It should be apparent that these parameters are referring to changes in the model not related to calibration. If changes are made to the render engine, some modeled surfaces, scaling factors of model or render surface "materials" or the transfer function then the calibration may change, and as such these changes are part of calibration and re-calibration steps. The parameters changed in optimization include, as examples, parameters like the location of the UV light sources, the target surfaces, the location of objects within the modeled enclosed space, the dimension of the enclosed space, and other parameters that may be desired to be explored or optimized which do not change the calibration of the simulation. In another example parameters to be investigated may be outside the model such as time factors.

[0047] In one example of optimization, it may be desirable to determine the optimal placement of a mobile UVC disinfection device within a hospital patient room. In this example, the optimal placement may be based on achieving a desired amount of UVC irradiance, and therefore predicted UVC disinfection on a maximal number of surfaces, or specific surfaces. In this example the model is modified to include multiple locations of a calibrated UVC light source consistent with the mobile UVC device. The calculated irradiance for each targeted area is examined for each modeled device location and the optimal placement is determined.

[0048] In another example of optimization, it may be desirable to determine the optimal disinfection treatment time, or how long to maintain UV illumination, of a mobile UVC disinfection device within a hospital patient room in one or more placement locations within the
room. The optimal time may be based on achieving a desired amount of UVC irradiance, and therefore predicted UVC disinfection on a maximal number of surfaces, or specific surfaces. In this example the model data is modified to convert irradiance per unit of time to accumulated irradiance corresponding to an accumulated predicted UVC disinfection dose per targeted surfaces, and the optimal disinfection time is determined.

[0049] Another example of optimization includes determining the best two combined locations of a UV light source which achieve the highest number of targeted surfaces at a desired predicted UVC disinfection dose.

[0050] Other outcomes of the fifteenth step 150 do not have to be optimizations of parameters, but can be investigations to discover the predicted effects of changing certain parameters. For example the effect of increased distance between a targeted surface and modeled UV light sources may be desired to be investigated. Another example of the use of the simulation and optimization steps includes the design of new UV lights sources and subsequent inclusion of those modeled UV light sources in further simulations.

[0051] The present invention allows for accurate prediction of UV irradiance on surfaces in complex spaces across several orders of magnitude of UV irradiance intensity. As such the application of the teachings of this invention can include any number of simulations.

[0052] It should be apparent that the teachings of this invention are not limited to the steps outlined in Figure 1. Figure 1 shows an embodiment but the teachings of this invention allow for alternative steps and alternative sequences of steps and parallel execution of steps or the merging or elimination of some steps. Some steps can be manual performed. Any steps can be part of a more automated process. Any number of ways to illustrate the output of the renderings, or the predicted irradiance, on modeled surfaces, or other outputs, is possible. The teachings of this invention can be applied to any number of problems that accurate simulation of ultraviolet can help solve. The teachings of this invention can also be applied to wavelengths outside of ultraviolet.

[0053] In another example embodiment, the optimization step is utilized to conceive, design or virtually verify devices. In a further embodiment the layout of UV lights in enclosed spaces can be optimized. In another further embodiment, a mobile UVC device can be designed using the teachings of this invention. In another further embodiment application protocols or guidelines for UVC disinfection can be derived and created from the teachings of this invention. Another
example of an embodiment includes using the teachings of this invention to design and iterate a UV reflector to achieve a desired output. An example of a desired output of an embodiment using the teachings of this invention for UV reflector design is a mobile UV device with multiple UV lamps and reflector mast designed and virtually validated to produce a uniform radial field of UV intensity. Another example would be designing and virtually validating the placement of UV lamps in fixed location of a room in a hospital, such as a patient room or operating room, to achieve desired UVC irradiance levels on targeted surfaces. Another example would be performing a sequence of simulations of rooms of various sizes with surfaces of various UVC reflectivity with various objects in the rooms with various orientation with a mobile UVC device or devices in various locations for varying times or UVC intensities, while simulating the UVC irradiance on targeted surfaces to produce guidelines or protocols, for example protocols indicating best placement locations and treatment times for the mobile UVC device for specific or general room configurations, to aid in UVC disinfection efforts. Another example would be using UV simulation when designing and virtually verifying a hospital bed, or other object uses in a healthcare environment, to incorporated elements into the design which facilitate surface UV disinfection.

EXAMPLE 1

[0054] A computer model of a mobile UVC device within a model of a hospital patient room. The 3D modeling program, Blender, with a render engine, Cycles, containing a model of a UVC light source calibrated by the teachings of this invention as part of the model of the mobile UVC device. Adjustments to the model surface material settings in Blender and Cycles made in accordance to a derived scaling factor. A C-code executable which imports the render outputs of Cycles and applies a derived transfer function to convert rendered brightness in HDR to UVC irradiance in microwatts per second per square centimeters. The C-code executable contains optimization algorithms to allow the user to determine the best combination of multiple chosen factors including device location, disinfection time, predicted dose, percent of targets at predicted dose and other factors and combinations of factors.
CLAIMS

1. A method of predicting ultraviolet irradiance on at least one surface illuminated by at least indirect or partially occluded direct ultraviolet light, within an at least partially enclosed space of complex shape, comprising the step of creating a calibrated model containing at least one ultraviolet light source.

2. The method of claim 1, wherein the space contains at least one object of complex shape.

3. The method of claim 1, wherein the predictive accuracy is maintained for more than two orders of magnitude of predicted ultraviolet irradiance, measured in microwatts per second per square centimeter.

4. The method of claim 1, wherein said ultraviolet light is ultraviolet-C.

5. The method of claim 1, wherein the predicted ultraviolet irradiance corresponds to a predicted ultraviolet disinfection dose on the surface.

6. The method of claim 1, further comprising the step of designing an ultraviolet device.

7. The method of claim 6, wherein said device is an ultraviolet-C disinfection device.

8. The method of claim 7, wherein said device is a mobile ultraviolet-C disinfection device.

9. The method of ultraviolet disinfection of Claim 1, further comprising the step of determining placement of at least one ultraviolet light source.

10. The method of ultraviolet disinfection of Claim 1, further comprising the step of determining the amount of disinfection time for at least one ultraviolet light source.

11. The method of ultraviolet disinfection of Claim 1, further comprising the step of optimizing a parameter of a model of the space.

12. The method of claim 1, wherein the steps do not utilize computational fluid dynamics.
13. The method of claim 1, wherein the steps utilize unbiased tracing algorithms.

14. The method of claim 13, wherein the steps utilize physics-based stochastic path tracing.

15. An ultraviolet device created using method of predicting ultraviolet irradiance on at least one surface illuminated by at least indirect or partially occluded direct ultraviolet light, within an at least partially enclosed space of complex shape, comprising the step of creating a calibrated model containing at least one ultraviolet light source.

16. The device of claim 15, wherein said device is an ultraviolet-C disinfection device.

17. The device of claim 16, wherein said device is a mobile ultraviolet-C disinfection device.
1. A method of predicting ultraviolet irradiance on at least one surface illuminated by at least indirect or partially occluded direct ultraviolet light, within an at least a partially enclosed space of complex shape, comprising the steps of creating a calibrated computer simulation model containing at least one ultraviolet light source; and using the calibrated computer simulation model to predict a level of ultraviolet irradiance on the at least one surface, whereby the need to take an actual measurement of ultraviolet irradiance on the at least one surface is eliminated.

2. The method of claim 1, wherein the space contains at least one object of complex shape.

3. The method of claim 1, wherein a predictive accuracy is maintained for more than two orders of magnitude of predicted ultraviolet irradiance, measured in microwatts per second per square centimeter.

4. The method of claim 1, wherein said ultraviolet light is ultraviolet-C.

5. The method of claim 1, wherein the predicted ultraviolet irradiance corresponds to a predicted ultraviolet disinfection dose on the surface.

6. The method of claim 1, further comprising the step of designing an ultraviolet device.

7. The method of claim 6, wherein said device is an ultraviolet-C disinfection device.

8. The method of claim 7, wherein said device is a mobile ultraviolet-C disinfection device.

9. The method of ultraviolet disinfection of Claim 1, further comprising the step of determining placement of at least one ultraviolet light source.
10. The method of ultraviolet disinfection of Claim 1, further comprising the step of determining the amount of disinfection time for at least one ultraviolet light source.

11. The method of ultraviolet disinfection of Claim 1, further comprising the step of optimizing a parameter of a model of the space.

12. The method of claim 1, wherein the steps do not utilize computational fluid dynamics.

13. The method of claim 1, wherein the steps utilize unbiased tracing algorithms.

14. The method of claim 13, wherein the steps utilize physics-based stochastic path tracing.

15. An ultraviolet device created using a method of predicting ultraviolet irradiance on at least one surface illuminated by at least indirect or partially occluded direct ultraviolet light, within an at least partially enclosed space of complex shape, comprising the steps of creating a calibrated computer simulation model containing at least one ultraviolet light source; using the calibrated computer simulation model to predict a level of ultraviolet irradiance on the at least one surface; and using the predicted level of ultraviolet irradiance on the at least one surface to design the ultraviolet device such that it achieves the predicted level of ultraviolet irradiance on the at least one surface, whereby the need to take an actual measurement of ultraviolet irradiance on the at least one surface is eliminated.

16. The device of claim 15, wherein said device is an ultraviolet-C disinfection device.

17. The device of claim 16, wherein said device is a mobile ultraviolet-C disinfection device.
Accompanying the amendment filed concurrently or with, Applicant submits the following statement under Article 19 (1).

The Harmon reference cited by the Examiner uses a handheld UVC measurement device to take actual, manual measurements of UVC light at various points in a room. The Applicant’s invention is actually the opposite of the method taught in Harmon. In the Applicant’s invention, a computer simulation is used to avoid having to take any actual measurements at all. In the version of Claims 1 and 15 as originally submitted, the term “calibrated model” was used to refer to the computer simulation mentioned herein. It is possible that the term “calibrated model” could be misinterpreted to refer to a physical model of a room or similar environment created by taking individual measurements in the actual room. Claims 1 and 15 have been amended by replacing the term “calibrated model” with “calibrated computer simulation model”, and a second step has been added to the method described in each claim to further distinguish the invention as a computer simulated model, not a physical model constructed of numeric measurements.

Additional minor amendments have been made to these and other claims to overcome defects in form.

These amended claims distinguish the Applicant’s claims from the prior art of record (as identified in the written opinion of the International Searching Authority).
10 Measure UV light source with sensor
20 Model UV light source and sensor surface
30 Render Surfaces
40 Quantify Render Brightness in HDR
50 Apply Transfer Function
60 Compare Transfer Function Output to Measure
70 Adjust Model, Render Engine, or Transfer Function
80 Model enclosed space containing UV light source
90 Designate Target Surfaces
100 Render Surfaces
110 Quantify Render Brightness in HDR
120 Apply Transfer Function
130 Adjust model parameter
140 Compare Transfer Function Outputs
150 Determine preferred output of the changed parameter

Fig. 1
Fig. 2
Prior Art
Fig. 4

Prior Art
INTERNATIONAL SEARCH REPORT

International application No.
PCT/US15/13871

A. CLASSIFICATION OF SUBJECT MATTER
IPC(B) - A61L 2/08, 2/10; C20F 1/32 (2015.01)
CPC - A61L 2/08, 2/10; C20F 1/32
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(B): A61L 2/02, 2/06, 2/10; C20F 1/32 (2015.01)
CPC: A61L 2/02, 2/06, 2/10; C20F 1/32

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); Google; Google Scholar; ProQuest; KEYWORDS: predict ultraviolet irradiance surface indirect partially occluded enclosed space complex shape calibrated model light source object disinfection dose

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category*</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>US 2010/0104471 A1 (HARMON, N. et al.) April 29, 2010; figure 2; paragraphs [0006, 0041]; claims 1 and 14</td>
<td>1-12, 15-17</td>
</tr>
<tr>
<td>Y</td>
<td>US 8,085,267 B2 (BROWN, J. et al.) December 27, 2011; column 17, line 63 to column 18, line 4</td>
<td>13-14</td>
</tr>
<tr>
<td>A</td>
<td>US 2013/0280126 A1 (INFECTION PREVENTION TECHNOLOGIES) October 24, 2013; entire document</td>
<td>1-17</td>
</tr>
</tbody>
</table>

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"G" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"I" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 30 March 2015 (30.03.2015)
Date of mailing of the international search report 15 APR 2015

Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201

Authorized officer Shane Thomas
PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (January 2015)