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# THE HISTORY OF FORMING VISUAL-COMMUNICATIVE COMPONENTS OF A NIGHT CITY LIGHT MEDIUM

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**Abstract**
The history of development of light and information illumination is considered, its separation into navigation, commercial and social lighting is traced. The importance of its influence on forming a light-and-colour medium of a city is analysed.

**Keywords:** city medium, light-and-colour medium, visual communications, light-and-information illumination, light advertising, orientation, navigation visual-communicative systems

The first attempts of designing city illumination as a comprehensive system can be traces to the 1960s and '70s. Precisely during this period, the principles of the light-and-colour arrangement of the architectural medium, meeting functional and aesthetic requirements, were substantiated. At the same time, a struggle against light advertising began in some European capitals. Wide application of light advertising led to considerable "light pollution" in London, Paris, Brussels, Stockholm etc. [1, p. 61, 63]. However, preconditions for the light chaos of big cities were formed at the end of the nineteenth and beginning of the twentieth centuries.

The first devices for city illumination in Russia were gas street lanterns and number lanterns on houses (Fig. 1). They provided functional and information (navigation) illumination of streets in the middle of the 19th century. Later, light became a part of outdoor advertising, very quickly becoming a dominant feature of nighttime cities and outshining the functional and navigation illumination because of its luminance and dynamics.

In the latter half of the nineteenth century, following gas lanterns for street illumination, in St. Petersburg, number lanterns with matte glass and black figs. appeared. These were hung out at gates and entrances on front facades of buildings, and at the end of the nineteenth century, they became a city standard [2].

A requirement for advertising arises in Russia during Peter's reform period. And the development of this type of visual communication began in the eighteenth and in the first half of the nineteenth centuries [3, p. 13–15]. Initially, advertising information was distributed using applied graphics facilities, the main forms of which were engravings and cheap popular prints. Russian signboards were based, to a large extent, on the medieval European tradition. The first original signboards arose during the reign of Catherine II, with the appearance


*Fig. 1. A number lantern, St. Petersburg, late 19 th – early 20 th century (illustration source: www.photoarchive.spb.ru)*

of shop banners [4, p. 5–6]. This innovation had a rapid development and quickly extended to the facades of buildings. In the 1750s, the placing and images of the signboards were regulated by government decrees, which required replacing "handwritten samples with font inscriptions" [4, p. 8]. Nevertheless, Russian handwritten signboards – being a unique cultural phenomenon – had a continued presence on the streets of Russian cities for more than a century and were only forced out with font at the beginning of the twentieth century.

In the middle of the nineteenth century, there were no luminous signboards and advertising in Moscow, and display windows were illuminated seldom and poorly: "their light did not even reach the sidewalks. Lanterns at entrances and gates of private residences and commercial apartment buildings as well as house number lanterns only gave weak light points." [5]. Additional, but not essential, devices for street illumination, were lanterns at entrances to commercial buildings. These often served as advertising [5].

At the turn of the twentieth centuries, along with handwriting and font signboards, outdoor light advertising appears in Russia. At the end of the nineteenth century, light came to be used intensely in city advertising in St. Petersburg: "… beautiful signboards and display windows are everywhere. They are imitations of shops of Gostinyi dvor, where lighting effects, various stars by means of electric bulbs, especially in windows of jewelry shops" were used [3, p. 99]. Passages and supermarkets came to replace little shops. "Instead of painted pictures, specific attention is given to "exhibition display windows", which are illuminated now with electricity and kerosene. In the meantime, signboards with luminous letters, announcement posts and columns appeared", [4, p. 8–9]. In the streets of Moscow "lighted signboards" also appeared. They represented arm boxes surrounded along their perimeters with a garland of electric bulbs [6, p. 221]. The first light advertising in Moscow appeared in 1885 on the Popov's passage building facade in Kuznetsky most street. "At the entrance, electric bulbs lit up forming the word 'ПАССАЖЪ'", [7, p. 65]. There were also signboards on metal gauze, stretched over a frame with superimposed relief or with plain metal letters added with electric lamps along the perimeter of the letters and of the signboard itself. One such signboard was placed on the shop of a tea seller Perlov in Myasnitskaya street [8].

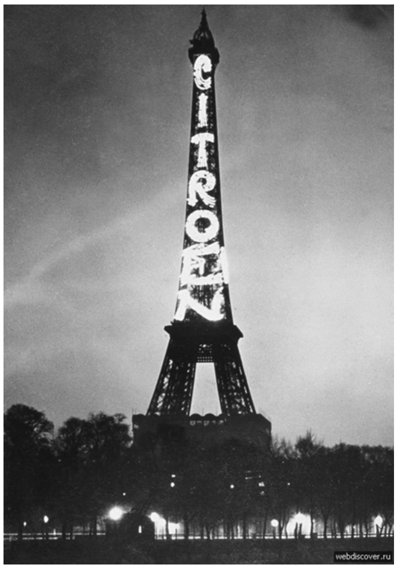


*Fig. 2. Tour d'Eiffel with a Citroen Company light advertising. Paris, 1925–1934 (illustration source: http://www.webdiscover.ru)*

At the beginning of the twentieth century, a peculiar glass crown in a metal frame was installed on gas lanterns illuminating city streets. Short advertising inscriptions were placed on the four pieces of glass. Due to the sophisticated structure of the envelope, the inscriptions were illuminated in the evening without throwing shadows on traffic ways and without disturbing when servicing the lantern [5].

Signboards, generally handwritten, and font, "clamorous" and superfluous, almost entirely covered the facades of buildings. In the 1900s, a question of style integrity and close interrelation of city advertising with town-building requirements and with specific architectural-and-art conditions arose [3, p. 133]. Beginning from this time, attempts to regulate advertising were undertaken in Russia at the state level [3, p. 200].

At the end of the nineteenth century, light advertising in Europe and in the USA developed intensively. In 1892 on Broadway in New York, for the first time in the USA (and most likely in the world), an incandescent lamp light tableau invented by T. Edison appeared. It advertised a popular resort Manhattan Beach [1, p. 51]. In the 1910s and '20s, in France and in the USA, the first gas-discharge (neon) advertising appeared, "which, as well as colour incandescent lamps, were operated in a dynamic mode" [1, p. 52]. A significant event was the emergence on the Eiffel Tower of "light-dynamics" advertising for *Citroën* impressive in size. Between 1925 and 1934, 30 metre tall letters shone from the tower (Fig. 2). Pe-

*Fig. 3. An announcement post. Observatory avenue. Paris, 1933. Photo© of Brassai (illustration source: http://1653.tumblr.com/post/2705050922/liquidnight-brassai-colonne-morris-avenue-de)*

riodically they were replaced with light “fireworks” and images of stars and of “running” sparks of the lines connecting them. This light show needed 250 thousand incandescent lamps and 600 km of electric wire. An American pilot Charles Lindberg was guided by this light during the last minutes of his legendary single nonstop transatlantic flight in 1927 [9].

In the epoch of gas lanterns, at the end of the nineteenth century, Paris showed unique examples of information tables combining lanterns and address into a uniform structure, which probably was a prototype for modern illuminated pointers. Some streets of a night city in the 1930s deserved separate attention: signboards, announcement posts and advertising, along with street illumination lanterns, filled the city with light, which formed a medium of unique imaginative characteristics. All of this was recorded by the photographer Brassai (Fig. 3).

In the 1920s in Germany, light advertising became a dominant feature of facade illumination. Its influence was so great that architectural facades were entirely lost to it, becoming “an advertising sign, a font and an illuminated panel” (Fig. 4). Due to efforts of German architects, this compositionally verified, laconic typographic was often a unique plastic element on a “sterile” functional style building facade [1, p. 52]. This “purity” was an essential difference of German advertising from superfluous, bright colour dynamics solutions sought in New York (Fig. 5), Paris, London and other European and American cities, which had led the light medium to


*Fig. 4. Shokken’s supermarket in Stuttgart. Germany, 1926–1928. Architect Erich Mendelsohn (illustration source: http://arx.novosibdom.ru/node/493)*

visual chaos in the second half of the twentieth century. In the 1930s, it became fashionable in the USA to illuminate commercial buildings without text advertising, which was a new unique experiment.

In the 1920s and ‘30s in Russia, the design of a medium for visual communications became more and more lapidary and “landmark”. Some projects, including light advertising and signboards, were made by A. Rodchenko and V. Mayakovsky [4, p. 148]. Visual communications became some kind of “architectural typography”, which organically supplemented the plastic arts of facades (Fig. 6).

In parallel with advertising, during the 1920s, propaganda and festive illumination developed. Illuminated typography on facades: “Workers of the world, unite”, “… anniversary of the October”, etc. was a part of festive architectural illumination of buildings. Such a “typographic” method during the Soviet period formed a light visual-communicative field creating additional light reference medium points on landmark architectural objects of cities for the holiday period.

Gas-discharge advertising, which appeared in the 1910s, due to the efforts of European and American light engineers, was extended in the 1930s to the Soviet Union. In 1932 in Moscow, the first gas-discharge installation “Garden” appeared over the entrance to a city park near Taganskaya square. It was manufactured by a factory of light-art works opened in 1930 within the external illumination Mosgorsvet trust of [10]. Initially, the palette of Soviet gas-discharge advertising was limited to three colours: neon generated orange-red glow, argon gave lavender, argon with mercury gave blue glow. In 1934, in order to widen the palette, the use of coloured glass as an optical filter appeared. For example, a tube of yellow glass filled with argon and mercury, generated green glow [10].) In 1935, the Mosgoroformlenie trust was established, which was tasked with external architectural, art and light decoration of the city. A factory of light-and-art works was included into the trust. In 1937 the factory began to manufacture brazed glass letters for gas-discharge signboards, and in ten years, due to the use of phosphor, their chromatic scale extended to twenty four colours. At the late 1940s "for the first time comprehensive solutions of gas-discharge advertising by a group of objects in a street or a square appeared" [10]. Gas-discharge letters obtained a widespread recognition in the 1960s, when signboards "Gastronome", "Produce", "Fish", "Meat", "Milk", etc. appeared on city streets, and in the 1970s these were supplemented with numerous political slogans.

The introduction of comprehensive projects by Moscow authorities, aiming to harmonise city advertising also had negative consequences. "By the middle of the 1980s, bright and original early night Moscow, represented a sad monotony of blue-white signboards mostly of a standard design. This sad fashion swiftly extended to other cities in the country" [10].

The visual-communicative medium of Soviet cities remained "silent" until the early 1990 s. The transition to a market economy provoked a natural advertising upsurge, which was unusual for city dwellers and caused light chaos. Opposition to these consequences continues to this day.

In parallel with commercial and social systems, navigation visual-communicative systems developed, primarily providing address information and information on city public transport.

New address signs inherited the full light tradition of house nineteenth century number lanterns.


*Fig. 5. New York. Times Square. The 1920$^{th}$ (illustration source: http://blog.thunderbaybooks.com/2011/09/picture-of-the-day-times-square-1920 s/nyc-at-night13–2/)*


*Fig. 6. Light visual communications in festive illumination. Illumination on November seventh, 1925, Moscow, Bolshoi theatre. Photo© of A.Rodchenko (illustration source: http://www.fresher.ru/2013/05/05/moskva-1925–1930-godov-v-obektive-aleksandra-rodchenko/)*

By 1924 about 25 000 address signs illuminated at nighttime were installed in Moscow [11, p. 75]. The signs were manufactured from enamelled metal, had round configuration with a trihedral roof-shaped cover, in which an electric bulb was placed. The street name was written in a circle in black against a white background. At the centre of the circle, the house number was written and duplicated with figs. at the top part of the sign. Thus, the bulb illuminated the whole sign field and allowed "shining" figs. on two roof-shaped cover sides being spaced from the wall, which made it possible to perceive the information at an angle and from any side of the street. Later on, these signs were extended over the whole country and actively operated until the nineteen eighties, and some signs are still used today.

Trams appeared in Russia at the beginning of the twentieth century. Originally, to designate their stops, cast iron columns for wires were used. Their bottom part was painted in white, with a vertical inscription of "Stop". Later in Moscow, the use of enamelled shields ruled into squares with numbers of passing trams began to designate stops. The pointer was placed on a separate support. Over the pointer a "roof" was mounted, under which an electric bulb illuminated the information during nighttimes [12] (Fig. 7). Stop pavilions appeared later. They were represented by different types of construction: open-aired, with a canopy and a bench; pavilions glazed from three sides; more large-scale pavilions placed on squares, which included office accommodations for the personnel and underground public lavatories [12].

*Fig. 7. A pointer of a tram stop. Beginning of the 20th century. Moscow (illustration source: http://www.signbusiness.ru/publications/history/1294-reklama-na-ostanovochnyh-pavilonah.php)*

One particular Moscow practice from the middle of the twentieth century deserves a special mention. This was the use of special lit curb stones for designation of tram stops. Besides the stop name, information on the fare, route plan, etc. was given on the curb stones. This effective method of stop identification was abandoned by city navigation arrangement practice for a long period. In today's Moscow examples of luminous signs are considerably inferior to their historical prototypes by their information value and art-aesthetic characteristics.

In modern practice, including European examples, for ground public transport stop designation, stop pavilions with luminous advertising and information modules are most often used. Due to these, the pavilions are illuminated, information on the routes, placed inside the structures, is sometimes illuminated as well. Most of the modern stops are equipped with electronic tableaux containing information on transport arrival time, and luminous identifying signs are rarely used (Düsseldorf, Amsterdam), unlike underground signs, which are illuminated in many cities of the world. Vivid illustrations of this historical accentuation tradition are the fanciful luminaires in the Art Nouveau style over pavilions of the Parisian underground metro, which were created by E. Gimar at the turn of the twentieth century.

Light visual-communicative components of a city medium, such as display windows, signboards, advertising installations of different types, navigation and social information, form a natural "light visual-communicative belt" [13] at a level of human sight. Commercial visual communications are placed on building facades at the ground and first floor height filling street space with chaotic bright light spots. Therefore, they demand a development of principal comprehensive approaches to their design and placing. Some regulating measures addressing this situation exist in many big cities, including Moscow and St. Petersburg. But the problem cannot be solved only through rationing and regulation.

*Fig. 8. A light curbstone designating a tram stop place. The stop name "Gorky Street", route plan, information on fare, etc. are specified on the curbstone. Moscow, circa mid 20 th century (illustration source: http://www.liveinternet.ru/community/2281209/post126068753/)*

Visual communications were always significant factors of forming the light-and-colour medium of a city. Dynamic historical development has created a complex reality, which complicates attempts to strictly regulate light-and-information illumination, because such an approach can deprive a city medium of its individuality and authenticity. Today, it is important to understand light-and-information illumination as a significant component of a comprehensively formed light-and-colour image of a city, because this image can be the basis of composition arrangement of the city. Such an "involvement" into the general structure is capable to level the negative influence of light-and-information illumination on the light medium and on its perception. In doing so, one of most prominent aspects of "intelligent" design is the separation of light visual communications into commercial, social and navigation. Unfortunately, today these are considered as an integrated whole. Separating these will allow objectively estimating the degree of influence of different visual-communicative systems on the light-and-colour medium and developing an effective approach to their rationing, design and contextual integration. The main objective of this approach is to form a complete, informative and at the same time, unique light image of a city.

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# ILLUMINATION OF NEW STATIONS OF THE MOSCOW UNDERGROUND

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**ABSTRACT**

The concept of modern interpretation of the architectural traditions of the Moscow underground and the use of new lighting technologies has been implemented in recent projects of the Metrogiprotrans Institute – the leading designer of the Moscow underground network of V.I. Lenin. This can be witnessed in the examples of six new underground stations: “Pyatnitskoye shosse”, “Alma-Atinskaya”, “Bittsevsky park”, “Novokosino”, “Zhulebino” and “Lermontovsky prospekt”.

**Keywords:** underground, architectural solutions, station, project, natural illumination, artificial illumination, luminaires, platform, entrance hall

The feeling of nature and safety, a harmony of functional purpose with artistic vision has been the tradition of the Metrogiprotrans Institute for more than eighty years of being the designer of the Moscow underground network of V.I. Lenin. Experience in design and construction allows specialists of Metrogiprotrans to perform at the highest professional level when implementing the programme of accelerated construction of new Moscow underground lines based on standard projects.

The implementation of new technologies and modern interpretations of architectural traditions of the Moscow underground can be seen in the examples of six new stations. These were designed under the direction of the main architect of the Metrogiprotrans, academician of the Russian Academy of Arts N.I. Shumakov:

– In the workshop of A.V. Nekrasov: Pyatnitskoye shosse station (architects E.V. Ilyin, A.L. Kurenbaev, V.Yu. Molchanov, S.A. Petrosyan, N.S. Trusilova, V.Z. Filippov, A.M. Shutov, D.V. Shchuchkin), Alma-Atinskaya station (E.V. Ilyina, A.L. Kurenbaev, V.Yu. Molchanov, G.S. Mun, A.M. Shutov) and Bittsevsky park station (A.V. Butusov, E.V. Ilyin, V.Yu. Molchanov, G.S. Mun, A.V. Nekrasov, E.V. Pavlova, A.A. Rasstegnyaev, D.V. Shchuchkin);

– In the workshop of L.L. Borzenkov: Novokosino station (architects M.V.Volovich, S.F. Kostikov, T.A. Nagieva, N.N. Soldatov, V.K. Uvarov), Zhulebiono and Lermontovsky prospect stations (M.V.Volovich, A.I.Vorontsova, O.A. Danilov, G.V. Dzhavadova, S.F. Kostikov, T.S. Nagieva, N.N. Soldatov, V. K. Uvarov).

All these stations are monolithic, subsurface: two of them are two-span stations of a rectangular cross-section with support on the central column, two are one-vaulted with a smooth vault, and two stations are one-vaulted with caissons. Each workshop used the all three structure types, and in doing so, no illumination methods were repeated anywhere.

Architects of the underground focused on creating a mood of security and comfort for the station passengers. A careful selection of luminaires and lighting methods allowed creating an impression of a light sunny day. Most significant places were accentuated with light both for architectural and artistic purposes, and according to the operation technology requirements.

Light in the underground not only illuminates, but also warns of danger. Platform edges are the most intensely illuminated places (not less than 250 lx). For passenger convenience and to prevent ac-

*Fig. 1. An example of a light-emitting diode strip*

cidents, self-luminous light-emitting diode stripes are installed along platforms at a distance of 600 mm from the edge to designate the dangerous area of the platform (Fig. 1). The stripe is glowing completely during the absence of a train. As the train approaches, there is a gong signal, and the light-emitting diode stripe gradually moves by 1.5 m sections. While the train is stopped, only point luminaires are glowing, which are installed with at 1.5 m intervals. When the train starts to move again, the light-emitting diode strip is switched on following the leaving train by sections of 1.5 m. An effect of light strip running synchronously with the train is achieved using a timer relay providing a timed sequence switching on and off of the light emitting diodes.

Near to the light-emitting diode strip, at a distance of 1200 mm from the platform edge, there is an additional safety line for passengers with disabilities; this is a restrictive tactile line, 100 mm in width and 5 mm in height.

Emergency illumination of steps is provided on all staircases. For visually impaired people, illuminant handrails made of stainless steel with built in light emitting diodes are installed. They are placed in two rows, at 900 and 650 mm from step level (Fig. 2).

*Fig. 2. Novokosino station. Interior of a pavilion over a stair approach to the underground*

Luminaires of the author's design, specially developed by architects to illuminate escalator tunnels, generate smooth reflected light, without blinding the escalator passengers. The luminaires are located in parallel with the escalator slope on supports inclined by 30°. Their fluorescent lamps (FL) shine through light-diffusing lattices simultaneously upwards on the vault and downwards onto the escalator handrail. As a result, a standard minimum of 100 lx is provided at step level (Fig. 3). The luminaire's structure allows for it to be turned by 90°, which is convenient for maintenance from the escalator steps.

*Fig. 3. View of an escalator descent with inclined stand lamps*

Lighting equipment for platforms, transfer hubs, entrance halls and pedestrian crossings was selected and/or developed together with Business Plus Light Open Company; a partner of the Metrogiprotrans.

Appearance and lighting characteristics of the luminaires are determined a set of established illumination standards, as well as the desire to maximise the visual effect, reflecting the architectural composition and strengthening a comprehensive pictorial image. Besides bespoke design luminaires, serial luminaires are also used in the stations. With the latter, some changes and additions to their geometry and fittings are often required. A special system of luminaire movement was developed for their convenient maintenance. This is used for the luminaires located over stair approaches of Novokosino station entrance halls. By means of a roller machine on the bus, the luminaire line of about 4 m length moves

*Fig. 4. Lermontovsky prospect station. A pavilion over a stair approach to the underground*

*Fig. 5. Pyatnitskoye shosse station. A radial luminaire at the platform end face*

from the stair approach area, where luminaire maintenance is constrained, to an area convenient for the service (Fig. 2).

At Zhulebino and Lermontovsky prospekt stations, linear luminaires of domestic production are used in their standard form with high efficiency FLs.

The stations designed by A. V. Nekrasov's workshop have one underground entrance hall and one aboveground, which are elliptic in configuration with big stained-glass windows; this allows combining artificial and natural light successfully. Station ensembles of the L.L. Borzenkov's workshop have two underground entrance halls, each with elaborate exit systems. Illumination of their underground crossings is standard: the luminaires should be anti-vandal and energy efficient. The height of the pedestrian crossing is 2.7 m from the floor to the ceiling. All exits feature identical pavilions with a coordinated illumination system. Luminous symbols with the letter "M" for metro are installed at the entrance to pavilion hubs over the roofs and at the staircase entrances (Fig. 4). The required number of evacuation light pointers is placed in the station ensemble service rooms.

One design feature of Pyatnitskoye shosse station, on the Mitino-Stroginskaya line, is the 162 m long station platform, which bends round in an arc. This feature was used when forming the station's architectural image (Fig. 5). The plasticity of the station is created using a ceiling with two lines of cornice covered illumination and with radial linear luminaires built in the counter ceiling. The luminaires are located in parallel with the horizontal axis of the station and due to the station bend, look like extended luminous arcs. The platform walls placed along the inner arc are covered with white marble, and the walls placed along the external arc – with black marble. The contrast remains in the covering of the floors and columns.

Escalators coming up from the station run into the central part of the aboveground entrance hall, which is elliptic in its configuration. Stained glass windows feature on two sides of the entrance hall; these open the entrance hall interior to be viewed from the outside. The windows connect the inner space with the surrounding landscape combining

*Fig. 6. Pyatnitskoye shosse station. Above-ground entrance hall #2. The ticket hall*

*Fig. 7. Alma-Atinskaya station. An entrance hall. Evening illumination*

*Fig. 8. Alma-Atinskaya station. An entrance hall. A radial luminaire*

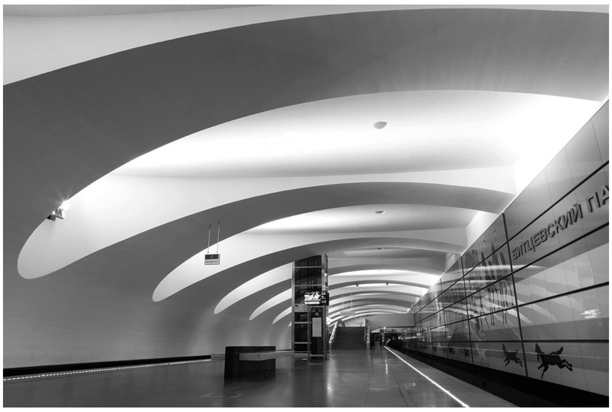

*Fig. 10. Bittsevsky park station. The platform*

*Fig. 9. Alma-Atinskaya station. The main light element of the station illumination*

natural and artificial light. Thin lines of luminaires are applied to illuminate the ticket hall using FLs located in parallel with the ellipse long axis, against a background of latticed counter ceilings (Fig. 6). Facade night time illumination is performed by means of luminaires with light emitting diodes. Thin lines on rotary arms are weightless and almost invisible in the daytime. At night, they encircle the entrance hall perimeter, accentuating the form.

The structure of the Alma-Atinskaya station entrance hall (Fig. 7) is similar. A terracotta coloured ceramic panel facade passes into the interior creating a vibrant and sunny combination with the entrance hall counter ceiling painted in blue. The main feature of the interior is a round luminaire made to look like a shanyrak, a traditional Kazakh circular dome topper for a yurt. This light radius system,7 m in diameter, has 9 cross connections and 12 straight lines for lamps. There are 30 *T5* FLs of 21 W in the circle, 24 FLs of 35 W and electron ballast. *PrevaLED Linear* light-emitting diode modules *OSRAM* are placed (Fig. 8) in the central crossing.

An important feature of the architectural solution of the entrance hall facades is the division of the wall's elliptic surface into two levels horizontally and the creation of rectangular sections, which are with a disturbed by level rhythm of light terracotta and dark metal facing with the night-time light emitting diode illumination.

Alma-Atinskaya station has the following dimensions: one-vaulted, 6 m in height, 10 m wide platform, 162 m long passenger platform. The illumination of the station platform is unusual. Vaulted poles, bright red in colour are used as luminaires. They are symbolic elements of a traditional Kazakh dwelling (Fig. 9). A spatial metal structure imitating such symbol represents two parabolic cantilever arcs, eleven metres in length, which have one support point on the platform. Between the arcs, fan-shaped guides of FL luminaires are placed. In addition, six searchlights are built into the top part to illuminate the areas between illumination structures with reflected light.

Extending the Butovskaya underground line from Starokachalovskaya Street to Novoyasenevskaya station on the Kaluzhsko-Rizhskaya line, places a station and a transfer hub to unload the existing Serpukhovsko-Timiryazevskaya line and improve transport services for the population of Northern and Southern Butovo districts.

Bittsevsky park station is designed with just one aboveground entrance hall, as there is also the possibility of exiting to the surface via Novoyasenevskaya station using the transfer hub crossing. The architectural solution of the platform section uses a brutal asymmetrical vault with extended caissons (Fig. 10). In the caissons located in the vault, powerful searchlights are placed, for which a service corridor (technological bridge) is provided along one side of the

*Fig. 11. Bittsevsky park. Evening illumination of an entrance hall*

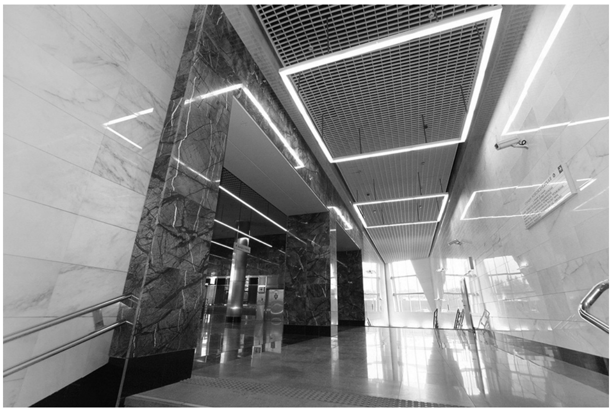

*Fig. 12. Bittsevsky park station. An aboveground entrance hall. Pendant frame luminaires*

entire station. The unique structure of the lighting devices represents a rotary frame with three installed searchlights of 400 W each and with linear FL inserts for emergency illumination.

Arms with rotary mechanisms provide for convenient maintenance. Their maximum rotation angle is equal to 160°.

*Fig. 13. Novokosino station. An entrance hall*

The aboveground two-storey entrance hall is of an ovoid shape laterally. Bulk terracotta colour ceramics with inclined stripes of external glass cover the entrance hall façade, which supplements the picture of the entrance hall's evening illumination (Fig. 11). The entrance area is accentuated with stained-glass windows of planar glass cover. Entrance hall illumination uses FL pendant luminaire lines along the entire entrance hall, as well as square luminous frames (Fig. 12).

Typically, all stations of L.L. Borzenkov's workshop have a larger sized platform: 12 m wide, instead of 10 m, and 163 m long. This increases the passing ability of passengers. A movement motif is expressed in all elements of the stations; it individualises their image beginning with a dynamic chromatic row on the platforms, and this motif itself is supported in the entrance halls by luminaires hidden behind a counter ceiling. The luminaires create continuous lines on the ceiling, which are directed along passenger movement lanes and pass through all entrance halls. Heating lattices and metal decorative elements on the entrance hall walls also follow this movement. They are inclined in the direction of passenger flow. The floor pattern also reflects the main direction (Fig. 13). Dynamic inclined forms of the pavilions over staircases are also following the flow of people, using natural daylight as much as possible (Fig. 2). An underground station in a suburb is not just a stop point; it is a district centre performing not only utilitarian, but also emotional and aesthetic functions. Illuminated pavilions of the underground give a cosy and more habitable feel to a monotonous landscapes of a typical housing system (Fig. 14).

*Fig. 14. Zhulebino station. Pavilions over stair approaches to the underground*

*Fig. 15. Novokosino station. The platform*

Novokosino station is a one-vaulted construction with an island type platform. The architecture of the station takes light as the main shaping element in the spatial composition of underground constructions. Light reveals the plasticity of architectural details of the vault, unites luminaire arrangement in an integral whole and adds simplicity and weightlessness to the appearance of underground structures (Fig. 15). Light movement features in the entrance halls as well. Luminaires placed behind the counter ceilings, shine through them and support the main direction of passenger flow with continuous lines. Being scattered into luminous triangles behind the open ceiling in the distributive hall in front of the entrance hall, they guide passengers out into pedestrian crossings with a clear rhythm of cross light stripes. A general pattern of the counter ceilings is subject to the main architectural idea of large-scale light forms.

The architecture of aboveground constructions is an integral part of the uniform architecture of the station system composition. Aboveground pavilions of underground exits, ventilating booths and pavilions of additional and emergency exits are significant elements of the underground transport construction architecture. Streamline shapes with inclined surfaces of the glass pavilions over underground staircase entrances control light around the clock (Fig. 16). Natural light passes through an glass cover to the underground space and smoothly mixes with artificial light in the pedestrian crossings. By contrast, in the evening, light from underground illuminates the pavilions from within, supplementing the surrounding space with bright accents.

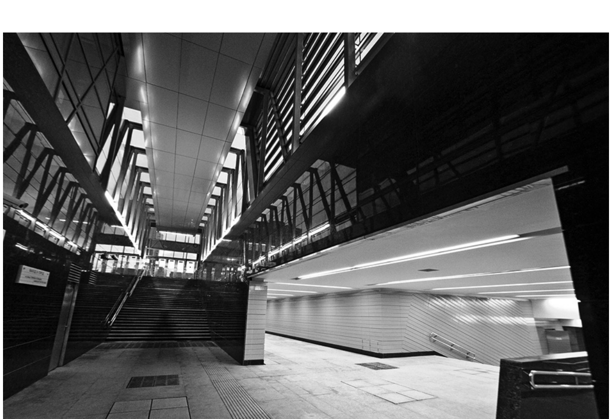

*Fig. 16. Lermontovsky prospect station. A descent from an above-ground pavilion to an underground pedestrian crossing*

*Fig. 17. Novokosino station. Mounting of a fragment of the light structure*

The basis of the architectural image of Novokosino station is a plastically designed ferroconcrete plastered vault in the form of caissons separated using diagonal ribs (nervures). The latter are accentuated with a darker hue than the caissons, and illuminated with a complex device formed by a group of pendant luminaires. A prototype model was first

*Fig. 18. Lermontovsky prospect station. The platform. Chromatic palette of the counter ceiling*

*Fig. 19. Zhulebino station. Chromatic transition*

*Fig. 20. Lermontovsky prospect station. The platform*

manufactured, and testing was performed onsite (Fig. 17). Service of the luminaires is carried out from the platform. Lighting structures of large dimensions perform several tasks here: illuminating the platform, creating comfort for the passengers and illuminating niches of the monolithic vault, accentuating the architectural lines.

The walls of the entrance halls and pedestrian crossings are covered in with ceramic plates (by contrast with the station) of *NBK Ceramic* Company on a metal frame, and every entrance hall has a different principle colour for the convenience of orientation. The western entrance hall has grass green walls, and the east entrance hall walls are ochre – orange. Counter ceilings of the entrance halls are steel in colour and are constructed of Luxalon panels (*Hunter Douglas* Company) or of *Loop* panels (*Durlum* Company). All technical equipment and luminaires are placed within the ceiling panels.

The architectural image of Lermontovsky prospekt and Zhulebino stations is based on an idea of moving the chromatic scale through the whole station ensemble from one entrance hall to the other entrance hall, going from green via yellow to red-orange shades (Fig. 18). Entrance hall walls of both stations located closer to central Moscow are covered in red-orange ceramic stone. The opposite entrance halls have green walls. The correspondent colours transit from walls of the pedestrian crossings to the end face walls and further to ceilings of the pavilion over the stair approaches. Transition from one colour to another, which takes place among plants in nature, transforms the underground space to a positive medium remaining all year round (Fig. 19). Different colours for entrance halls are an additional element of the standard information system accepted in the underground. This innovation helps passengers have a good sense of direction in the underground space.

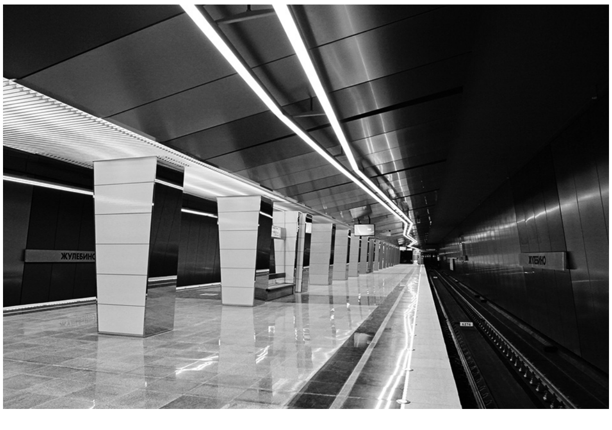

*Fig. 21. Zhulebino station. The platform*

Lermontovsky prospekt station on the Tagansko-Krasnopresnenskaya line is one-vaulted station with a maximum vault height of 6.2 m from the platform level. The basis of the architectural image of the station is a smooth reinforced concrete plastered vault. It serves as a reflecting surface for the luminaires fixed on the top side of the triangular configuration ribs turned divergently and installed at one metre intervals. The ribs are used as diffusers (Fig. 20). The ribs are manufactured from aluminium three-layer panels with cellular filling and grouped into 10 units with intermissive inserts of horizontal ribs with a low relief. At the boundary of each unit, inclined colour partition-walls are installed presetting a scale rhythm of the ceiling at 16 m intervals. In the socles of the track walls, cable ducts are placed. The socles are covered with plates of glazed terracotta bulk ceramics with a metal frame. The plates are divided into five sections of different colours, which change synchronously with the colour of the vault partition-walls.

Zhulebino is a subsurface two-span station, with a maximum ceiling height of 4.8 m from the platform ground level, with columns placed in a row along the platform axis with a pace of 6 m (Fig. 21). Counter ceilings in the passenger area are made of *Linear V100* aluminium panels from *Hunter Douglas* Company, the distinctive feature of which is the vertical placement of the panel at100 mm intervals. Due to this feature, luminaires with high efficiency FLs are placed behind the ceiling in the form of an uninterrupted strip. They are serviceable through gaps between the panels without the need to dismantle the ceiling elements. This structural feature makes it possible for light to pass easily through the ceiling, to form smooth and continuous light lines on it and to illuminate the surrounding space. In this way, the light sources are not visible. Surfaces of the track walls and of the greater part of the ceiling are faced with inclined three-layer aluminium panels with cellular filling, within which column planes, faced with plates of glazed terracotta bulk ceramics on a metal frame, are reflected. In order to reduce a visual mass, the surface of the columns turned to the track walls, is covered with three-layer aluminium panels with cellular filling and with a front surface of polished stainless steel (as a matter of fact, being specular). All this strengthens illumination by means of reflected light (Fig. 21). The platform edges are illuminated with paired strips of linear luminaires having smooth turnings laterally along the platform. A general pattern of the counter ceiling is congruent with the central architectural idea of large-scale light forms. Counter ceilings in the passenger area and illumination of the underground entrance halls of the station are designed to be analogous with entrance halls of the Lermontovsky prospekt station: long lines of FL luminaires behind the ceiling panel lattice.

*Fig. 22. Zhulebino station. The platform. Specular light reflecting pylon surfaces*

Using the features of modern illuminating facilities, the architectural solutions described have allowed creating a bright and recognisable image, which represent current trends in world and domestic architecture of this type. Both, traditional and modern materials, products, as well as new technologies, including energy saving ones, have been applied.

The whole design project on illumination of the station ensembles is performed in cooperation with BPS-Business Plus Light Open Company, the General Director of which is I. V. Karavaeva, together with specialists of Metrogiprotrans Open Society under the direction of V. I. Siluyanov.

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# NEW METHODOLOGY OF LIGHT SOURCE SPECTRAL DISTRIBUTION SELECTION AND DESIGN FOR USE IN MUSEUMS TO PROPERLY EXHIBIT AND PRESERVE ARTWORK.

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**ABSTRACT:**

A new methodology to select light source spectral distribution for use in museums is presented. It is based upon obtaining the Representative Spectral Reflectance Curve (RSRC) for each artwork and then lighting it with a light source the spectral power distribution of which is coincident in shape with the objects RSRC. This should cause minimum damage due to radiation on the object, as the deterioration of the object due to radiation is an effect of energy absorbed. In order to evaluate quality of presentation, colour differences were calculated for the three primal colours present in an artwork sample, illuminated under Illuminants D65 and under a simulated illuminant the spectral power distribution of which matches the RSRC of the illuminated object. Results are in general lower than 3 CIELAB units, considered the limit for strict tolerance in normal colour reproduction.

**Keywords:** methodology, spectral reflectance, illuminants, presentation, preservation

## I. INTRODUCTION.

The current protocol for exhibition object preservation in museum lighting is based upon the combined use of dual criteria: object classification according to their risk of deterioration due to radiation and the standards for total accumulated exposition [1,2]. Considering a certain degree of object deterioration is inevitable when exposing an exhibit to radiation, due to the physical phenomena that cause it [3], it becomes necessary to rely on more precise information about an object's vulnerability to deterioration from radiation, particularly on information about its material qualities and methods, which can predict their performance under visible and non-visible radiation.

The hypothesis tested as part of this ongoing project is explained by the following propositions:

a) It is possible to obtain a reflectance curve of an artwork or an exhibition object, which is sufficiently representative of its surface area [4];

b) Lighting an artwork or an exhibition object, under a light source the spectral emission power of which matches the object's representative reflectance curve, allows for minimum damage to the object caused by light incidence, given that object deterioration due to radiation is the effect of energy absorbed [3].

The visual stimulus resulting from the interaction between an artwork's representative spectral reflectance curve (RSRC) and a light source, the spectral emission power of which matches the RSRC, allows for adequate and acceptable performance in terms of exhibition standards.

## 2. METHODOLOGY.

During the development of a methodology for determining the spectral curve, the following criterion was adopted: to consider a reflectance curve as representative of an artwork or an exhibiting object when it contains within itself, not only the spectral information of the different parts of the objects and artwork, but also all their variations proportionately at the final integration of the curve [5].

When characterising artwork – more precisely painting reproductions in the process of deducting their reflectance curves – they were considered as randomly distributed colour on a surface. Thus, factors of such characterisation are essentially: the amount of measurements on a surface to sufficiently inform of all its sectors, and the proportion in which all the sectors information is represented into the final spectral curve [5].

### 2.1. SAMPLE. Definition and processing

Four artwork reproductions have been selected as the sample, considering them as colour displayed on a surface, progressively from a discriminated and plain form, as in the work of Piet Mondrian "Composition in Red, Yellow and Blue 1921" named M1, to other three more randomly colour-displayed artworks by Paul Klee: "Farbtafel 1930", "Arkitecturder" and "Highway", respectively named M2, M3 and M4 (Fig. 1).

**2.2.** Reflectance data from the reproductions was acquired with a photo-spectrometer Spectrascan PR 715, in order to construct a representative spectral reflectance curve RSRC for each sample. The light source used for these measurements were incandescent lamps operated with continuous electrical current, regulated to 45 A., in a specially built cabinet of white non-textured internal walls. The criteria for data acquisition was to take a significant amount of one-sized measurements of the surface divided into quadrants, which sufficiently described every colour present on the surface and all its transition and change areas [6].

**2.3.** A procedure to characterise the spectral curve for each sample was developed. It consisted in weighing up each measurement, each colour and each colour zone into the resulting overall spectral curve.

The procedure includes finding both a ratio between each measurement and the total surface, and an average ratio between every colour surface and the total surface area. This is done first in the divided quadrants of the surface and then in the total surface area. The obtained curve was considered to be the RSRC (Representative Spectral Reflectance Curve) for the specific artwork reproduction sample.

A sensitive part of the procedure is finding out the proportion of every measurement and of every colour zone in the total integration of the spectral reflectance curve. This was done through two methods. The first method identified an area proportion index (API), considered as the one expressing the weighed value of each measurement in terms of the total area of the sample. It comes from dividing the area of each colour zone and of each measurement over the total area of the sample. The API obtained is multiplied by the spectral data of its correspondent measurement, which is considered as the weighed value of every measurement into the final integration of the representative spectral reflectance curve (RSRC).

The second method for weighing the value of each measurement and each colour zone in the RSRC has been developed by analysing histograms of the digital image for every sample. The RGB pixel distribution present in the histogram of every measurement and of every colour zone was related to the RGB pixel distribution of the entire sample's digital image. The proportion of that relationship is found as a ratio of both partial and total RGB pixel distributions, named Píxel Quoeficient (P.Q.), which is then multiplied by the spectral information of the correspondent measurements resulting in every case

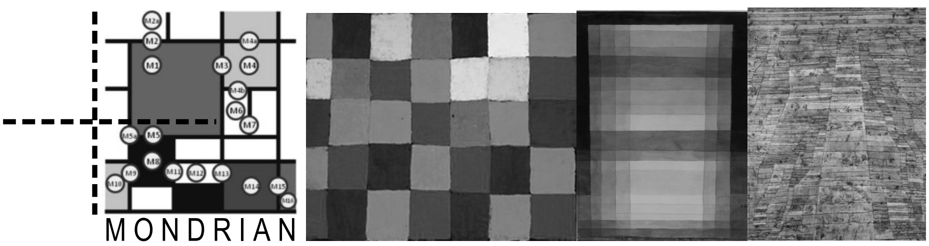


Fig. 1. Artwork reproductions sample (M1, M2, M3, M4)

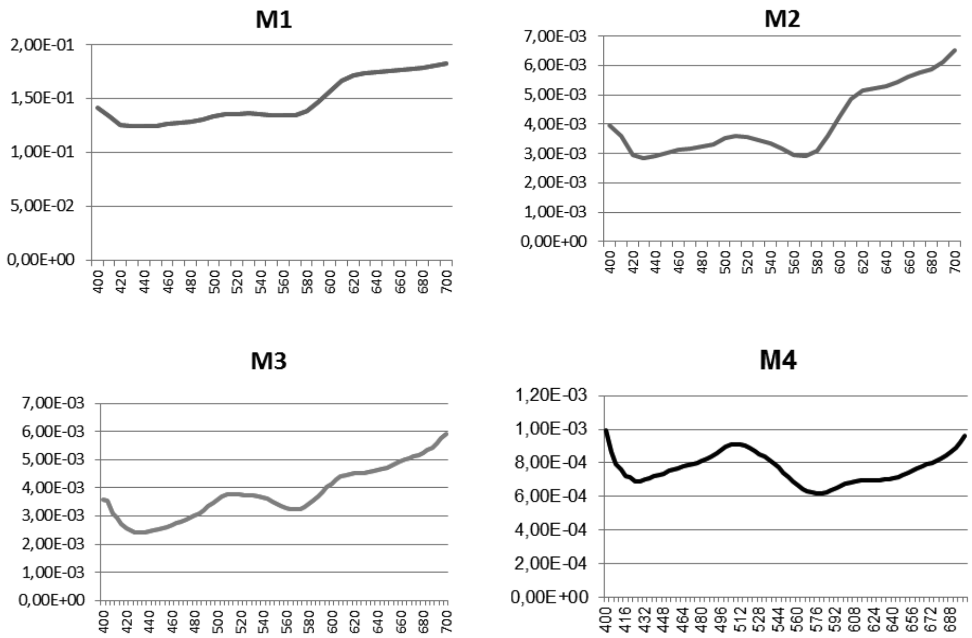


Fig. 2. Representative Spectral Reflectance Curves (RSRC) for the Samples.

the weighed value of each measurement and colour zone.

Comparison between the two RSRCs obtained with the above mentioned methods allows for mutual confirmation of the representative spectral reflectance curve for all artworks in the sample (Fig. 2).

The obtained curves, which are considered to be the RSRC (Representative Spectral Reflectance Curve) for each specific artwork reproduction sample, have been used in designing the spectral emission of a light source, which coincides with the RSRC´s shape, called MATCH 1, 2, 3 and 4 according to the sample from which they derive. They have also been used for selecting and evaluating spectral power emissions of CIE illuminants according to the preservation and presentation parameters stated in the hypothesis.

## 3. EVALUATING ILLUMINANTS AND SOURCES ACCORDING TO PRESENTATION AND PRESERVATION

One of the goals of this work is to develop a method for selecting and evaluating CIE illuminants in terms of the achieved results in presentation and preservation, which can be inserted into a controllable emission Illuminator, all to comply with the museum mission.

A criteria to evaluate CIE illuminants has been applied, consisting of:

a) Selection of CIE illuminant spectral curves, which coincide closely in shape to the representative spectral reflectance curve (RSRC) of the reproduction sample to be illuminated in the simulation. In order to do so, a calculation method has been developed to establish the existing power gap between every CIE illuminant and the RSRC of the sample to be illuminated. The power gap calculated for an illuminant and a given sample reflectance curve is called the deteriorating factor. The lesser the deteriorating factor – power gap – between the two curves, the better preservation performance for the CIE illuminant can be expected. Deteriorating factor calculation results are shown in Tables 1–4;

b) The design of four Illuminant curves based upon the representative spectral reflectance (RSRC) of the each sample (M1, M2, M3, M4), the shapes of which coincide with the corresponding sample and are endowed with an amount of emission power. The illuminants designed are named MATCH 1, 2, 3 and 4, according to the sample from which they originate;

c) Given that the hypothesis of this work implies adequate compliance with presentation parameters, the presentation quality of the sample colours has been evaluated as follows: CIE L*a*b* colour differences [8] have been calculated for the colours present in each sample under all CIE and MATCH illuminants in comparison under CIE illuminant D65, taken as reference illuminant for colour rendering measurements.

**TABLES 1-4**

| RESULTS: Deteriorating Factor -ILLUMINANTS CIE and MATCH 1 for M1 | | |
|---|---|---|
| ILUMINANT CIE | | DETERIORATING FACTOR- M1 R.S.R.C. |
| 1 | MATCH 1 | 0,00 |
| 2 | B | 10,16 |
| 3 | D 50 | 12,64 |
| 4 | E | 13,58 |
| 5 | A | 14,47 |
| 6 | F11 | 14,52 |
| 7 | F2 | 15,80 |
| 8 | D65 | 26,27 |
| 9 | C | 29,02 |
| 10 | F7 | 32,22 |
| 11 | D75 | 36,67 |

| RESULTS: Deteriorating Factor -ILLUMINANTS CIE and MATCH 2 for M2 | | |
|---|---|---|
| ILUMINANT CIE | | DETERIORATING FACTOR- M2 R.S.R.C. |
| 1 | MATCH 2 | 0,00 |
| 2 | A | 15,20 |
| 3 | F11 | 15,73 |
| 4 | B | 22,36 |
| 5 | D 50 | 23,72 |
| 6 | F2 | 26,50 |
| 7 | E | 29,73 |
| 8 | D65 | 41,37 |
| 9 | C | 43,66 |
| 10 | F7 | 44,57 |
| 11 | D75 | 52,10 |

| RESULTS: Deteriorating Factor -ILLUMINANTS CIE and MATCH 3 for M3 | | |
|---|---|---|
| ILUMINANT CIE | | DETERIORATING FACTOR- M3 R.S.R.C. |
| 1 | MATCH 3 | 0,00 |
| 2 | A | 13,09 |
| 3 | F11 | 15,63 |
| 4 | B | 19,61 |
| 5 | D 50 | 20,06 |
| 6 | F2 | 25,45 |
| 7 | E | 28,17 |
| 8 | D65 | 39,71 |
| 9 | C | 41,59 |
| 10 | F7 | 41,64 |
| 11 | D75 | 51,09 |

| RESULTS: Deteriorating Factor -ILLUMINANTS CIE and MATCH 4 for M4 | | |
|---|---|---|
| ILUMINANT CIE | | DETERIORATING FACTOR - M4 P.R.E.R. |
| 1 | MATCH 4 | 0,00 |
| 2 | E | 7,82 |
| 3 | B | 8,43 |
| 4 | D 50 | 8,49 |
| 5 | F11 | 14,46 |
| 6 | D65 | 15,66 |
| 7 | C | 20,33 |
| 8 | A | 20,69 |
| 9 | F2 | 23,07 |
| 10 | F7 | 23,86 |
| 11 | D75 | 24,09 |

## 4. RESULTS

L*a*b* colour differences were calculated for the colours present in the samples under curves MATCH 1, 2, 3 and 4 compared against CIE D65 illuminant. Curves MATCH 1 through 4 were then inserted into a controllable emission Illuminator and spectral measurements of their resulting emissions were

**TABLE 5. Results of colour difference CIE L*a*b* (1976) for samples M1–4 under MATCH 1–4 and D65**

| **SAMPLE M1** | **M1** | **M4** | **M14** | |
|---|---|---|---|---|
| | | | | |
| Calculation | 3,22 | 2,24 | 1,27 | |
| Experimental | 3,64 | 2,69 | 1,38 | |
| **SAMPLE M2** | **M2 19** | **M2–47** | **M2 b-20** | **M2 c-12** |
| | | | | |
| Calculation | 2,30 | 2,13 | 1,30 | 1,19 |
| Experimental | 3,07 | 2,56 | 1,89 | 1,39 |
| **SAMPLE M3** | **M3 c8** | **M3 45** | **M3 b6** | **M3 d5** |
| Calculation | 2,17 | 2,98 | 0,24 | 0,33 |
| Experimental | 2,19 | 2,98 | 0,25 | 0,33 |
| **SAMPLE M4** | **M4 a50** | **M4 e33** | **M4 g40** | **M4 c50** |
| Calculation | 0,22 | 0,11 | 0,44 | 0,06 |
| Experimental | 0,22 | 0,11 | 0,44 | 0,06 |

taken. The outputs were used for a new L*a*b* calculation for the same colours present in the samples and the same comparison to the CIE D65 illuminant, obtaining a set of both calculation and experimental results, shown in Table 5.

## 5. CONCLUSIONS.

A new methodology has been developed to select and design light source spectral distribution for use in museums to properly exhibit and preserve artwork. The methodology has been tested on a sample of artwork reproductions, to evaluate presentation and preservation potential. On presentation, L*a*b* colour difference results, both calculated and experimental, fall generally under 3 CIE L*a*b* units. On preservation, CIE illuminants and sample-designed illuminants have been evaluated and ranked according to a deterioration factor originating in the gap between each RSRC and the given illuminant.

Curves of spectral information can be used in the described manner in a lighting system capable of regulating its spectral emission to be used in museum lighting. To achieve a controlled link between spectral information from the illuminated object and the visible radiation emitted by a source, would imply an important advance in the precision with which object deterioration is controlled, along with adequately addressing the museum's standards of presentation. Further studies may include experimenting with human observers as well as conducting damage measurements and other assessments to corroborate the results with preservation goals set by the museum.

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# LIGHT GUIDE USE AND FACADE LIGHT REFLECTION FOR IMPROVED INSOLATION AND INCREASED DAYLIGHT FACTOR AS PART OF THE RECONSTRUCTION OF CITY HOUSING SYSTEMS

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## ABSTRACT

Domestic and foreign technologies are analysed based on their potential to increase insolation and daylight factor when reconstructing city housing systems. Problems are described, the solution of which can improve the ecological situation and levels of comfort for city dwellers when using light guides and reflection of light using facades.

**Keywords**: town development, city housing system, reconstruction, insolation, daylight factor, light guides

## 1. INTRODUCTION

Town planners face several challenges when reconstructing urban housing system, one of which optimising insolation [1]. When developing projects connected with construction and reconstruction of a city housing system, insolation of spaces and buildings should be one of the important primary considerations. Insolation standards cannot be observed within existing city housing systems. This is explained by the absence of standards and methods of calculation for levels of insolation at the time these buildings were designed. Problems are also associated with point building up. New tall building erected under a wrong design can shade surrounding buildings. Problems also exist with industrial building reconstruction projects, which are inside the housing system. When reconstructing industrial buildings, the building's functional purpose often changes. Limitations present themselves, firstly caused by design features of the buildings and by their location relative to cardinal directions. When designing and siting administrative and industrial buildings, the question incoming solar energy is considered differently than it is for residential buildings. Therefore, the orientation of a building, the functional purpose of which will change after reconstruction, frequently interferes with its uniform irradiation. In the process of developing projects for building reconstruction, the compatibility of the reconstructed building exterior with its surrounding buildings should be taken into consideration. Due to the all above listed reasons, designers have a limited choice of space-planning solutions. Therefore, it is imperative to find new effective planning solutions and create new technologies of accounting for conditions of insolation and natural illumination (NI). This should help address existing problems of insolation and NI in a housing system for a more comfortable and economic lifestyle.

## 2. USE OF FAÇADE LIGHT REFLECTION FOR IMPROVEMENT OF INSOLATION CONDITIONS IN CITY HOUSING SYSTEMS

Considering limitations of insolation conditions caused by geometrical features of buildings within an existing housing system, one should pay attention to U-shaped configuration buildings and to buildings with courtyards. It is known that such buildings are often poorly insolated. In order to improve insolation conditions, hypothetically it is possible to reflect

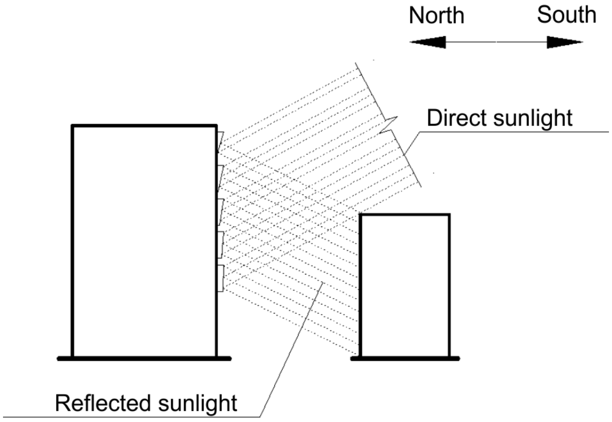


*Fig. 1. Use of façade light reflection*

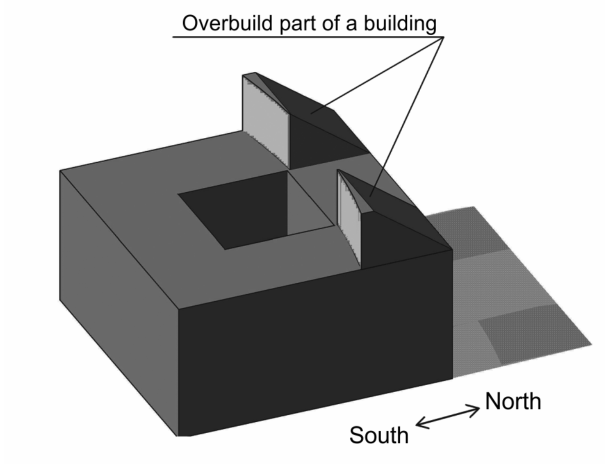


*Fig. 2. A conceptual model of a superstructure building with a well-shaped yard to increase reflected solar energy to poorly insolated building sites*

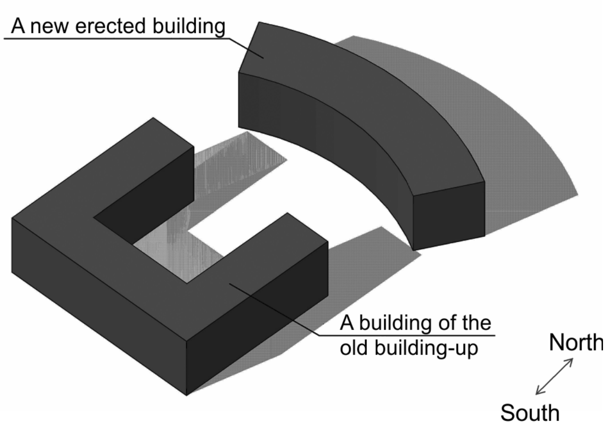


*Fig. 3. A conceptual model of a new building with a concave configuration to increase reflected solar energy to northern facades of a U-shaped building*

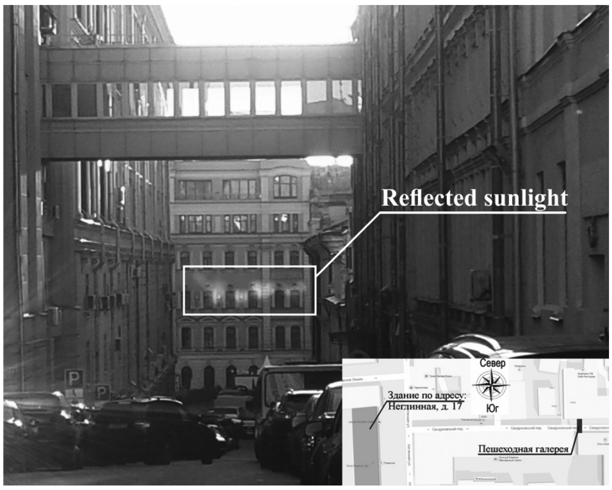


*Fig. 4. Sunlight reflected by windows of a through passage gallery located in Sandunovsky by-street in Moscow. It falls on the east facade of the building located in Neglinnay street, 17. Picture taken on 06.09.2014 at 19:35*

sunlight using close located facades (Fig. 1). Surface facades of existing buildings of the surrounding housing system can be used; or extending the height of the reconstructed building, constructing glass screens or inserting buildings of a special geometrical configuration. Standards of insolation and of NI for the surrounding housing system should be observed (Figs. 2, 3).

However, when exploring the possibility of using sunlight reflected by facades for improving insolation conditions, we should consider the health and safety properties of sunlight and account not only for visible but also for UV and IR intervals of the sunlight spectrum. We also need to determine optimum time periods for use of reflected sunlight, possible façade orientations and their geometrical configuration. Concerning facades orientation, it should be noted that, for example, at the Moscow latitude, the most insolated building facades are southern, southeast and southwest facing. The density of radiant solar energy is sufficiently high on these facades. However, the energy is either absorbed by these facades, or reflected in various directions. This energy can hypothetically be used for improving insolation conditions of the shaded buildings with north, west or east orientations. It is important to pay attention to sunlight reflected by building windows. The reflected rays fall on nearby buildings, especially in the hours just after sunrise and just before sunset, due to the small incidence angle of solar rays on the building façade plane and, therefore, a small angle of reflection (Figs. 4, 5).

This shows that the use of façade sunlight reflection on shaded buildings is possible with the well-designed arrangement of the housing system. Looking closely at the housing system reveals shad-


*Fig. 5. A picture of the east and northeast facades of buildings located in Smolnaya street, 33 and 41, Moscow, with sunlight falling on them and reflected by windows of western and southwest facades of the building located in Smolnaya street 24 a, Moscow. Picture taken on 24.10. 2014 at 15:03*

ed yard territories or building facades requiring additional solar irradiation. Research into the physical properties of reflected sunlight is needed to determine whether reflected sunlight has similar physical properties as direct solar light. In order to find out people's attitude towards reflected sunlight, sociological studies interviewing inhabitants are needed in places where reflected sunlight penetrates house windows twice a day.

## 3. USE OF LIGHT GUIDES WHEN RECONSTRUCTING A CITY HOUSING SYSTEM FOR IMPROVEMENT OF NI CONDITIONS

The use of radiation reflected by building facades can hypothetically improve insolation conditions of the surrounding housing system; however, the task of improving NI conditions of reconstructed buildings remains unresolved. For this purpose, other technological solutions, for example application of light guides, should be explored. These can deliver sunlight to rooms which are far from light openings. Therefore, they can be especially useful when reconstructing buildings. Moreover, they have an important benefit in comparison with normal light openings [5]. It appears that when using hollow tubular light guides (HTLG), total natural illuminance is delivered (both diffuse sunlight, and direct), which in its turn considerably increases room illumination.

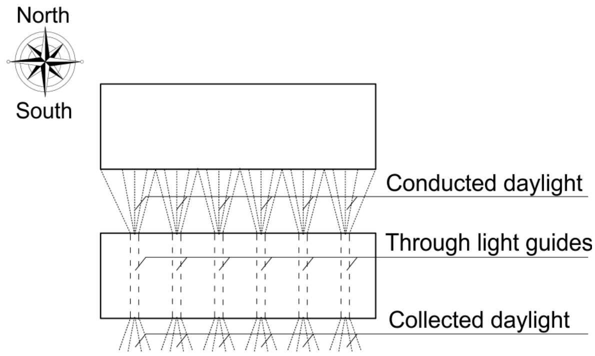


*Fig. 6. Potential systems of through light guides*

Therefore, the use of light guides can improve NI of rooms with an insufficient daylight factor.

Besides using light guides, it is possible to raise the daylight factor in normalised rooms. For this purpose, it should be determined, which part of the building is perceived as having the greatest deficit in penetrating natural light. Obviously, these are inner rooms most distant from light openings: bathrooms, corridors, lift sites, ground floor rooms, as well as deep rooms[1].

Light guides could solve NI problem for: 1) underground rooms such as basement floors of buildings; underground garages, shops, shopping and entertainment malls and cinemas, civil defence interiors; 2) transport and pedestrian tunnels, etc. In particular, it is important to explore this opportunity given the increasing trend in the use of underground space when reconstructing city territories, where there is currently a lack of associated research. In paper [7] only two small paragraphs are dedicated to the question of natural illumination of underground room, which shows its little developed in the reconstruction field of inquiry. The author states that this direction, including the application of fiber light guides is prospective, in particular for sunlight extension to underground rooms [7].

In order to solve NI problems using light guides for reconstructing housing systems, additional scien-

[1] In particular it is known that household sewage collection systems are usually located close to the building centre; therefore, bathrooms are artificially illuminated at high cost. Ventilation exhaust systems usually lead to the building's roof; it is possible to place light guides for bathroom NI near ventilation ducts.

The placing of inner storm water drain systems is also worth considering. These usually pass through corridors, which could be illuminated with natural light, if the light guides were arranged near a drop pipe of the storm water drain.

tific research is needed. In the first instance, it should be determined, what type of light guide, fiber or HTLG, are capable of transmitting solar radiance of a necessary spectral composition over a large distance. For example, fibre-optical system "*Parans SP3*" [8] only transmits the visible spectrum of solar radiance. However, it is possible to use additional fibre optics transmitting IR and UV spectral intervals.

## 4. EXISTING AND POTENTIAL TECHNOLOGIES FOR IMPROVING CONDITIONS OF NI AND INSOLATION, ECONOMIC FEASIBILITY OF THEIR USE, AND DESCRIPTION OF THE PROBLEMS

Different technologies, methods and devices are currently being applied and developed to increase sunlight irradiation periods for rooms of existing buildings and city territories. There is a need for improved structuring and coordination of these efforts.

Existing NI devices include:

– HTLGs, such as *Solartube*, *Solarspot* [4], *Lightway* or *Solarway*;

– Fibre-optical systems, for example, *Parans SP3* [8];

– Systems of specular light guides of *Daylighting Technology SUNPORTAL* type [9];

– *Heliobus s*ystem;

– Creation of atriums, zenith lanterns and different dome light-guide structures on top floors of buildings, etc.

Potential possible technologies include the following:

– Application of flow-through optical light guide systems (Fig. 6);

– Use of special reflecting façade surfaces (Fig. 1);

– Application of active and passive solar optics;

– Use of full inner reflection prisms (Fig. 7);

– Application of electro chromic films.

Solar irradiation, besides its unique insolation and lighting functions, is a prospective energy source. Together with developing new technological solutions for the purpose of improving solar energy irradiation time for buildings, building energy efficiency can also be addressed. D. Jenkins and T. Muneer have calculated energy savings due to use of HTLGs and showed the environmental benefits of their application [2]. Furthermore, research into the efficiency of light guide use carried out at the VNISI, showed that the use of sunlight can achieve savings between 40% and 70% of electrical energy consumed for illumination [1]. One more benefit of using HTLGs, in terms of *Solarspot*, is shown in article [3], in which the presented heat-conduction coefficients are compared for HTLG and zenithal lantern applications. The results showed that HTLGs are more energy efficient than traditional zenithal lanterns.

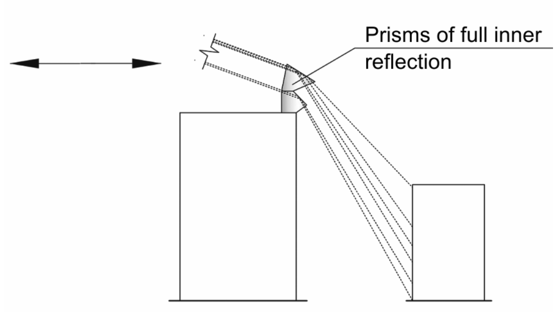


*Fig. 7. Potential technology for use of full inner reflection prisms*

Further on the economic justification of light guide use, one should consider the scenario of their installation not on a building roof, but on its southern insolated facade. Thereby, it is hypothetically possible to raise heat supply into the building by decreasing heat losses caused by ascending thermal flows in winter period and to simplify the problem of insufficiently illuminating rooms distant from the external walls. As to the warm period of the year, when solar energy leads to building overheat, it would be possible to insert into the light guide a transparent element with deposited electro chromic film so as to overlap its cross-section and to block IR radiation components.

Use of the principles proposed in the dissertation [6], can facilitate optimisation of light guides and facades for effective reflection of sunlight.

To solve problems presented by housing system reconstruction in terms of insolation as an important town planning consideration, the following steps should be taken:

– To unify, certify and improve light guides;

– To develop town planning solutions which site facades so that they can reflect sunlight effectively;

– To investigate the ability of light guides to transport, and of facades to reflect all necessary spectral components of sunlight;

– To develop requirements for application of light guides and for reflected solar energy in different climate regions;

– To develop the economic case for the expedient installation of light guides and the advantages of proper facade reflection;

– To develop a method to calculate building façade reflected solar energy;

– To develop recommendations on improvement of insolation conditions when reconstructing a housing system.

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# CHARACTERISTICS OF RETROFIT LAMPS FOR INCANDESCENT LAMPS

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## ABSTRACT

There is a global trend to phase out inefficient light sources like incandescent lamps from the market through legislation and voluntary measures. The objective of this paper was to find out the characteristics of the replacement lamps for incandescent lamps. Both compact fluorescent lamps and LED lamps are energy-efficient alternatives for incandescent lamps. LED lamps have some features that make them more preferable than CFLs, like instant light output, better operation in cold conditions and longer life time. The price of LED lamps is higher than CFLs. The costs evaluation shows that both LED lamps and CFLs are economical in use even if the purchase prices are higher than the price of incandescent lamp.

**Keywords:** LED, CFL, incandescent, retrofit lamps

## INTRODUCTION

Currently, there is a global trend to phase out inefficient light sources from the market through legislation and voluntary measures. In EU, Regulation 244/2009 sets requirements for non-directional lamps typically used in households: incandescent lamps, halogen lamps, compact fluorescent lamps with integrated ballast (CFLi) and LED-lamps with E27-base [1].

The efficacy requirements gradually phased out incandescent lamps from market. After September 2012 incandescent lamps are practically non-existent on the market. Since the luminaires in households are mostly designed for incandescent lamps, in this text the term retrofit lamp means a lamp with E27-base. Retrofit lamps are CFLi-lamps, LED-lamps or halogen lamps. CFLis can be pear shape (look-a-like), tubular or spiral. LED dies are used with direct current and therefore the LED-lamps with E27-base includes necessary current source. Replacement of incandescent lamps is leading to substantial energy savings in household lighting energy [2]. The share of incandescent lamps of household's light sources is still quite high e.g. in Russia (95.2%) and in USA (62%) [3]. Aizenberg points out that incandescent lamps are today completely out dated light sources and phase out is already on going in USA, Australia and Russia [4]. In this paper some of the characteristics of retrofit light sources are studied in more detail.

## MEASUREMENTS

### Luminous flux and luminous efficacy

Instead of taking notice of the power of the lamp the consumer should buy lumens. Table 1 shows the equivalent lumens for different lamp types and the corresponding power of incandescent lamps. The power is not compulsory information. Power can be calculated by linearly extrapolating from the values in table. For instance, if the luminous flux of a CFL lamp is 850 lm, then the equivalent incandescent lamp power is 67 W. With CFL and LED lamps the lamp life is longer than with incandescent lamp, the higher initial lumens compensate the lumen depreciation during burning hours [1].

**Table 1. Incandescent lamp power and equivalent luminous fluxes of different lamp types [1]**

| Incandescent lamp (W) | Luminous flux (lm) | | |
|---|---|---|---|
| | CFL | LED | HG |
| 15 | 125 | 136 | 119 |
| 25 | 229 | 249 | 217 |
| 40 | 432 | 470 | 410 |
| 60 | 741 | 806 | 702 |
| 75 | 970 | 1055 | 920 |
| 100 | 1398 | 1521 | 1326 |
| 150 | 2253 | 2452 | 2137 |
| 200 | 3172 | 3452 | 3009 |

In Fig. 1 are luminous fluxes vs. luminous efficacies of different lamp types [5, 6]. Photometric and electrical values were measured with an integrating sphere including Labshpere diode array spectrometer and Yokogawa WT13 digital power meter. With the spectrometer we measured also spectral power distribution (SPD) and colour parameters, correlated colour temperature (CCT) and CIE general colour rendering index (Ra). The temperature in the room varied between 22 and 24 °C. The burning position was base up.

Vertical lines show the luminous fluxes of 15 W, 40 W, 60 W, 75 W and 100 W incandescent lamps. There are also the curves for energy classes A, A+ A++ and C [7]. Energy classes described in more detailed in the forthcoming chapter. Luminous efficacy of CFLis were between 50 and 70 lm/W. The luminous efficacy of the LED-lamps, which were purchased in 2010, was near 40 lm/W. However, lamps purchased in 2013 had mean luminous efficacy 81 lm/W and one lamp exceeded 100 lm/W. This shows the rapid development of LED technology and retrofit lamps. The luminous efficacy values are a mean of three lamps, except in group LED2013, there were five lamps. CFL2012 means a value of one lamp. In groups CFL2010 and LED2010, the lamps were purchased in 2010.

The initial luminous flux was measured after 100 burning hours and the lumen depreciation was measured after 1000 hours. With look-a-like CFLis the lumen depreciation was ranging between 8 to 14% after 1000 burning hours. With tubular or spiral the depreciation was smaller ranging from 2 to 7%. With LED-lamps the luminous flux was even increased during burning hours with some lamps. With 4 lamp types it was increased 1 to 3% and with one lamp type it was the same and with another lamp type it was decreased 1%

### Quality of the light

In indoor lighting the recommendation for colour rendering index is more than 80. Colour rendering indexes (Ra) of CFLis were between 80 and 90. With LED-lamps there was more variation, most of the lamps had colour rendering between 75 and 85, but there were two lamps, which had Ra 55 and 65.

Correlated colour temperature of incandescent lamp is 2700 K and light is yellowish, white light is 3000 K and cool white 4000 K, daylight lamps

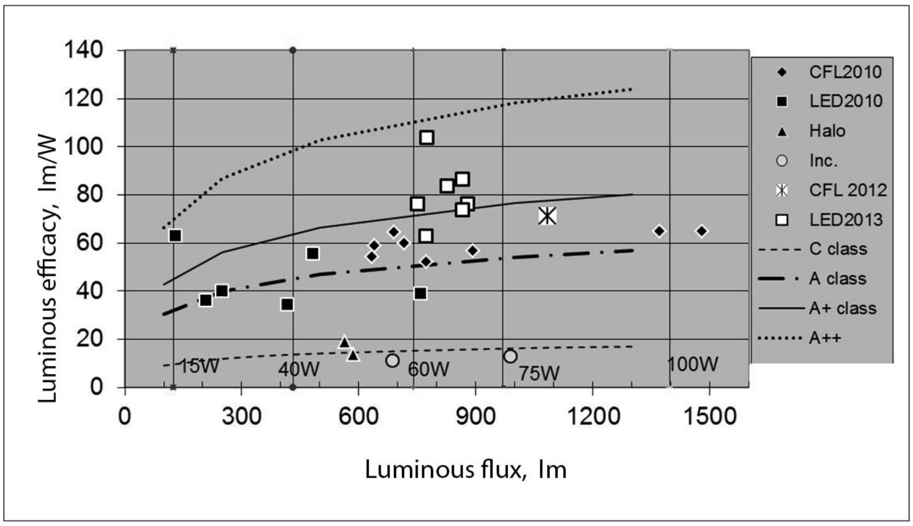


Fig. 1. Luminous efficacies of different lamps [5,6]

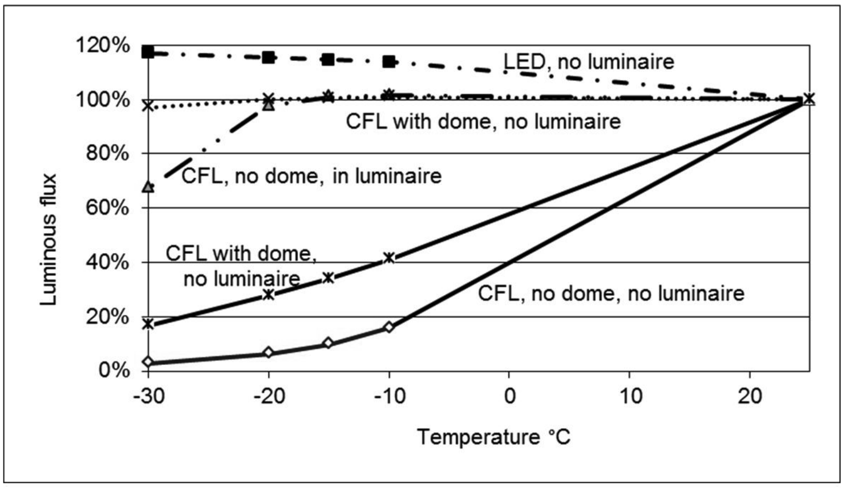


Fig. 2. Effect of ambient temperature on luminous flux

have usually CCT 5000 K or 6500 K. All the measured CFLis had CCT between 2500 and 3000 K. Colour temperature is thus quite similar to incandescent lamps. With LED-lamps the range was between 2600 K and 3600 K.

**Energy classes**

Energy classes of household lamps are given in Commission Directive EU No 874/2012 [7]. In the previous version of the Directive 98/11/EC A+ and A++ classes did not yet existed. The most efficient one is now class A++ and the most inefficient one is class E. Energy class is based on energy efficiency index EEI, which is calculated by dividing the rated power $P_{cor}$ by the reference power $P_{ref}$. For instance, non-directional CFL lamps with integral ballast belong to class A if $0.17 < EEI \leq 0.24$. Reference power is calculated from the useful luminous flux $\Phi_{use}$. If $\Phi_{use} < 1300$ lm, then $P_{ref} = 0.88\sqrt{\Phi_{use}} + 0.049\,\Phi_{use}$. Thus if the luminous flux is 741 lm, then the reference power is 60.26 W. The limit of EEI for class A is 0.24 and in order for the lamp to reach the class A limit, the rated power should be less than 14.46 W (14.46/60.26=0.24). The luminous efficacy in this case is 51 lm/W. Similarly, the luminous efficacies with same luminous flux 741 lm for A+ and A++ would be 72 lm/W and 112 lm/W, respectively. All the CFLs in Fig. 1 belong to class A and most of the new LED-lamps (2013) belong to class A+.

**Switching on and warming up**

CFL is a low-pressure gas discharge light source, in which light is produced predominantly by fluorescent powders activated by ultraviolet radiation generated by a mercury arc. It takes some time after the switch-on for the discharge to reach the operating temperature and pressure inside the tube. Instead incandescent, halogen and LED lamps have full lumen output immediately after starting.

Regulation 244 defines "Lamp start time", as the time needed, after the supply voltage is switched on, for the lamp to start fully and remain alight. On the other hand "Lamp warm-up time", refers to the time needed for the lamp after start-up to emit a defined proportion of its stabilized luminous flux [1].

At the moment the requirements for CFL lamps start time is less than 2 seconds and the warm up time to 60% of stabilized luminous flux is less than 60 seconds. If mercury is in amalgam form, the warm up time is increased to 120 seconds. Amalgam is used in some lamps, because it makes the luminous flux more stable despite of the ambient temperature, both in cold and warm conditions.

The lamp was considered to have started when the current was regular. Current was measured with current clamp, which was connected to oscilloscope. The start time with the measured CFLs were between 0,02 s … 120 s, average was 0,64 s. Warming up happened in 15 to 100 s, average was 41 s.

With LED-lamps the starting is immediate and the light is instantly also 100%. In fact, the luminous flux decreases a little when the lamp warms thus increasing the junction temperature of the LED die. According to measurements the luminous flux of LED lamps dropped 4–21% from the maximum value. When lamps were mounted in closed luminaire, the drop was about 20% higher compared to lamps burned in open air.

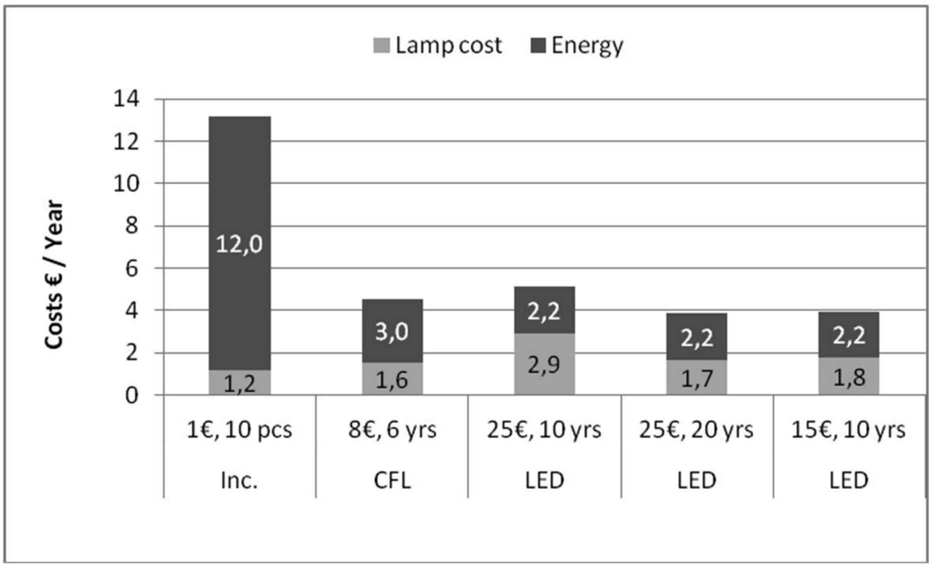


Fig. 3. Investment and operating costs of incandescent (Inc.), CFL and LED lamps (€/year)

The slow warm-up time of CFL lamp can be annoying in some applications, like in corridors or entrance halls. In these rooms it is better to choose a LED-lamp.

**Switch-on on low temperatures**

Low ambient temperature affects both the starting characteristics and light output of CFLs. At room temperatures there is sufficient amount of vaporised mercury to allow the ionisation of mercury to begin immediately. At low temperatures most of the mercury is in the form of small liquid droplets on the inside of the tube, and the starting is more difficult.

Starting of CFLi lamps were measured in temperatures 0 °C, –10 °C, –20 °C and –30 °C. All the tested lamps were seasoned 100 h in room temperature. Before the test, lamps were kept in the test temperature for 2 hours. The supply voltage was 230 V and the burning position was base up. All the measured lamps started, although the starting time increased slightly with some lamps. For instance, with one lamp the starting times were 1.5 s, 1.8 s, 2.2 s and 2.5 s, when temperature was from 0 °C to –30 °C.

**Ambient temperature**

The temperature of the cold spot determines the pressure inside the CFL discharge tube and thus also the light output. The cold spot has an optimum temperature and both lower and higher temperatures decrease lumen output. In cold temperatures, CFLs should be used in closed luminaires. The optimal burning position in cold temperatures is base down. With LED lamps the effect is opposite. Low ambient temperature decreases the junction temperature and the lumen output is increased.

Fig. 2 show relative luminous fluxes in different temperatures. If CFLs are used in closed luminaire, the temperature inside the luminaire will increase gradually and the temperature of the cold spot can be close to optimal. This phenomenon is strengthen if lamp has an extra dome around the discharge tube, like is the case in look-a-like lamps. In Fig. 2 curve "CFL with dome, no luminaire" shows that also CFL lamp can maintain its lumen output in cold temperatures. This lamp was amalgam lamp, which was designed also for cold temperatures. With LED lamps the lumen output was increased almost 20% due in –30 °C.

**Disposal**

CFLs contain 2–5 mg mercury and, therefore, they are hazardous waste after the lamp has been used and the mercury should be recycled. On the other hand the electricity production can cause some mercury emissions as well. In Finland this was estimated to be 3.9 µg/kWh. Lamp life of CFLi can be 10 000 hours. If 60 W incandescent lamps are burned the same time, the electricity consumption would be 600 kWh and related mercury emissions would be 2.3 mg. LED-lamps do not contain mercury and because of the low energy consumption, the mercury emissions caused by the usage of the lamp are reduced when compared to incandescent lamps.

### Luminous intensity distribution curve

The light distribution curve of different lamps can be quite different, incandescent lamps radiate their light in every direction (solid angle almost 4 π), while some LED-lamps have opening angle of 120° or narrower. The effect of luminaire is on one hand direct the light where it is needed and on the other hand provide shield from glare. In households luminaires there is normally not a reflective material to direct the light and sometimes the lumen output from the luminaire can be modest. Luminous intensity distribution curve was measured with goniometer from lamps and when lamps were mounted in luminaire. Conclusions were that LED-lamps are especially suitable for luminaires that provide task lighting like table lamps. Tubular CFLs give most of the luminous flux to vertical surfaces (when lamp base up). Spiral and look-a-like CFLs have luminous intensity distribution more similar to incandescent lamps.

### Lamp cost and operating costs

The annual lamp costs are calculated by multiplying the lamp price by the capital recovery factor.

$$C_I = I \times \frac{i(1+i)^n}{(1+i)^n - 1}, \qquad (1)$$

where

*CI* is annual costs of the initial investment, €;

*I* is investment cost (here lamp price), €;

*i* is interest rate (i = p/100, where p is interest rate in percentage);

*n* is number of years (service life of lighting installation).

Energy costs are calculated by multiplying the lamp power by annual burning hours and the price of electricity.

The initial values used in calculation were:

- Electricity price 0.2 €/ Kwh;
- Lamp power 60 w inc., 15 W cfl, 11 w led;
- Burning hours 1000 h/ year;
- Interest rate 3%;
- Lamp price 1 € inc., 10 € Cfl, 15 €/ 25 € led;
- Lamp life 1 year Inc., 6 years CFL, 10/ 20 years LED (Lamp life in burning hours would be 1000 h for inc., 6000 h for CFL, 10 000 or 20 000 for LED. Lamp life is based on manufacturer information);
- Number of years 10/ 20 (calculation time for the investment).

The energy cost is a dominant cost with incandescent lamps. The total costs (lamp price and energy costs) of CFL and LED lamps are only 30 to 40% of the total costs of incandescent lamps with the used initial values. CFL- lamps costs is smaller than LED lamps, but LEDs are already more energy-efficient and therefore their annual energy costs are smaller. LED lamps will come more economical compared to CFLs, if their burning hours are higher than in Fig. 3. Although there are differences in lamp and electricity prices, annual burning hours etc., still one can conclude that it is beneficial for the end-user to pay more for the energy-efficient alternative.

## CONCLUSIONS

Residential lighting is mostly based on incandescent lamps and therefore the energy consumption is high. Incandescent lamps are inefficient light sources, only 5 to 10% of the input electricity is converted to light. The energy savings possibilities when replacing incandescent lamps is high and the phase out of incandescent lamps from EU market has already lead to increase in energy-efficiency in residential lighting.

The luminous efficacy of incandescent lamps is about 12 lm/W, the average luminous efficacy of CFLs was 60 lm/W and of LED-lamps 80 lm/W. In the future the lm/W –value of LED-lamps will continue to increasing. LED lamps are better than CFLs in some application, like places where immediately light output is preferred after switch-on and also in cold conditions.

At the moment the price of CFLi and LED-lamps is higher than the price of incandescent lamps, but the total costs including energy costs and lamp prices are lower with CFLis and also with LED-lamps in most cases. Thus the consumer wins when she or he replaces the more than century old incandescent lamp with a modern CFLi or LED-lamp.

## ACKNOWLEDGEMENT

This work was supported by the Aalto University School of Electrical Engineering and Automation EffiNano project.

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**Table 2. Comparison of the characteristics of household lamp types**

| | Incandescent | CFL | LED-lamp |
|---|---|---|---|
| Costs | | | |
| Lamp price | cheap | moderate | expensive |
| Energy costs | high | low | low |
| Luminous efficacy | 12 lm/W | 60 lm/W | 40 lm/W |
| Lamp life | ~ 1000 h | 5000 - 15 000 h | >10 000 |
| Size | small | pear shape, tubular, spiral | heat sink weighty in some lamps |
| Ballast | not needed | integrated | integrated |
| Ambient temperature | | | |
| Hot | no effect | no big effect | lamp life shortened, light output decreased |
| Cold | no effect | light output reduced | light output increased |
| Switching cycle | not much effect | lamp life shortens | no effect |
| Switch on | immediately | 1-2 s | immediately |
| Warming up | immediately | 30 s-2 min (60 %) | immediately |
| Dimming | easy with voltage | only special lamps dimmable | only special lamps dimmable |
| Voltage | effect on luminous flux and lamp life | not much effect | not much effect |
| Mercury | | | |
| Lamp | no | 2 - 5 mg | no |
| Energy production* | 2,3 mg | 0,4 mg | 0,4 mg |

* 3,9 μg/kWh (1999) 10 000 h, 60W/11W

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Fig. 2. Outside view of the office

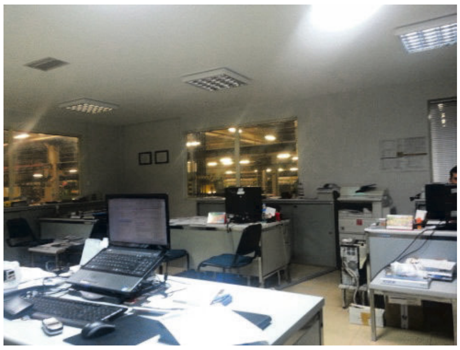

Fig. 3. Inside view of the office

Fig. 4. Inside view of the office

Fig. 5. Inside view of the office

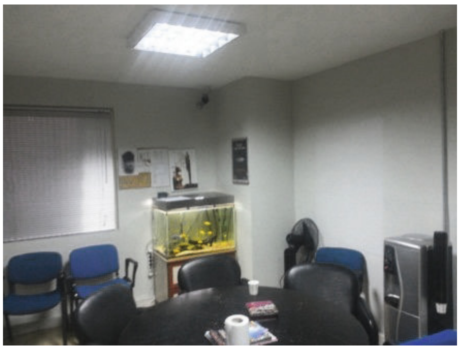

Fig. 6. Meeting room view

Fig. 7. Camera system view

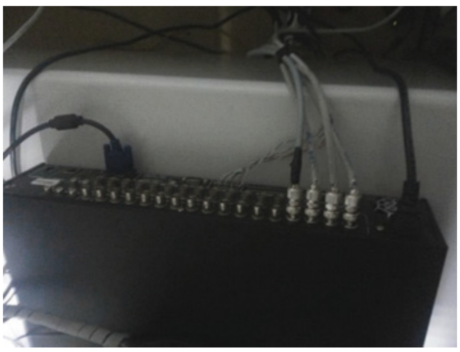

Fig. 8. Camera system view

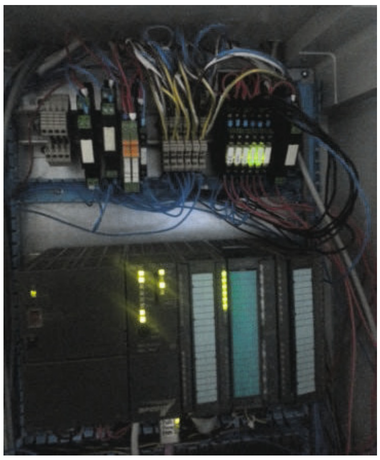

Fig. 9. PLC

*Fig. 4. Lermontovsky prospect station. A pavilion over a stair approach to the underground*

*Fig. 7. Alma-Atinskaya station. An entrance hall. Evening illumination*

*Fig. 9. Alma-Atinskaya station. The main light element of the station illumination*

*Fig. 14. Zhulebino station. Pavilions over stair approaches to the underground*

*Fig. 8. Alma-Atinskaya station. An entrance hall. A radial luminaire*

*Fig. 13. Novokosino station. An entrance hall*

*Fig. 16. Lermontovsky prospect station. A descent from an above-ground pavilion to an underground pedestrian crossing*

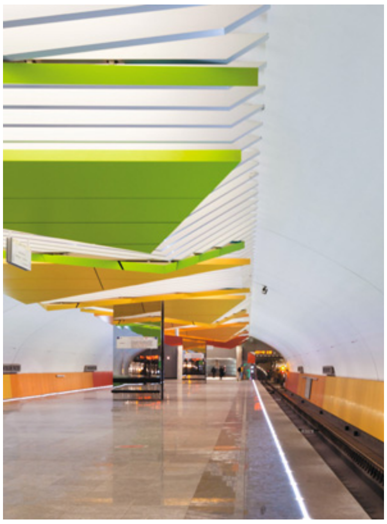

*Fig. 18. Lermontovsky prospect station. The platform. Chromatic palette of the counter ceiling*

*Fig. 19. Zhulebino station. Chromatic transition*

*Fig. 20. Lermontovsky prospect station. The platform*

*Fig. 21. Zhulebino station. The platform*


*Fig. 22. Zhulebino station. The platform. Specular light reflecting pylon surfaces*


Fig. 1. Artwork reproductions sample (M1, M2, M3, M4)

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# A STUDY OF PREFERRED ILLUMINANCE AND CORRELATED COLOUR TEMPERATURE FOR LED OFFICE LIGHTING

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## ABSTRACT

In order to study the preferred combination of the illuminance level and correlated colour temperature (CCT) and the preferred CCT of different ethnic groups in office lighting, a full-scale experiment was conducted in an office room with a light-emitting diode (LED) luminaires. Fifty-three observers from three different ethnic groups (Asian, European and African) rated nine different preset lighting situations after performing different office activities. The combination of 750 lx with 4000 K was statistically significantly preferred for office lighting. It was also found that the impression of brightness increases with a higher CCT and that people feel more stimulated under a higher CCT compared to a lower CCT. The European group preferred a lit environment under CCT 4000 K for office lighting and with the Asian and African groups the preference between 4000 and 5000 K depends upon illuminance levels.

**Keywords:** illuminance level, correlated colour temperature, LED lighting, office lighting

## 1. INTRODUCTION

Lighting preference is related to variety of human reactions to lighting, such as comfort, aesthetics and performance [1]. The improvement of office lighting with the preferred luminous conditions creates a positive influence on employees that leads to higher performance, improved productivity, creativity and social behaviour [2–4]. Illuminance (E) and correlated colour temperature (CCT) are two important characteristics of light to be considered with regard to human perception [5]. There is a quantitatively recommended illuminance value for indoor spaces but no equivalent recommendation for CCT. However, the CCT is an important component for the colour appearance of a space.

The European standard [6] for office lighting recommends an illuminance value of 500 lx for general offices. Several research studies have been conducted to investigate the preferred illuminance level for office lighting. Some studies [7–9] reported a preference for an illuminance level higher than the recommended, while other studies [10–12] showed a preference for lower illuminance than the recommended level for office lighting. Hence, the literature presents divergent data on illuminance preferences for office lighting. Studies about the effect of CCT on different aspects of lighting suggest that the CCT has an effect on the visual impression of a lit space, on physiological responses and on subjective mood [2,13–15]. In addition, preferences for CCT vary widely according to culture and geographic location [16].

In order to investigate the preferred combination of illuminance and CCT for office lighting, a full-scale experiment was designed in an office room illuminated with light emitting diode (LED) lighting. An additional objective of the study was to investigate the CCT preferences of different ethnic groups. Fifty-three observers from three different ethnic groups (20 Asians, 20 Europeans and 13 Africans) took part in the study. The observers performed different office activities under nine different preset lighting situations and rated the lit environment of the room. The results can be used in office light-

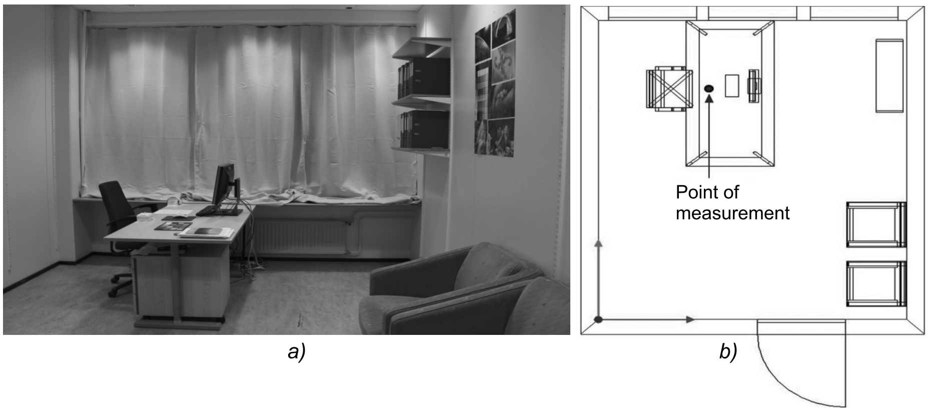


Fig. 1. The test room: (a) a view of the test room from the door and (b) the layout of the test room

ing automation to maintain the preferred choices.

## 2. USER STUDY

### 2.1. Experimental set-up

The user study was conducted in an office room built at Aalto University. The dimensions of the office room were width 3.51 m x length 4.22 m x height 2.80 m. There were three windows in the room, facing west. These windows were covered with light grey opaque curtains to avoid daylight entering into the room. The ceiling and the walls of the test room were white and the floor was grey. Reflectance was measured on the ceiling ($\rho_c$) = 0.89, walls ($\rho_w$) = 0.85, and floor ($\rho_f$) = 0.25. The room was equipped and furnished to provide a work space, as shown in Fig. 1. A light beech coloured rectangular work desk and office chair (red fabric colour) were placed near to the windows. The work desk surface was at a height of about 0.72 m from the floor. On the desk there was a 17″ LCD monitor, a Macbeth Colour Checker (MCC) chart and office work related materials. The positions of the monitor and keyboard were kept constant and the monitor's settings were the same throughout the experiment. In the room, there were also two identical armchairs in the right-hand corner near the door, posters, a book shelf and a filling cabinet.

Nine round (27 W, Ø 200 mm) downlight recessed ceiling LED luminaires were installed to illuminate the test room. All nine luminaires were controlled as a group through a digital addressable lighting interface (DALI). This interface was connected to a computer that had lighting control software installed. Nine preset lighting situations combining three illumination levels (300, 500 and 750 lx) and three CCTs (3000, 4000 and 5000 K) were saved for the user study. European standard [6] for indoor lighting recommends a factor of 1.5 between illuminance differences to give a perceptual difference. The illuminance levels and CCTs were measured form the measurement point marked in Fig. 1 (b). The relative spectral power distribution of three CCTs at an illuminance level of 500 lx is shown in Fig. 2.

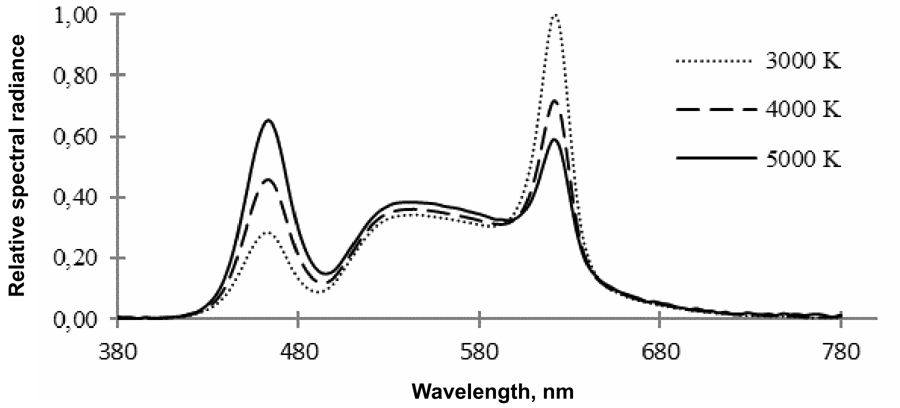


Fig. 2. The relative spectral power distribution under three CCTs at 500 lx

1) Please mark inside the box that most accurately describes how you feel about the lighting inside the room for office activities:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Very Unpleasant | O | O | O | O | O | O | O | Very Pleasant |
| Very Dim | O | O | O | O | O | O | O | Very Bright |
| Very Uncomfortable ( visually) | O | O | O | O | O | O | O | Very comfortable (visually) |
| Not Stimulating | O | O | O | O | O | O | O | Stimulating |

2) The light in this room to perform the office activities is:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Too little light | O | O | O | O | O | O | O | Too much light |

3) The room in this lighting appears:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Not spacious | O | O | O | O | O | O | O | Spacious |

4) The lighting inside the room make
   a) Hand looks

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Very unnatural | O | O | O | O | O | O | O | Very Natural |

   b) Color Checker Chart looks

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Very unnatural | O | O | O | O | O | O | O | Very Natural |

5) Furniture's and other objects looks

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Very unnatural | O | O | O | O | O | O | O | Very Natural |

6) In general, I prefer this lighting for office activities:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Not at all | O | O | O | O | O | O | O | Prefer very much |

Comments: ……………………………………………………………………………………………

Fig. 3. The questionnaire used in the study

CIE colour rendering index (CRI) values were 93 (3000 K), 94 (4000 K), 92 (5000 K) at all three illuminance levels and Duv values were within the limit of ± 0.0054. The illuminance uniformity (E_min/E_avg) in the whole room was around 0.70. Horizontal illuminances were measured in a 60 x 60 cm grid, from a total of 42 discrete points around the room, 0.72 m above the floor (at the same height as the work desk).

### 2.2. Method

Altogether, 53 observers, aged 20 to 53 years (mean = 29 years, standard deviation (SD) = 6 years), took part in the experiment. Among the 53 observers, 20 were of European ethnicity, 20 were of Asian ethnicity and 13 were of African ethnicity. All the observers were tested for visual acuity and colour vision before the experiment and only those observers who had normal visual acuity (with or without eyeglasses) and colour vision took part in the experiment. The observers were either office employees or students, and none of them were from the lighting field.

Nine different preset lighting situations were presented to the observer in a random order. The lighting situation was turned on before the observer entered the room. When entering the test room, the observer was instructed to sit in an armchair in the corner of the room for one minute. During this time, the observer was given an oral explanation of the questions and rating scale. The observer then moved to the work table and spent five minutes performing the reading task, matching task and typing task, to be familiar with the activities performed in an office environment. The reading task was to read a paragraph printed in black on white A4-sized paper with text in 12 point Times New Roman font, using 1.5 line spacing. The matching task was to compare two columns of an Excel sheet consisting of random, five-digit alpha-numerical codes and to find out whether the two columns had the same alpha-numerical codes in the same order or not. The typing test was to type sentences from a paragraph for one minute. Following the tasks, the observer was asked to fill the questionnaire and to write open-ended comments (Fig. 3) regarding the lighting situation inside the room.

The questionnaire was developed to investigate various aspects of office lighting: pleasantness, brightness, visual comfort, stimulation, the amount of light, the apparent spaciousness of room, the naturalness of colours and overall preference. The rating scale of the questions was a seven-point scale. The right end of the seven-point scale was labelled with terms related to the most positive response and the left end with the most negative response. After evaluating all the questions, the observer was asked to go outside the test room and wait in the corridor for one minute. There were no windows in the corridor, so the illuminance conditions in the waiting area remained constant regardless of the outdoor lighting conditions. The experimenter changed the lighting situation in the room to a new one and asked the observer to come back again after one minute of waiting time. This process was repeated until all nine preset lighting situations had been presented to the observer.

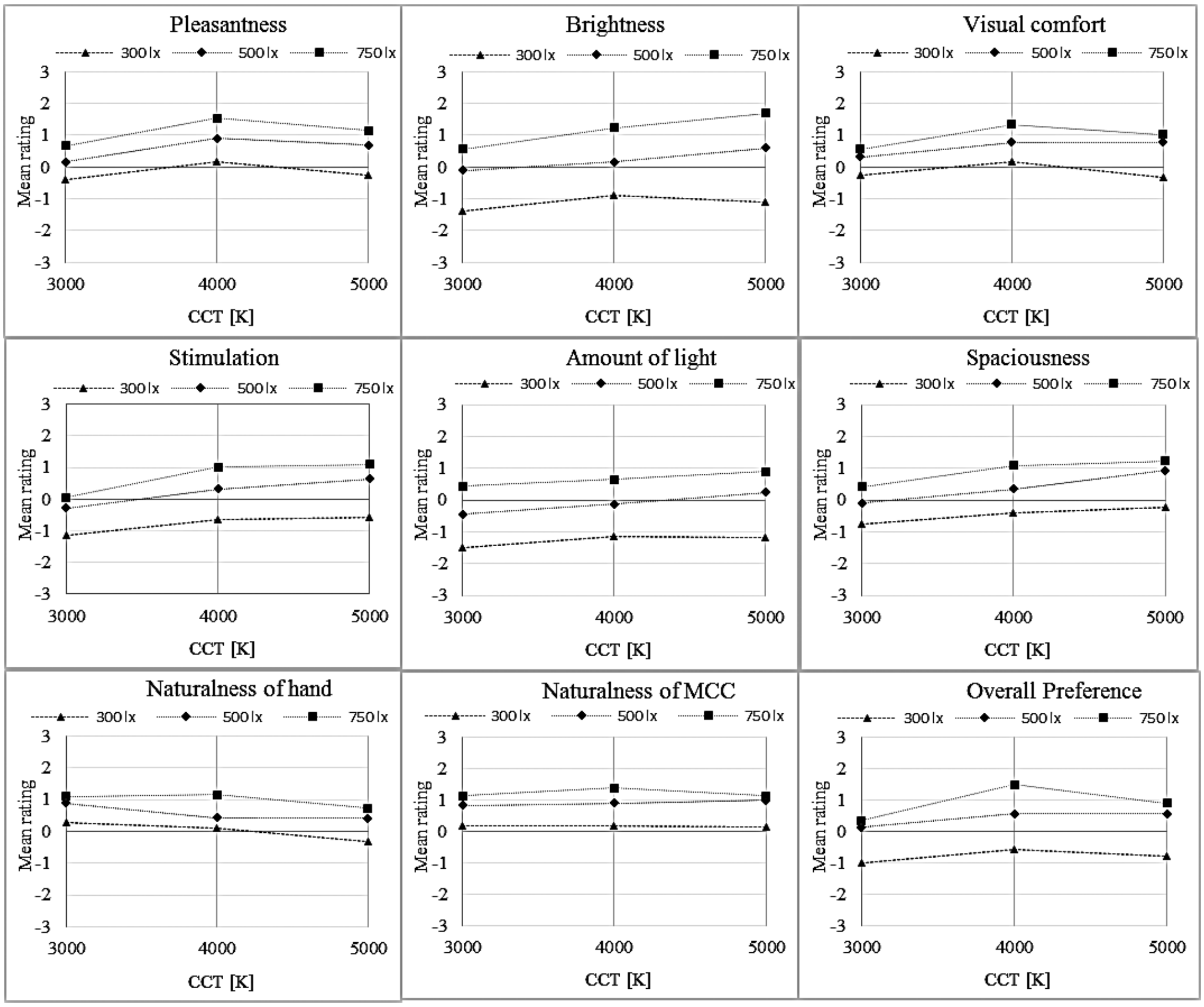


Fig. 4. The observers' mean rating for a particular question under different preset lighting situations

## 3. RESULTS

The questionnaire ratings were converted into numerical values on a seven-point scale between –3 and 3. The observers mean ratings for different questions are shown in Fig. 4. The observers mean ratings for the CCT preference of the three ethnic groups for naturalness of hand and overall preference at 300 lx, 500 lx, and 750 lx are shown in Fig. 5.

### 3.1. Statistical analysis

An analysis of variance (ANOVA) with a significance level of $p = 0.05$ was performed to investigate the statistical significance of the observers' ratings for a particular question. A *post-hoc* analysis was performed using the Duncan procedure to investigate which lighting situations and which CCT observers preferred for the questions for which the differences in observers' mean ratings were statistically significant. Summary of statistical analysis for the preference among nine different lighting situations, for the preference of CCT at 300 lx, 500 lx, and 750 lx, and for the CCT preference of three ethnic groups (Asian, European and African) at 300 lx, 500 lx and 750 lx are shown in Appendix (Table A1-A3 respectively).

## 4. DISCUSSION

Among nine different preset lighting situations the combination of 750 lx with 4000 K had the highest observers' mean rating for the pleasantness of the lit environment, visual comfort, the natural appearance of the observer's hand, the natural appearance of the MCC's colours, and the natural appearance of the furniture. In addition, for the overall preference of the lit environment, the observers' mean rat-

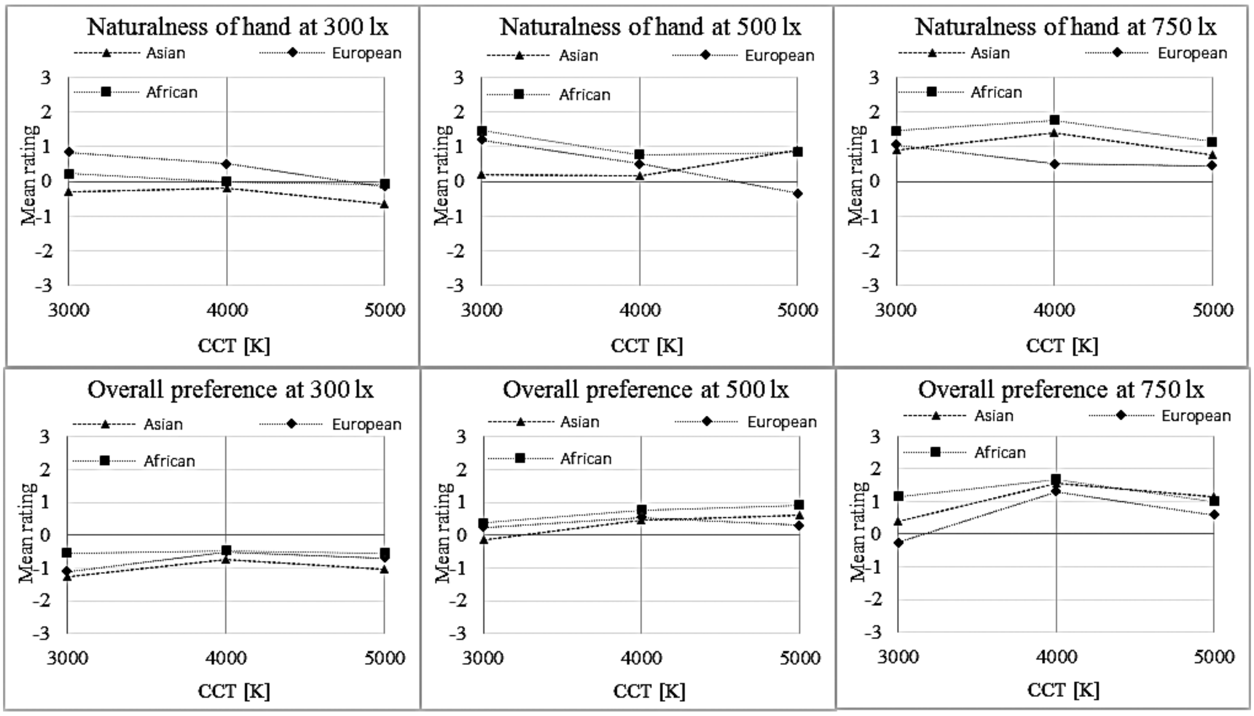


Fig. 5. The observers' mean rating for the CCT preference of three ethnic groups (Asian, European, and African) for naturalness of hand and overall preference

ing for the combination of 750 lx with 4000 K was statistically significantly highest of all the combinations. The combination of 750 lx with 5000 K was rated highest of all the combinations for perceived brightness, stimulation, amount of light and spaciousness. It is also worth noting that although the combination of 750 lx with 3000 K was a higher illuminance level than the combinations of 500 lx with 4000 K or 5000 K, the observers' mean ratings for pleasantness, visual comfort, brightness, stimulation, spaciousness and overall preference for this combination were lower. Hence, this indicates that the observers' preference in an office room was not only influenced by illuminance level changes but also by light source CCT changes, and that the proper combination of the illuminance level and CCT is more important than a higher illuminance level for giving a better visual impression through lighting in an office room.

Although there were no statistically significant differences between the observers' ratings for pleasantness at 300 lx, the observers mean rating for the lit environment under 4000 K was pleasant and under 3000 K and 5000 K were unpleasant. In a study by Viènot *et al.* [13] with LED panels inside a light booth, the lit environment under 4000 K was also rated higher for pleasantness than the lit environment under 2700 and 6500 K at 300 lx. At 500 and 750 lx, the observers' mean ratings for pleasantness were statistically significantly higher under 4000 K than under 3000 K. Dikel *et al.* [17] also found a

**Table A1. A summary of the statistical analysis of the observers' preference among nine different lighting situations**

| Questionnaires | | Preferred lighting situation |
|---|---|---|
| Pleasantness | | 750 lx, 4000 K |
| Brightness | | **750 lx, 5000 K** |
| Visual comfort | | 750 lx, 4000 K |
| Stimulation | | 750 lx, 5000 K |
| Amount of light | | 750 lx, 5000 K |
| Spaciousness | | 750 lx, 5000 K |
| Naturalness of | Hand | 750 lx, 4000 K |
| | MCC colour | 750 lx, 4000 K |
| | Furniture | 750 lx, 4000 K |
| Overall Preference | | **750 lx, 4000 K** |

Lighting situations in regular font was in the group of the highest mean value in the Duncan test and had the highest mean value among other lighting situation in the group

Lighting situations in bold font had statistically significantly highest mean value of all the combinations

**Table A2. A summary of the statistical analysis of the observers' preference of CCT at 300 lx, 500 lx, 750 lx respectively**

| Questionnaires | | 300 lx | 500 lx | 750 lx |
|---|---|---|---|---|
| Pleasantness | | 4000 K | **4000 K** | **4000 K** |
| Brightness | | 4000 K | **5000 K*** | **5000 K*** |
| Visual comfort | | 4000 K | 4000 K and 5000 K | **4000 K** |
| Stimulation | | **5000 K** | **5000 K** | **5000 K** |
| Amount of light | | 4000 K | **5000 K*** | 5000 K |
| Spaciousness | | 5000 K | **5000 K*** | **5000 K** |
| Naturalness of | Hand | 3000 K | 3000 K | 4000 K |
| | MCC colour | 3000 K | 5000 K | 4000 K |
| | Furniture | 4000 K and 5000 K | 4000 K | 4000 K |
| Overall Preference | | 4000 K | 4000 K and 5000 K | **4000 K*** |

CCT in regular font had the highest observers' mean ratings for a particular question at particular illuminance level but the difference in observers' ratings were not statistically significant

Bold font CCT was in the group of the highest mean value in the Duncan test and had the highest mean value in the group for particular question at particular illuminance level

Bold font CCT* had statistically significant highest mean values of all the CCTs

similar result in an experiment conducted with LED panels in a light booth, where the lit environment under 3728 K was rated more pleasant than under 2855 K at 500 lx. In contrast, another study [13] found that the lit environment under 2700 K was rated more pleasant than under 4000 K at 600 lx. Our study is not entirely comparable with the studies [13] and [17] since they were done in a light booth. According to the authors of the above-mentioned study [13], the reason for the highest rating for pleasantness at the lowest CCT in their study may be due to the restricted illuminated field of view in the light booth and dark surroundings.

At 500 lx and 750 lx, the observers' mean rating for perceived brightness was statistically significantly highest under 5000 K. This result supports the finding of previous research [18–20], which found that observers' impressions of brightness increased with an increased CCT. The observers' mean rating for the apparent spaciousness of the room was also highest under 5000 K at all three illuminance levels. The reason for the highest observers' mean rating for apparent spaciousness under 5000 K might be due to the fact that brightness prompts the impression of spaciousness [21]. The observers' mean rating for an insufficient amount of light for office activities under 3000 K and 4000 K, but a sufficient amount of light under 5000 K at 500 lx is also due to the highest perceived brightness being under 5000 K, compared to 3000 K and 4000 K. The observers' mean rating for stimulation under 5000 K is statistically significantly higher than under 3000 K at all three illuminance levels. The reason for the highest mean rating for stimulation at 5000 K might be due to the observation that mental activity levels are higher under a higher CCT compared to under a lower CCT [22]. It was found that the observers' mean rating for visual comfort under 4000 K was higher than under 3000 K at 300 lx and 500 lx and statistically significantly higher under 4000 K than under 3000 K at 750 lx. This result supports the findings of Lin *et al.* [15] who found that the observers' mean rating for comfort under 4000 K was higher than at 3000 K and 600 lx. Although there were no statistically significant differences between the observers' ratings, the skin of an observer's hand looks more natural under 3000 K at 300 and 500 lx, whereas at 750 lx it looks more natural under 4000 K. The colour of furniture looks more natural under both 4000 K and 5000 K than under 3000 K at 300 lx; at 500 and 750 lx it looks most natural under 4000 K.

**Table A3. A summary of the statistical analysis of CCT preference of three ethnic groups**

| Illuminance level | Ethnicity | Pleasantness | Brightness | Visual comfort | Naturalness of Hand | Overall Preference |
|---|---|---|---|---|---|---|
| 300 lx | Asian | 4000 K and 5000 K | 4000 K | 4000 K | 3000 K | 4000 K |
| | European | 4000 K | 4000 K | 4000 K | 3000 K | 4000 K |
| | African | 4000 K | 4000 K | 4000 K | 3000 K | 4000 K |
| 500 lx | Asian | **5000 K** | 5000 K | 5000 K | 5000 K | 5000 K |
| | European | 4000 K | 4000 K | 4000 K | **3000 K** | 4000 K |
| | African | 5000 K | 5000 K | 5000 K | 3000 K | 5000 K |
| 750 lx | Asian | 5000 K | **5000 K** | 4000 K | 4000 K | 4000 K |
| | European | 4000 K | **5000 K** | 4000 K | 3000 K | **4000 K** |
| | African | **4000 K** | 5000 K | 4000 K | 4000 K | **4000 K** |

CCT in regular font had the highest observers' mean ratings for a particular question at particular illuminance level but the difference in observers' ratings were not statistically significant

Bold font CCT was in the group of the highest mean value in the Duncan test and had the highest mean value in the group for a particular question at particular levels of illuminance

The statistical analysis of the CCT preference for pleasantness of light perceived by ethnic groups showed that the European preference for a lit environment under CCT 4000 K was significantly higher than under 3000 K at 750 lx, and the Asian preference for a lit environment under 5000 K was significantly higher than under 3000 K at 500 lx. The results showed that, generally, observers from the European ethnic group found a lit environment under 4000 K more pleasant than under 3000 K and 5000 K, and observers from the Asian ethnic group found a lit environment under 5000 K more pleasant than under 3000 K or 4000 K. At 300 lx and 750 lx all three ethnic groups' mean ratings for visual comfort, as well as their overall preference, were highest under 4000 K. However, at 500 lx, observers from the Asian and African ethnic group had the highest mean rating under 5000 K and those from the European ethnic group had the highest mean rating under 4000 K for visual comfort and an overall preference. The observers from the European ethnic group preferred 3000 K for the natural appearance of their hand at all three illuminance levels, which is in line with the results of Quellman and Boyce [23] who found that a compact fluorescent lamp (CFL) with 3000 K was preferred over the 4000 K and 5000 K when considering the apparent naturalness of hands. It was also found that the brightness perception of all three ethnic groups increases with a higher CCT. The results showed that observers from the European ethnic group preferred a lit environment under CCT 4000 K for pleasantness, visual comfort and overall preference for the office lighting. Although observers from both Asian and African groups preferred a higher CCT than 3000 K for office lighting, the choice between 4000 or 5000 K depends upon illuminance levels.

## 5. CONCLUSION

The user study described here demonstrated that the combination of 750 lx with 4000 K was statistically significantly preferred for office lighting. There were indications that the observers' preference in an office room was not only influenced by illuminance level changes but also by light source CCT changes and the proper combination of the illuminance level and CCT is more important than a higher illuminance level for giving a better visual impression through lighting in an office room. It was also found that the brightness perception increases with increased CCT, which prompted the impression of spaciousness in the office room and people feel more stimulated under higher CCTs compared to under lower CCTs.

The results of CCT preference by ethnicity showed that none of the three ethnic groups preferred 3000 K for office lighting except for giving a natural appearance to the skin of their hand. The results also showed that observers from the European ethnic group preferred a lit environment under 4000 K for pleasantness, visual comfort and overall preference for office lighting. Although observers from both Asian and African ethnic groups preferred a higher CCT than 3000 K for office lighting, the preference between 4000 and 5000 K depends upon illuminance levels.

The results provide guidelines for the preferred choices for illuminance and CCT in office lighting suggesting that people statistically prefer to have higher illuminance level than given in today's indoor lighting standards and they prefer CCT of 4000 K for office lighting.

## 6. ACKNOWLEDGEMENTS

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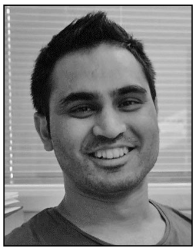

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# CHALLENGES OF NEW STANDARDIZATION IN LIGHT MEASUREMENT OF SSL-PRODUCTS

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## ABSTRACT

The basic requirement for development and advancement of good lighting systems is provided by precise and reliable measurements. International standards ensure that different laboratories across the world apply uniform measurement conditions and that the results obtained can be compared with each other. In the past, there has been no standard of this kind for photometric data from LED lamps and luminaires. This "unstandardized" era has come to an end over the past few months. A draft standard has now been drawn up by the International Commission on Illumination (CIE). This document was first published in September 2014 and it is commercially available. In the future, this new standard will provide a platform for international standardization when taking photometric measurements from Solid-State Lighting (SSL) sources. This article presents the key content of the standard and outlines the associated challenges to users. It also provides examples for correct application of the new standard.

**Keywords:** standartization, SSL lighting, goniospectroradiometer, tolerance interval, accteptance interval

## BACKGROUND TO STANDARDIZATION FOR MEASUREMENT PROCEDURES USED IN TESTING SSL PRODUCTS

In the past, the lack of alternatives has meant that since 2008, the IES LM-79–2008 testing method developed by the subcommittee "Solid-State Lighting" of the Illuminating Engineering Society (IES) "Testing Procedures Committee" has effectively been used as the international standard for measurements taken from SSL products. However, as a purely North American standard, the LM-79 lacked the coverage of worldwide accreditation. A number of national documents, such as the draft standard DIN 5032–9 in Germany, the CQC and GB Standards in China or the JIS Test Methods in Japan, existed in parallel to the North American standard.

Over a period of many years, standardization committees have been working to close this gap by creating an international standard. 2013 therefore saw publication of the European standard prEN 13032–4:2013, which had been developed by the Working Group WG7 "Photometry" of the Technical Committee CEN/TC 169 "Light and Illumination". The secretariat of this committee is managed by the DIN German Standards Organization. The "Photometry" Working Committee of the Light Metrology Standards Committee (FNL) within the DIN German Standards Organization was responsible for drawing up the German national version. Simultaneously and in close cooperation with the WG7 Working Group, the TC2–71 Technical Committee of the International Commission on Illumination (CIE) was working on a reference standard with the same content. In autumn 2014, the draft standard CIE DIS 025:2014 was published (http://www.techstreet.com/cie/products/1883425). This represents a milestone in the development of an international standard for the analysis and presentation of photometric data from lamps, luminaires and modules based on LEDs. In contrast to LM-79, which does not include LED modules, the

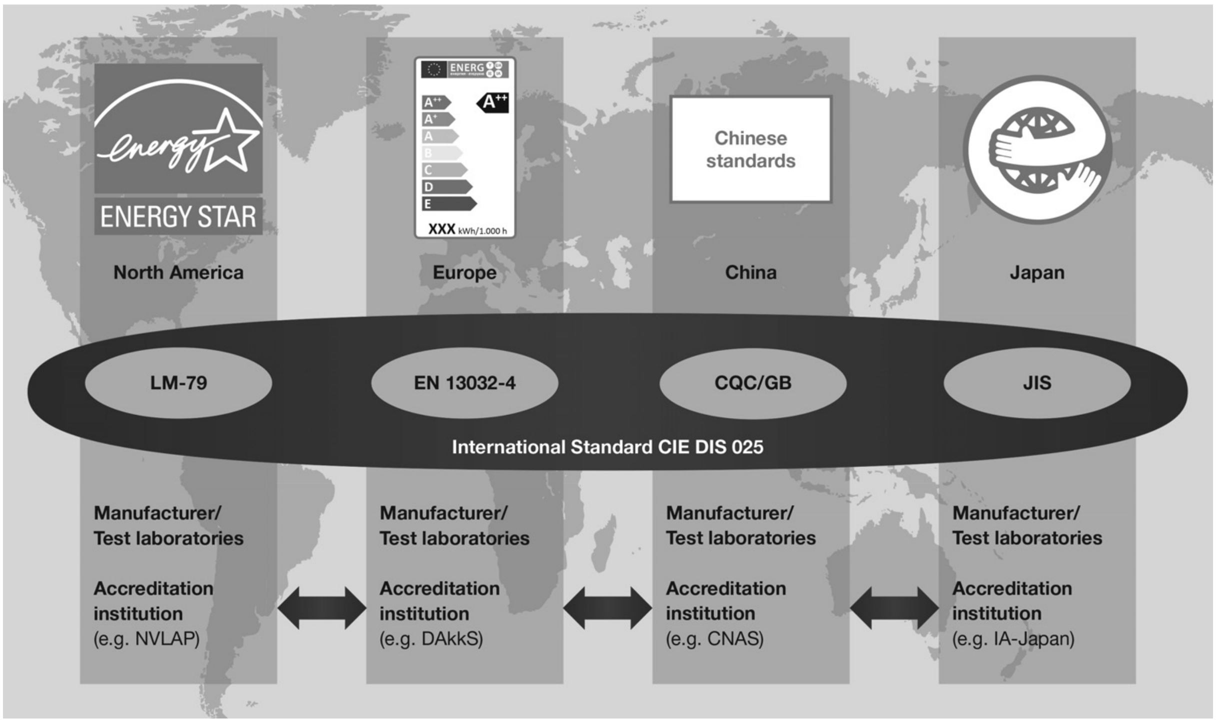


Fig. 1. Simplified situation of global standardization in light measurement. The new international standard will exert a significant influence on the desired harmonization and comparability of different metrology and accreditation institutes (indicated by the red arrow)

standard encompasses LED modules, LED lamps, LED light engines and LED luminaires. The only devices not included in this draft standard are LED packages and products based on OLEDs. Adoption as a CIE Standard is anticipated within the next six months and publication of the CIS S 025 is then planned as an ISO/CIE/IEC "Triple Logo" Standard. The new standard will be the first international guideline to cover the measurement procedures for SSL products and will exert a significant influence on the proposed harmonization, Fig. 1.

## THE NEW STANDARDS AND THEIR PRINCIPLES

LM-79–2008 partly includes restrictions on measuring equipment, which are not absolutely necessary, if the latest state-of-the-art in research is taken into account, in order to obtain precise and reliable measuring results. Furthermore, many users of the standard adhere strictly to the formulations. As a result, some measuring systems or test setups may be disqualified, which would be in a position to achieve equivalent or even better measuring results.

The CIE DIS 025:2014 eliminates the restrictions under the LM-79 described above. In principle, all measurement techniques are permitted. However, verification is sometimes requested that the technique being applied delivers equivalent results to an established measurement method.

The measured quantities covered by the new standard include measurement of luminous flux (including partial luminous flux and derived parameters, such as luminous efficacy), luminous intensity distributions, luminance and colorimetric quantities, such as chromaticity coordinates, correlated color temperature (CCT), distance from the Planckian locus (Duv), color rendering indices and angular color uniformity. Appropriate test setups recommended for all measured quantities and some restrictions are defined. In the case of luminous flux, for example, integrating sphere photometers and integrating sphere spectroradiometers are recommended for modules, lamps, and small luminaires.

However, a goniophotometer or goniospectroradiometer have to be used for measuring the luminous flux of larger luminaires and to determine the luminous intensity distribution. The CIE C, γ-coordinate system must be used here. The resolution of the measurement, i.e. the angular interval defined by the user, is determined taking into account the type of distribution and the symmetrical characteristics, such that an interpolation is possible during postprocessing. The classic tristimulus colorimeter

**Table 1. The standard test conditions and tolerance intervals of CIE DIS 025**

| | Standard test condition | Tolerance interval | Applicable for |
|---|---|---|---|
| Ambient temperature | 25.0 °C | ±1.2 °C | LED lamps/luminaires, light engines |
| Surface temperature | Nominal operating temperature tp | ±2.5 °C | LED modules |
| Air movement | Stationary air | 0 m/s to 0.25 m/s | |
| Test voltage/Test current | Nominal voltage, nominal current | ±0.4% for root mean square value (RMS) alternative voltage;<br>±0.2% for direct voltage and current | |

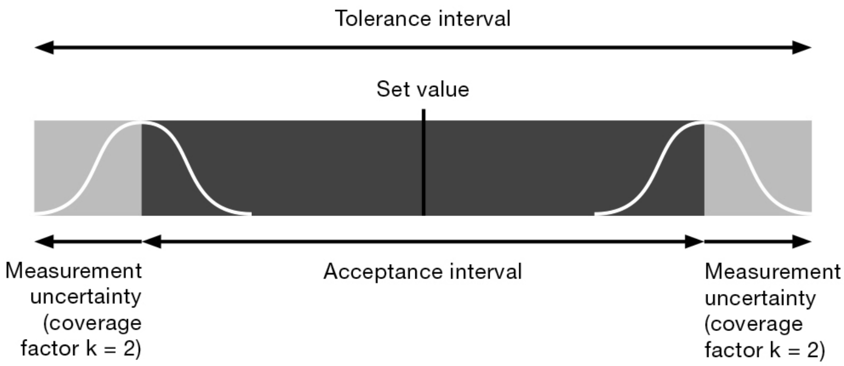


Fig. 2. Connection between set value, expanded measurement uncertainty, tolerance and acceptance interval. The definition of the tolerance interval does not take account of measurement uncertainty.

is excluded for determination of colorimetric values and only integrating sphere spectroradiometers and goniospectroradiometers are authorized for this analysis.

## STANDARD TEST CONDITIONS AND CORRECTIONS

In order to exclude unnecessary restrictions in selection of the measurement technique on the one hand, while also obtaining an accurate, reliable and comparable measurement on the other hand, CIE DIS 025 defines uniform standard test conditions (Table 1), as well as special requirements and instrumentation (Table 2). These conditions are specified for the laboratory, the environment, and the test instruments. Each standard test condition is subject to a set value and a tolerance condition, which is specified by a tolerance interval. Since the definition of the tolerance interval does not take account of measurement uncertainty, different accuracy characteristics can be accepted for the measuring device. The range yielded by deduction of the extended calibration uncertainty (twofold standard deviation) of the instrument being used is known as the acceptance interval (Fig. 2). The measured parameter must be within the acceptance interval for a standard-compliant measurement. The measuring results can be corrected to the set value of the tolerance interval in order to reduce the measurement uncertainty. The special requirements for the test setup may also be corrected in some cases.

The operator carrying out the test is responsible for generating an appropriate measurement uncertainty budget. All additional factors contributing to measurement uncertainty, such as those arising from the application of corrections, must be taken into account. The standard recommends an analysis of measurement uncertainty in conformity with ISO/IEC Guide 98–3 or CIE 198. It is very challenging to draw up a measurement uncertainty budget, particularly for colorimetric quantities determined from spectral data. The CIE is working on a so-called “Technical Note” which is intended to supplement the standard in the future with the aim of providing some assistance in this matter.

**Table 2. Summary of special requirements defined by the CIE DIS 025 standard for measuring instruments**

| | Requirement |
|---|---|
| Calibration uncertainty for voltmeter and ammeter | AC: ≤0.2%<br>DC: ≤0.1% |
| Calibration uncertainty and bandwidth of AC power meters | ≤0.5%<br>Bandwidth ≥ 100 kHz[1] |
| Internal impedance voltmeter | ≥1 MΩ[2] |
| Drift and fluctuation of the voltage supply | Within the acceptance interval for test voltage and test current |
| Harmonic content and frequency uncertainty of operating voltage | ≤1.5%[3]<br>±0.2% of the required frequency |
| AC component for direct-current supply | ≤0.5% (rms) |
| Electric and photometric stabilization for the device under test | LED lamps and luminaires:<br>≥30 min and relative difference of maximum and minimum measured values of the previous 15 minutes <0.5%<br>LED modules:<br>Operating temperature tp achieved and retained for 15 min in an interval of ±1 °C |
| Spectral sensitivity photometer | V (λ) mismatch index $f_1'$ ≤3% |
| Surface device under test for measurements with integrating sphere | 4 π: ≤2% of the inside surface of the sphere<br>2 π: diameter of the sphere aperture ≤1/3 of the sphere diameter |
| Cosine correction of the detector for measurements with integrating sphere | Cosine Correction Index $f_2$ ≤15% |
| Repeatability for sphere opening/closing | ±0.5% |
| Stability of the spectral sensitivity of a sphere between recalibrations | <0.5% |
| Wavelength range and wavelength uncertainty for the spectroradiometer | 380–780 nm<br>≤0.5 nm (k=2) |
| Bandwidth and scanning interval spectroradiometer | ≤5 nm |
| Angular alignment and resolution angular display goniometer | ±0.5 °<br>≤0.1 ° |
| Photometric (test) distance | Beam angle ≥90°: ≥5 xD<br>Beam angle ≥60°: ≥10 xD<br>Narrow angular distribution / steep gradients: ≥15 xD<br>Large non-luminous areas with maximum distance S: ≥15 x (D+S) |
| Burning position | Measurement in specified burning position or correction to behavior of the device under test in the specified burning position (e.g. with the auxiliary photometer method)[4] |

[1] 5 kHz or 30 kHz are authorized without high-frequency components

[2] An even higher internal impedance of the measuring instrument is necessary for devices under test with high impedance

[3] ≤3% for power factors >0.9

[4] Not necessary for LED modules with temperature regulation

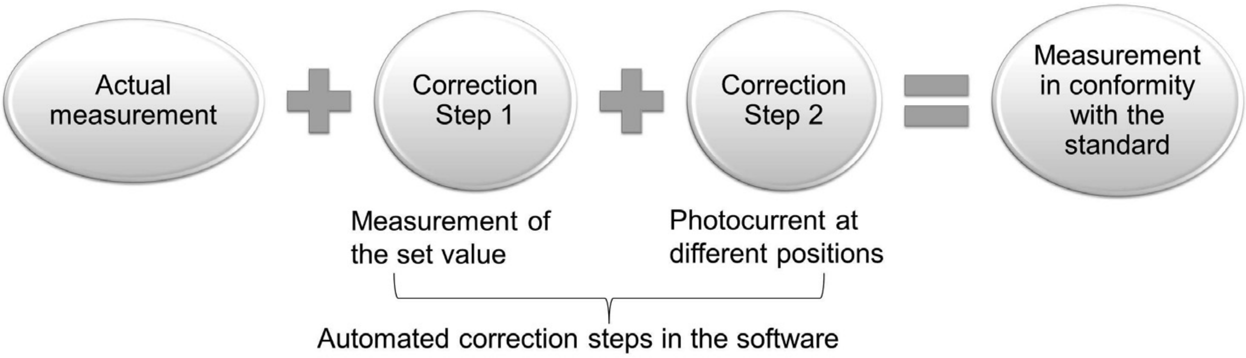


Fig. 3. Schematic diagram of the position correction with support from a software routine

The following example is used to highlight the correct application of standard test conditions, set value and tolerance and acceptance intervals. A tolerance interval of ±1.2 °C for ambient temperature is defined by the standard with a set value of 25 °C. Using a thermometer with extended (k=2) calibration uncertainty of 0.2 °C yields the acceptance interval of ±1.0 °C. A reading from this thermometer from 24 °C to 26 °C therefore corresponds to a measurement compliant with the standard. If the thermometer reading is, for example, 25.5 °C, it is not necessary to carry out a correction and an amount of 0.7 °C (0.5 °C for the deviation from the set value and 0.2 °C for the measurement uncertainty) must be included in the measurement uncertainty budget.

Although the standard test conditions have been complied with, the test engineer may wish to reduce the amount in the measurement uncertainty budget. This is possible by making an additional correction. A test can be carried out in order to correct the result of the measured value at 25.5 °C to the value, which would have been measured at 25.0 °C. This test determines the correction factor to be applied, which is based on the sensitivity coefficient of the device under test. The luminous flux of an LED lamp typically has a relative sensitivity of 0.5%/°C with respect to the ambient temperature.

A correction test can also be carried out using the same procedure if a test condition lies outside the corresponding tolerance condition or if the special requirements for the test instruments have not been complied with. One example for the application of this correction test is presented in the following section.

## CASE STUDY ON POSITION CORRECTION FOR GONIOSPECTRORADIOMETER

If the previous specifications of LM-79 are interpreted in strict terms, only goniometers with rotating detector or rotating-mirror goniophotometers are authorized in the special case of goniospectroradiometry. The disadvantages, such as the maximum sample size in goniometers based on a rotating detector or stringent requirements for the test laboratory and the financial investment required for the rotating-mirror goniometer are well known. As already discussed, strict restriction is no longer defined in the new standard. This means that other types such as a turning luminaire goniometer are also authorized in addition to the goniometers specified above. These compact and attractively priced far-field goniometers enable the outlined disadvantages of the other goniometer types to be avoided.

A turning luminaire goniometer can have the disadvantage that some test devices cannot be analyzed in the specified burning position. However, the new standard permits this type of measurement in principle. Although the resulting test condition is outside the tolerance condition, the behavior of the test device in the specified burning position can be corrected by applying an appropriate correction. The so-called auxiliary photometer method is one option for carrying out this correction. In addition to the actual detector, a monitoring auxiliary photometer is used. The relative position of this auxiliary photometer to the device under test is maintained constant throughout all measurements. The so-called reference value is determined in correction step 1, Fig. 3. The reference value is the photocurrent of the auxiliary pho-

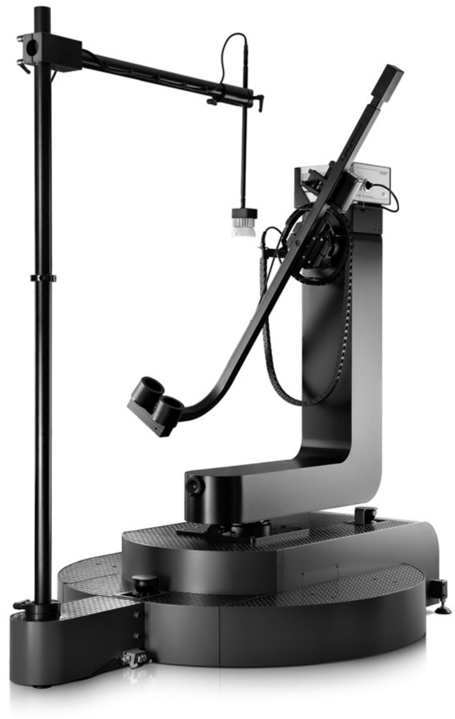

Fig. 4. LGS1000 with luminous flux integrator, photometer and radiometer

tometer, which is measured after the stabilization process of the light source in the specified burning position. Only a single measurement therefore needs to be carried out in the burning position and this can easily be implemented with an additional setup.

The final correction factor is measured in correction step 2. It is determined from the ratio of the reference value to the photocurrent reading of the auxiliary photometer for each angle pair approached by the goniometer (and hence for any change in position outside the specified burning position).

The method presented therefore delivers measurements in conformity with the standards and skillful implementation provides an easy opportunity to correct the measurements. The means to carry out the positional correction with the support of a special software routine is a significant advantage from the perspective of the user. Aside from the obvious benefits of simple operation and guidance through the sequence based on concrete instructions, the software helps operators to save valuable measuring time and avoid incorrect implementation of the correction process. The reduction in the measuring time can be achieved by making use of two facts:

– Firstly, potential disruption of the convective airflow through the fins of the heat sink is the reason why some LED sources are dependent on position. However, in the case of type C turning luminaire goniometers, changes in the $\gamma$ angle do not yield any change in orientation of the device under test with respect to the earth's gravitational force. It should therefore be anticipated that only one additional measurement lasting a few seconds (rotation of the C axis at a fixed $\gamma$ angle) is necessary in order to determine the correction factors;

– Secondly, when a number of identical light sources are being tested in the same test batch, the standard permits the correction of a typical source to be used. As a result, the amount of time required to determine the correction is significantly reduced.

As an example, in Fig. 4 is shown goniophotometer LGS1000 with luminous flux integrator, photometer and radiometer, which realizes these principles of measurement.

The luminous flux integrator is an optional accessory that offers the possibility of determining the total luminous flux of lamps and modules in their required burning position within a compact setup. The position of the sample remains unchanged during the measurement and the detector moves around the test specimen on a spherical envelope surface.

Two alternative versions of the luminous flux integrator can be supplied to match the specific measurement task.

The first version uses a fast operating photometer as a detector and is cost-effective. The second version combines photometer and spectrometer to offer the full range of options. It provides the speed of the photometer while also enabling the extremely precise spectroradiometric calculation of all characteristics.

Similar to the standard configuration, the test specimen can be supplied from an AC current source and electrical characteristics can be measured with an integrated power meter when the luminous flux integrator is used

## SUMMARY

The new standards for the photometric analysis of light sources based on LEDs are ready to be implemented at European and international level. The content requirements for measurement and evaluation methods have already been defined. The new standards offer more scope for freedom but also require more responsibility from the user. The complexity of handling the operating conditions, requirements of the measurement procedure and the generation of a measurement uncertainty budget require a high level of expertise. The examples described in this article, particularly the correction to the burning position, are intended to provide assistance in effectively interpreting the regulations defined in the new standards.

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# INTERNATIONAL INTERLABORATORY COMPARISON *IC* 2013 EXPERIENCE AND PARTICIPATION RESULTS OF THE VNISI TESTING CENTRE

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## ABSTRACT

Between October 2012 to August 2013 an International Interlaboratory comparison *IC 2013* light-emitting diode products measurements was undertaken by a group of international experts as part of a special programme of the International Energy Agency "IEA 4 E SSL Annex". During the following year, analysis and processing of the measurement results were carried out. Then progress reports were published. In September 2014, a final report was published, which contained the data and measurement result analysis of all participants[1]. 54 laboratories from 18 countries took part in the measurements directly. In addition, results from 35 US laboratories were included in the comparison report. They performed measurements for similar lamps using similar methods shortly before the start of the IEA 4 E SSL Annex project. Besides, data from 21 laboratories of the Asia Pacific Laboratory Accreditation Cooperation (APLAC) were included in the final report. Thus in total, measurement data from 110 laboratories worldwide were included in the *IC 2013* final report. The measurements were performed for 123 sets of test samples. Every set contained four or five types of lamps, including light-emitting diode lamps. The parameters measured for each test sample included luminous flux, active power, luminous efficacy, effective values of current and voltage, power factor, chromaticity coordinates, correlated chromatic temperature and colour rendition index.

This article considers the differences in measurements results obtained by participant laboratories, including the VNISI Testing Centre (VNISI TC), and between the measurement results obtained in the nucleus organising laboratories (NIST (USA), VSL (Europe), NLTC and AIST (Asia Pacific)). The obtained results were processed according to ISO 13528 international standard requirements (z'-index indicator was determined). In cases where a participant laboratory submitted evaluations of measurement uncertainties in its report, the $E_n$ value indicator was determined according to ISO/IEC 17043. An analysis of the results is given here.

**Key words:** interlaboratory comparison *IC 2013,* luminous flux, active power, rms (effective) current, rms voltage, luminous efficacy, chromaticity coordinates, correlated colour temperature, colour rendition index, power factor, measurement uncertainty and error, standard deviation

## 1. INTRODUCTION

The international comparison IC 2013 was arranged in order to evaluate professional capacities of laboratories offering their services for measuring lighting products parameters.

In order to involve laboratories from as many different regions of the globe as possible, four nucleus laboratories were selected as organisers and executors of the comparison:

– NIST (the USA, the National Institute of Standards and Technologies),

[1] The laboratories specified agreed to be entered into the published *IEA 4 E Annex list.*

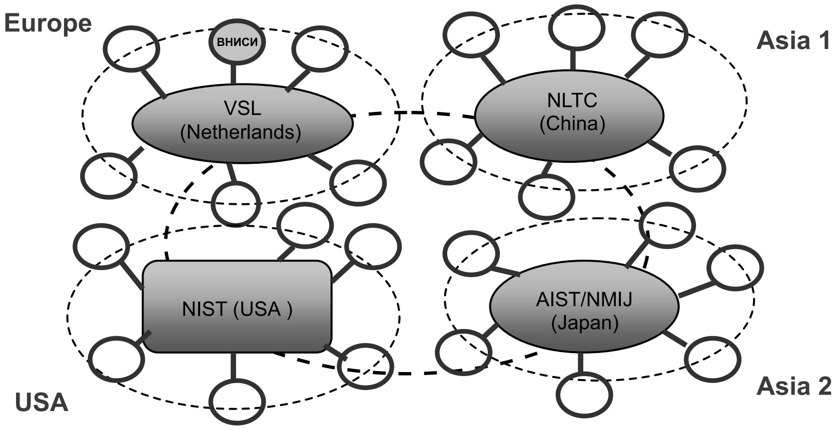


Fig. 1. A diagram showing the interaction of nucleus laboratories and participant laboratories when carrying out the comparison

a) b) c) d)

Fig. 2. Types of the lamps used as the transported samples to be compared: a) IAC - incandescent lamp; b) OD - "omni-directional" lamp (a light-emitting diode lamp with a removed phosphor); c) D - light-emitting diode lamp of directional light; d) LPF - light-emitting diode lamp with a low power factor

– VSL BV (Netherlands, the Dutch Metrological Institute);

– NLTC (the National Lighting Measurement Centre);

– AIST (Japan, the National Metrological Institute of Japan).

In the first instance, the nucleus laboratories performed a comparison between themselves. Following this, each participating laboratory was attached to one of the Nucleus Laboratories: VSL included mainly the European region, NLTC included China and Asian-Pacific, AIST/NMIJ covered Japan, and NIST the American region (Fig. 1). The nucleus laboratory for the VNISI Test centre was the Dutch Metrological Institute VSL (Van Swinden Laboratory, Netherlands, Delft).

Each participating laboratory received an identification code "Lab Code" and number "Lab #" before the measurements, which were known only to the participant and to the reference (nucleus) laboratory. Therefore, the results of the comparison measurements for all participants (except for the nucleus laboratories) are presented anonymously in the final report. It should be noted that participation in the international comparison fee based and cost 3,425 Euros per participant.

## 2. MEASURED VALUES, MEASUREMENT METHODS, AND UNCERTAINTY EVALUATION

For each test sample, the following characteristics were measured: luminous flux Φ (lm), effective (rms) values of current *i* (A) and voltage U (V), active power P (W), luminous efficacy η (lm/W), chromaticity coordinates (x, y), correlated colour temperature $T_{cc}$ (CCT), K, general colour rendering index $R_a$ and optionally, power factor PF. The measuring methods for the comparison process were developed by the International Energy Agency as

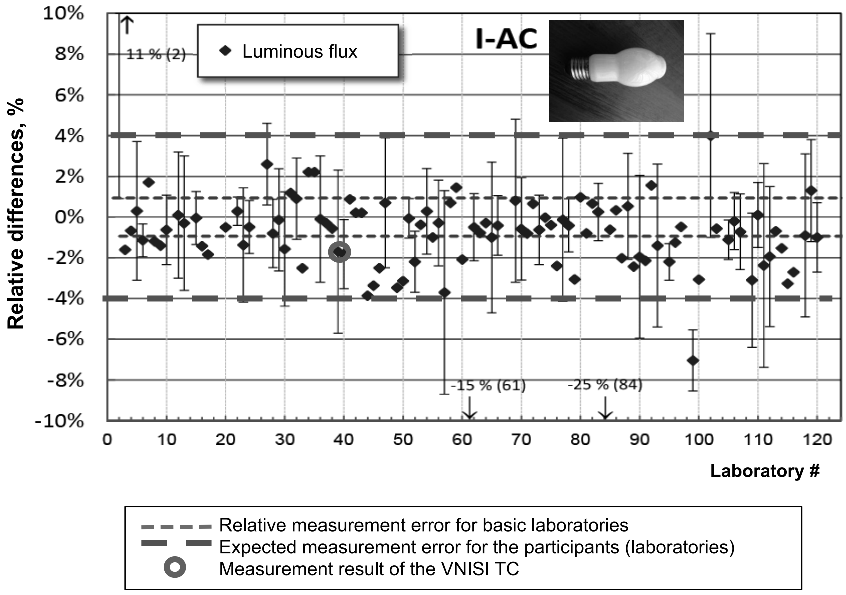


Fig. 3. Relative differences in luminous flux measurement results for an incandescent lamp

part of the 4E project (Efficient Electrical End-Use Equipment). The prepared document was published in October, 2012 [1].The stipulated the requirements for environment temperature and its evaluation, for humidity, installation conditions in the comparison process of the transported samples (artefacts) and for their power supply, for electric characteristic measurement conditions and for parameter stabilisation of the lighting devices used in the comparison. When measuring light and, mainly, chromatic characteristics of lighting devices, special attention is given to spectroradiometric methods in combination with sphere and goniophotometer methods. This is connected with an angular dependence of radiation spectral distribution of the samples based on light emitting diodes and with the necessity to average this characteristic for calculation of chromaticity coordinates, correlated chromatic temperature and colour rendition index.

Evaluations of the measurement uncertainty (error)[2] [2–4] in the comparison process were regulated by international standards. Values of the parameters under test were attributed to the measured samples by their corresponding nucleus organising laboratory and calculated as an average between the measurement results of each parameter before sending and after returning for each participant laboratory. Analysis and evaluation criteria for the measurement results obtained were based on calculating z'-index and $E_n$ value parameters, which are widely used in international practice of interlaboratory comparisons.

Which parameters are more appropriate depends on the state of the measuring baseline and therefore, on the uncertainty declared by a participating laboratory. In general, if $|E_n| > 1.0$, it is an unsatisfactory result, because it means that the measurement difference between the nucleus laboratory and a participant laboratory is more than the measurement error declared by the participant laboratory. From the other side, if a participant of the comparison declared big errors (low measurement accuracy), the participant can pass by this parameter, although the measuring baseline of that laboratory may not correspond to the measurement requirements for light-emitting diode light sources.

## 3. SAMPLES OF LIGHTING DEVICES FOR CARRYING OUT THE COMPARISON

In total during the comparison, 123 sets of lighting device samples were measured. One such sample set, which was obtained by the VNISI TC, is presented in Fig. 2. A linear tubular fluorescent lamp with a high chromatic temperature is absent among the pictures, because the VNISI TC had to give up its measurement due to the complexity of its transportation and custom procedures.

[2] In international practice, the uncertainty theory is applied for measurement result evaluation. In domestic practice, the error theory is used, and the uncertainty theory is only used at a level of primary references.

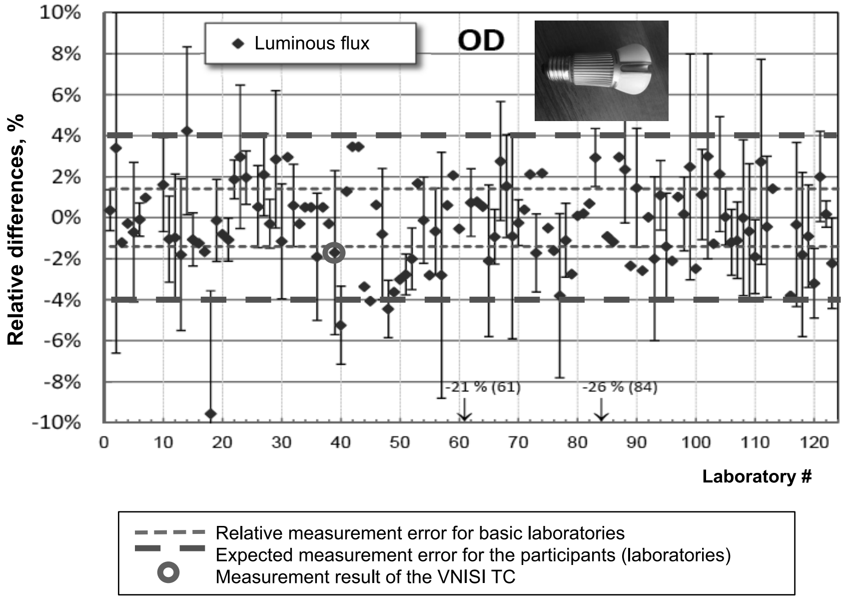


Fig. 4. Relative differences in luminous flux measurements for an "omnidirectional" light-emitting diode lamp with removed phosphor

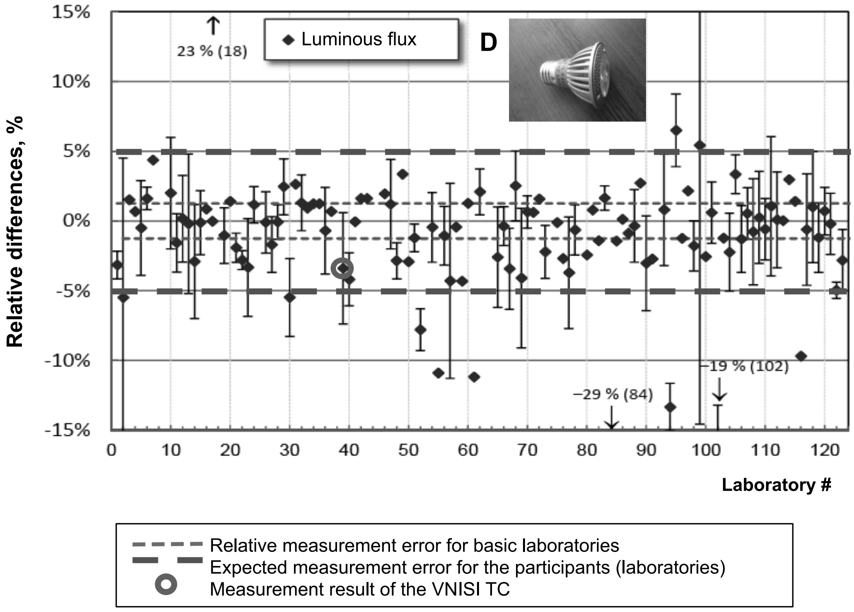


Fig. 5. Relative differences of luminous flux measurements for a directional light-emitting diode lamp with removed phosphor

## 4. RESULTS OF INTERNATIONAL INTERLABORATORY COMPARISON *IC2013*

### 4.1. A comparison between the nucleus laboratories

This large-scale international comparison of the lighting test laboratories comprised two stages. At the first stage, a group of four organising laboratories formed the group of reference (nucleus) laboratories to carry out comparisons between each other; at this stage measurement methods for the comparison process were developed and defined more precisely [1]. A set of six lighting devices was used for the comparison samples: lamps #1 and #2 were halogen incandescent lamps in a light-diffusing envelope of 150 W power and in a transparent envelope of 60 W power, lamp #3 was a light-emitting diode lamp with active feedback to provide stable chromatic parameters, lamp #4 was a light-emitting diode lamp with a removed phosphor, lamp #5 was a lamp with

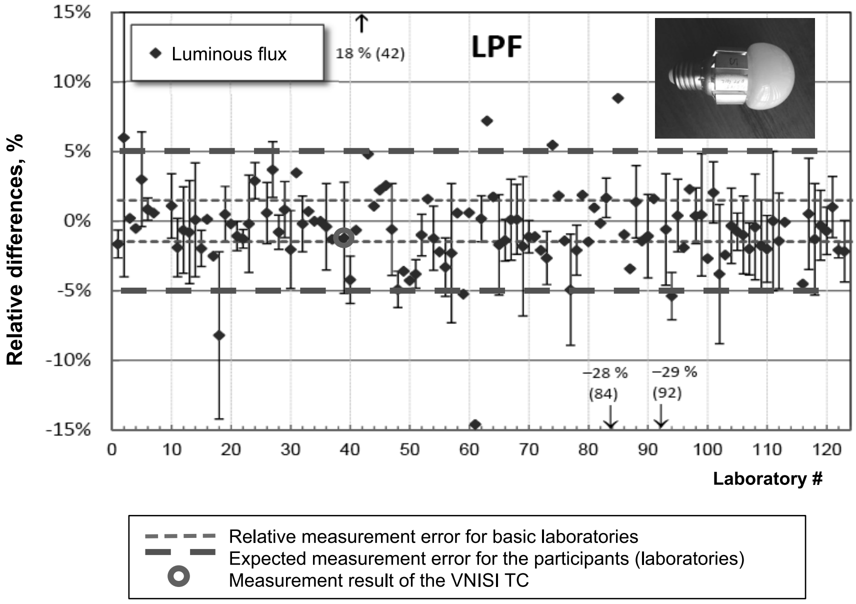


Fig. 6. Relative differences in luminous flux measurements for an LED lamp with low power factor

a big distortion of current waveform and total harmonic distortion (THD), lamp # 6 was a lamp of directional light of PAR20 type with a narrow beam.

The NIST (National Institute of Standards and Technologies of the USA) was the central laboratory between the organising laboratories, because laboratories of this institute had a high-precision baseline of primary photometric, colorimetric and spectroradiometric standards. They also made the greatest contribution to the preparation of standard materials for the comparison and to development of national and international standards regulating measurements of lighting devices with light emitting diodes. Comparisons of nucleus laboratories showed a high level of measurement accuracy of all organising laboratories and of the reproducibility of the measurement result. When measuring luminous flux, relative differences between measurements for all six samples amounted to no more than 1%, and for correlated chromatic temperature CCT – no more than 20°K. The nucleus laboratories' results are presented in more detail in their report [3].

The second stage of the international comparison included the following steps: forming sets of samples in the nucleus laboratories, measuring their parameters before sending to the participating laboratories, sending samples to the participating laboratories, measuring samples at the participating laboratories, return of the samples and repeated measurements in the nucleus laboratories after the samples are returned, preparation of progress and final reports.

Fig. 7. Goniophotometer RIGO-801 installed in the VNISI TC and used to measure luminous flux

### 4.2. Measurement results in the laboratories, which took part in the comparison

In the final report [4], all of the participating laboratories' measurements results are presented. Due to the great volume of material, only some of the data and graphs are mentioned in this article, but they allow drawing some conclusions about the state of domestic metrological support for luminous and chromatic measurements.

In Figs. 3–6, generalised results of the luminous flux measurements for some samples are presented, in which the VNISI TC took part. In the diagrams,

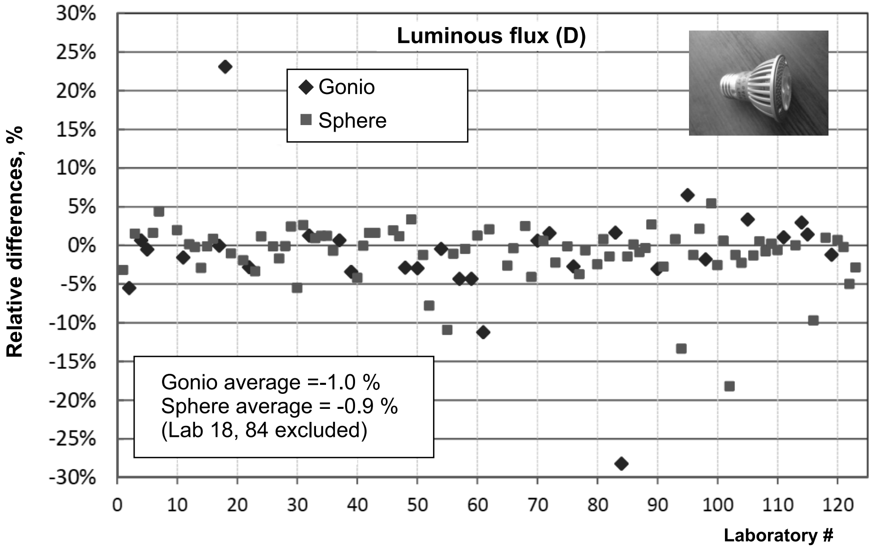


Fig. 8. Relative differences in measured luminous flux using the integrating sphere method and the goniophotometer method for light-emitting diode lamp D

participating laboratory numbers are placed on the x axis, and the relative differences between the measured values (in percent) are plotted on the y axis. These differences are determined using the formula:

$$d\Phi = 100 * (\Phi_{Lab} - \Phi_{Ref}) / \Phi_{Ref}, \quad (1)$$

where $\Phi_{Lab}$ is the measured value obtained by a participating laboratory,

$\Phi_{Ref}$ is the measured value obtained by the reference laboratory.

The dotted lines near zero show limits of the illustrated differences caused by expanded measurement uncertainties, which are attributed to the group of nucleus laboratories. The dotted upper and lower lines show an expected measurement error for participating laboratories. The circle marks the result of the VNISI TC measurements. The diagrams also show uncertainty error bars for most participant laboratories.

Based on Figs. 3–6 it can be seen that relative differences in measurements of full luminous flux of the samples are within ± 4% (IAC, OD) to ± 5% (D, LPF, HCCT), for most laboratories; an expected error limits according to the agreement between the laboratories.

The VNISI TC used a modern goniophotometer RIGO-801 for the comparison measurements of luminous flux (Fig. 7). The relative difference in luminous flux values from the VNISI TC compared to values obtained at the reference nucleus laboratory (VSL) amounted to:

– VSL-IAC – 1.73%;
– VSL-RP (OD) – 1.73%;
– VSL- D – 3.43%;
– VSL- LPF – 1.18%.

All of the measured values slightly lower than values of average luminous flux measured in samples from the nucleus laboratory (VSL), but they are well within the expected error limits of ±5%, which is attributed to the goniophotometer RiGO-801 after its certification at the VNIIOFI using SIP type luminous flux measurement lamps [5,6].

When measuring luminous flux, the participant laboratories did not only use the goniophotometer method, but also the integrating sphere method into the measurements. This allowed analysing and comparing measurement accuracy between laboratories and between methodologies. In Fig. 8, as an example, a relative difference is shown when measuring luminous flux using two methods for a light-emitting diode directional light sample lamp (type D).

The results of measuring differences in luminous flux for different types of samples using different methods are presented in Table 1.

It can be seen from Table 1 that the difference between the methods was no more 0.2%, which allows both methods to be considered as equivalent for this type of measurement.

We now turn to the comparison of colorimetric measurements for chromaticity coordinates ***x, y*** and for correlated chromatic temperature $T_{cc}$. In the nucleus laboratory comparison, differences in chromaticity coordinate measurements were small (± 0.001

**Table 1. Relative differences in measured luminous flux using the integrating sphere method and the goniophotometer method for three sample types**

| Sample type | Goniophotometer method | Iintegrating sphere method |
|---|---|---|
| I-AC (Incandescent lamp) | - 0.6% | - 0,7% |
| OD ("Omnidirectional" lamp) | - 0.5% | - 0.3% |
| D (Light-emitting diode directional lamp with a high $T_{cc}$) | - 1.0% | - 0.9% |

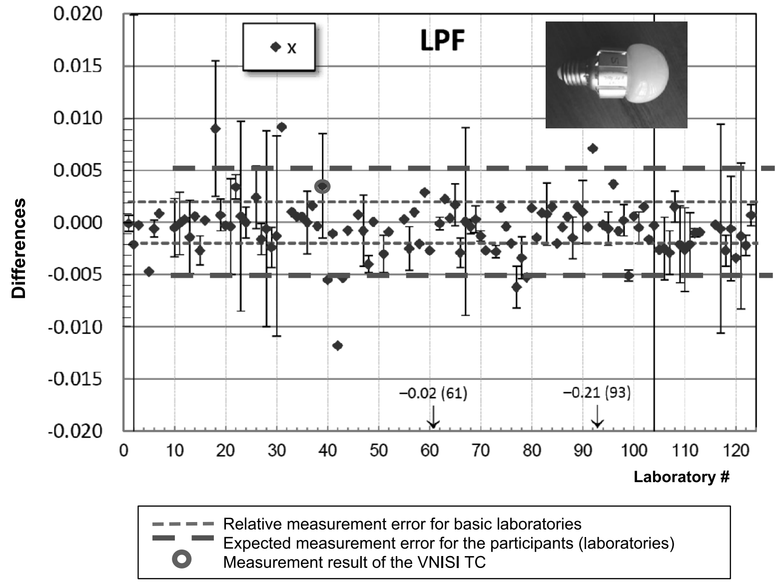


Fig. 9. Differences when measuring chromaticity coordinate ***x*** of a light-emitting diode lamp LPF

error margin). The comparison of results for chromaticity coordinates for participant laboratories showed different error values by every coordinate, which was between ± 0.002 and ± 0.006. As an example, diagrams Figs. 9 and 10 show results of measurement differences for chromaticity coordinates ***x*** and ***y*** for a lamp with a low power factor (LPF).

Due to a great number of measurements, it was possible to process the results statistically, calculating the standard deviation of the measured values relative to the true value. The true value is the value attributed by the nucleus laboratory. However, spikes in the measurement results necessitated the application of robust algorithms (algorithm A) for processing statistical data and calculating a robust standard deviation $s^*$ of the measured values [7].

The robust standard deviation $s^*$ for luminous flux measurement is presented in Fig. 11. From this diagram, it is clear that measurement differences for light-emitting diode samples occurred an average of 1.6 times more than deviations for incandescent lamps, which is indicative of greater error associated with measuring these lamps. Deviations between various types of LED lamps appeared to be insignificant.

Using a confidence level ρ = 0.95 as accepted in measurement practice, the relative error of luminous flux dΦ measurement can be estimated for all participant laboratories based on the data from diagram in Fig. 11 using the following [8]:

$$d\Phi \approx \pm 2\, s^*, \quad (2)$$

where s* is the robust standard deviation (RSD).

For example, RSD s* ≈ 2% for light-emitting diode LPF lamp. Accordingly, the relative error of luminous flux measurements amounts to ± 4%. The greatest relative error of ± 4.6% occurs when measuring a directional light light-emitting diode lamp (sample D); the smallest error ± 3% occurs when measuring incandescent lamps.

In the final report [4], the data of robust standard deviation for all types of the tests and for all test samples are given. Using these data and formula (2), it is possible to estimate the relative/absolute error of all measured parameters (luminous flux, power,

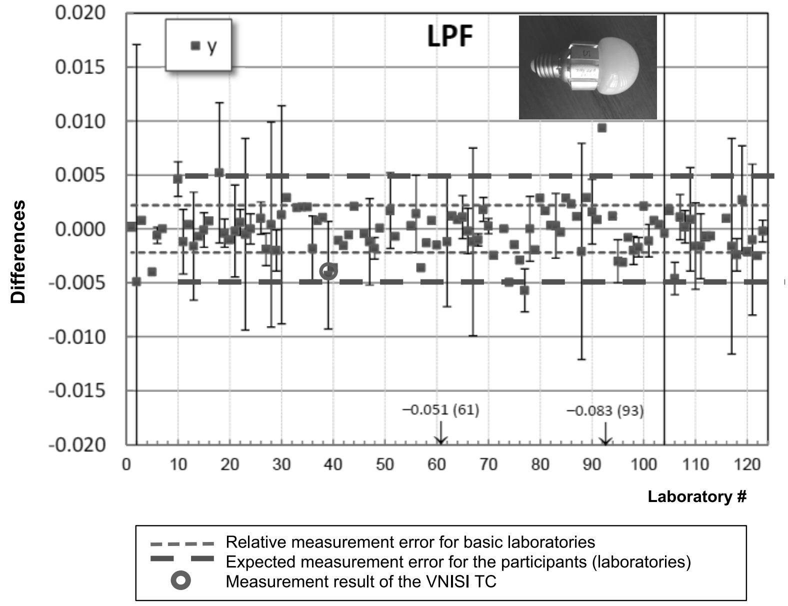


Fig. 10. Differences when measuring chromaticity coordinate ***y*** of a LED lamp LPF

etc) for 123 sets of the samples in 110 laboratories worldwide and thus to compute, a relative (or absolute) error of the measurements. These results are presented in Table 2.

## 5. AN ANALYSIS OF THE INTERNATIONAL COMPARISON RESULTS

From Table 2, it is clear that after the elimination of outliers, using the robust algorithm, the global relative or absolute error value for most of the measured parameters was within the expected margin of measurement error (the green dotted line on the diagrams). For example, when measuring luminous flux of light-emitting diode lamps, error value amounted to between 4.2% and 4.6%, while the expected margin of error was estimated to be 5% (Fig. 3–6). The greatest luminous flux measurement error of 4.6% was for a lamp with a narrow light beam (lamp D).

Differences in chromaticity coordinates ***x*** and ***y*** are similar for all samples with light emitting diodes and are no more than ± 0.002 – ± 0.005 for the majority of laboratories. It follows from Table 2 that light-emitting diode samples have approximately double the chromaticity co-ordinate deviation than incandescent lamps. These results confirm an essential specific error component inherent in light-emitting diode lamps, which increases measurement errors of their photometric and colorimetric characteristics.

Some difficulties were also caused by measurement of correlated chromatic temperature $T_{cc}$ and of colour rendition index CRI for HCCT/TL lamps with a high $T_{cc}$ (~ 6500 K). The error of determining general colour rendition index (CRI) $R_a$ does not depend usually on chromatic temperature $T_{cc.}$ Therefore, a large disparity of determined $R_a$ values when measuring HCCT lamps with a high $T_{cc}$ occurs. This can be explained by a difference in the spectral composition of calibration lamps used for the spectral radiometer calibration (usually these are halogen incandescent lamps), in relation to the tested lamp spectrum. This spectral composition difference is freater for high $T_{cc}$ lamps in comparison with low $T_{cc}$ lamps, which leads to significant measurement errors, due to, for example, diffused light in the spectral radiometer.

Differences in power factor measurements were also greater than expected, mainly from ± 0.01 (OD, D, HCCT) to ± 0.026 (LPF). Such big differences in electric measurements can be caused by differences in characteristics of alternating current sources used by the participants, in particular of the output impedance. This is an unresolved issue for current test methods for LED products. Further improvements are expected in this field.

## 6. CONCLUSION

• A large-scale international interlaboratory comparison project *IC 2013* was performed over two years and successfully completed in September

**Table 2. Values of relative/absolute errors after statistically processing the measurement results for 123 sample sets from 110 laboratories worldwide**

| Sample designation | Sample appearance VSL | Luminous flux (%) | Current (%) | Active power (%) | Luminous efficacy (%) | X Absolute units | y Absolute units | Correlated chromaticity temperature °K Absolute units | General colour rendering index (*CRI*) Absolute units | Power factor (PF) Absolute units |
|---|---|---|---|---|---|---|---|---|---|---|
| VSL-IAC (Incandescent lamp OSRAM) |  | ±3.0 | ±0.3 | ±0.3 | ±3.0 | ±0.0022 | ±0.0020 | ±24 | ±0.4 | ±0.0002 |
| **VSL-RP** (Distant phosphor lamp Philips) |  | ±4.2 | ±2.5 | ±1.3 | ±4.2 | ±0.0042 | ±0.0026 | ±58 | ±0.8 | ±0.018 |
| **VSL-D** (Lamp with a directed light beam) |  | + 4.6 | ±1.9 | ±1.2 | ±4.5 | ±0.0050 | ±0.0052 | ±103 | ±1.1 | ±0.015 |
| **VSL-LPF** (Lamp with a low PF and envelope and non-uniform chromaticity) |  | ±4.4 | ±4.2 | ±1.6 | ±4.4 | ±0.0038 | ±0.0038 | ±73 | ±1.1 | ±0.026 |
| **HCCT/TL** (Tubular led or fluorescent lamp with a high CCT) | – | ±4.4 | +1.0 | +1.0 | +4.4 | ±0.0042 | ±0.0056 | +236 | +1.5 | +0.008 |

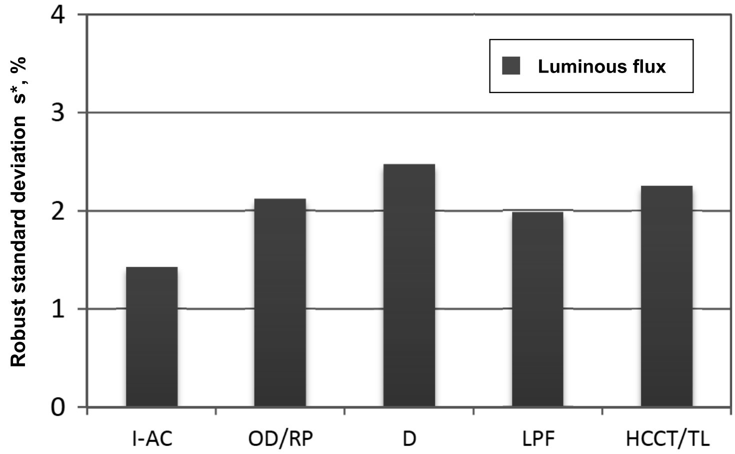


Fig. 11. Statistical processing of luminous flux measurement results
Robust standard deviation of luminous flux values for different types of lamps is plotted on the y axis, samples (lamp type) under test are presented on the x axis.

2014. A final report was published [4], comparing the results; the report is freely accessible to all interested stakeholders.

• The *IC 2013* comparison was an attempt to carry out a general evaluation of laboratory performance, which can support accreditation programmes and state programmes by using various regional test methods. With this aim in sight, a special test method for LDs with light-emitting diode light sources was developed and applied as part of the international comparison project IC 2013.

• The IC 2013 comparison project provided new knowledge and experience in measuring light-emitting diode products for the majority of participating laboratories in many countries. The comparisons also promoted the system of laboratory accreditation, for testing light-emitting diode products. These products are supported all over the world. They are harmonised by standards and state programmes aimed at the rapid development of the light-emitting diode lighting industry.

• The comparison measurements were successful and useful for the VNISI TC. They allowed estimating the VNISI TC's level relative to the level of laboratories all over the world and encouraged plans for further increasing the accuracy and improving the quality of measurement.

At the same time, some metrological difficulties, which were revealed during the comparison, should be noted. In particular, differences in chromaticity coordinate measurements for some samples were slightly greater than expected. This was in part due to the fact that it was not possible to apply the chromaticity coordinate measurement methods developed in the NIST [6] due to absence of primary standards of flux spectral concentration unit size reproduction and transmission in Russia and of measuring standard lamps of radiation flux spectral concentration[3]. A standard for total flux spectral density could be created in the VNIIOFI FSUO on the basis of the primary state standards of luminous intensity and of luminous flux [10,11]. As portable standard measuring instruments, light measuring lamps of the SIP type and special standard light-emitting diode light sources can be used.

• Furthermore, based on the experience of the IEA 4 E SSL Annex, it is planned to continue the practice of the international comparisons (see http://ssl.iea-4 e.org/testing-standards) and some day to perform the following stage of the comparison of light-emitting diode product parameters based on goniometric measurement methods. In particular, it is planned to perform measurements of luminous intensity of the samples using not only lamps, but also light-emitting diode luminaires. As with this comparison, all interested organisations will be able to take part, including Russian test laboratories and centres.

[3] When comparing in the VNISI TC, the method of measuring relative spectral distribution of axial irradiance was applied. A spectral radiometer with a diffuse attachment on the input fibre-optical cable was calibrated using a measuring lamp of SIS 40–100 type as a standard of irradiance spectral distribution

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# PROVIDING ENERGY EFFICIENCY IN INTERIOR LIGHTING OF OFFICES AND INDUSTRIAL BUILDINGS USING IMAGE PROCESSING TECHNIQUE

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## ABSTRACT

Energy saving approaches for interior lighting, especially for governmental and nongovernmental offices, is significant for every country around the world. As energy sources decrease, greenhouse gas emissions increase. So, lighting energy savings should be considered more seriously. In this study, energy saving potential of an office building is examined by using electrical data collected from the camera integrated automated lighting control system and energy consumption is reduced by an image processing technique accordingly. The goal of this study is to improve the system energy parameters and increase the energy saving potential of the lighting system.

**Keywords:** lighting energy savings, lighting control, lighting quality, image processing technique

## 1. INRODUCTION

The world's energy resources are limited. The demand for energy is constantly increasing depending on population growth and technological developments. Therefore, efficient use of energy and energy-saving has been one of the most current topics in recent years. It is a fact that resources used in the production of electric energy in our country are providing from imported sources increasingly day by day. Efficient use of electrical energy is very important for the development of the national economy and the reduction of dependence on foreign countries.

## 2. DESCRIPTION OF THE PROBLEM

Energy-saving has an important place in the field of lighting. With the developing production technologies and exponential researches on the subject, it is proposed to increase the efficiency of the energy saving in lighting devices and make them more common. Also, energy saving has become a part of the national and international policies [1]. International organizations such as International Energy Agency (IEA), which was founded in 1974, and Commission Internationale de L'éclairage (CIE), which was founded in 1931 and redoubled its recent worldwide activities in the direction of energy efficiency in lighting, are in a collective work with communities of countries such as the European Union (EU), United Nations (UN) and Organization of Economic Cooperation and Development (OECD) [2]. The overall objective of these studies is to maximize the efficiency by limiting the consumption of lighting energy.

For instance, The Green Light Programme [3], which is founded and conducted by EU and Canada Green Building Council (CaGBC) [4], which is launched by Canadian government on national basis, is the most recent example that serve this purpose.

Energy saving is one of the most important topics in our country as well as Europe. There are a lot of studies about the subject [5]. Turkish National Committee on Illumination and The Chamber of Electrical Engineers, they have important stud-

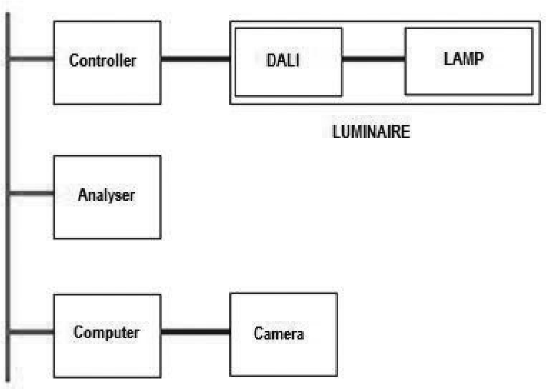



Fig. 1. General hardware structure

Fig. 2. Outside view of the office

Fig. 3. Inside view of the office

Fig. 4. Inside view of the office

Fig. 5. Inside view of the office

Fig. 6. Meeting room view

Fig. 7. Camera system view

ies and activities devoted to energy efficiency and saving in lighting. They are organising events to help public to understand the importance of energy savings in lighting. They also hold congresses and conferences in accordance with their objectives and tasks, support numerous scientific meetings and trainings, and try to lead to academic and technological studies in order to develop science and technology in fields of lighting. It is useful to examine the national and international energy statistics to understand why these efforts are so important. According to Turkish Statistical Institute's statistic in 2010, total electricity consumption was 172 TWh and office buildings consumed approximately 16% of this amount [6]. An estimated 15–20% of these values were consumed by the use of artificial lighting systems. With a simple calculation, lighting energy consumed in office buildings can be found as 5, 5 TWh in 2010.

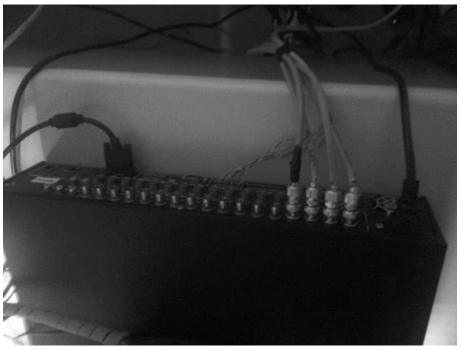


Fig. 8. Camera system view

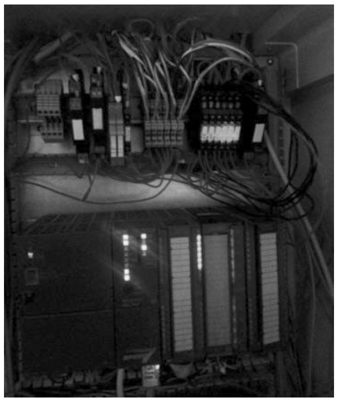
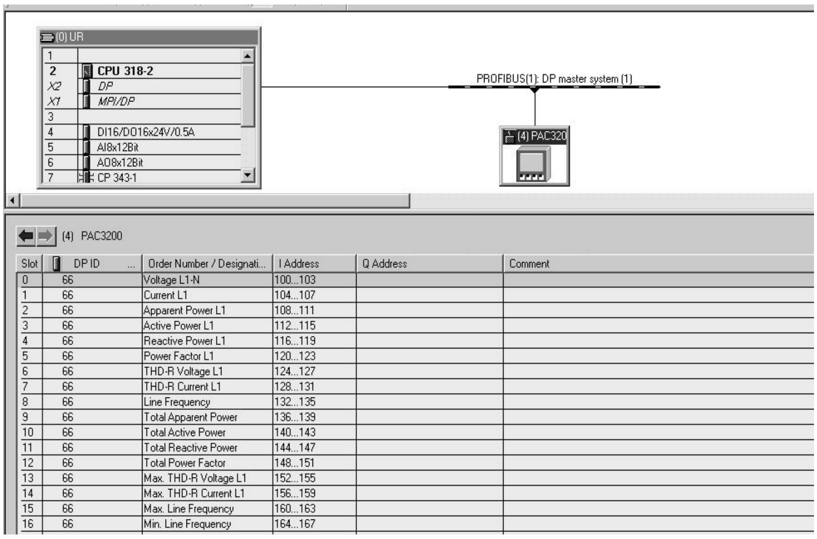


Fig. 9. PLC

When it is examined the energy consumption guide [7], which was published by International Building Research Establishment (BRE) in 2007 and the previous reports of Chartered Institution of Building Services Engineers (CIBSE) [8] in the worldwide, it can be seen that 20% or 40% of total energy consumption of these buildings is the lighting energy consumption. In the USA, public buildings consume more than 30% of the national energy consumption and artificial 25% or 40% of this energy is consumed for lighting [9]. Statistics about Canada show that in 2006, 10% of energy consumption of corporate sectors is used for lighting [10]. In Europe, annual lighting energy consumption excluding the houses is approximately 160 TWh and 40% of this amount is consumed only in buildings [11]. The latest statistical information and prediction about the rate of lighting energy consumption in the future can be found in Energy Efficiency Report which was published by IEA in 2009 [12]. And this information is supported by the regulations of the energy performance of the European Parliament [13]. According to this document, 19% of the world's electricity consumption is consumed for lighting purposes and according to studies, this rate will increase by around 80% and reach 35%.




| Slot | DP ID | Order Number / Designati... | I Address | Q Address | Comment |
|---|---|---|---|---|---|
| 0 | 66 | Voltage L1-N | 100...103 | | |
| 1 | 66 | Current L1 | 104...107 | | |
| 2 | 66 | Apparent Power L1 | 108...111 | | |
| 3 | 66 | Active Power L1 | 112...115 | | |
| 4 | 66 | Reactive Power L1 | 116...119 | | |
| 5 | 66 | Power Factor L1 | 120...123 | | |
| 6 | 66 | THD-R Voltage L1 | 124...127 | | |
| 7 | 66 | THD-R Current L1 | 128...131 | | |
| 8 | 66 | Line Frequency | 132...135 | | |
| 9 | 66 | Total Apparent Power | 136...139 | | |
| 10 | 66 | Total Active Power | 140...143 | | |
| 11 | 66 | Total Reactive Power | 144...147 | | |
| 12 | 66 | Total Power Factor | 148...151 | | |
| 13 | 66 | Max. THD-R Voltage L1 | 152...155 | | |
| 14 | 66 | Max. THD-R Current L1 | 156...159 | | |
| 15 | 66 | Max. Line Frequency | 160...163 | | |
| 16 | 66 | Min. Line Frequency | 164...167 | | |

Fig. 10. The hardware structure of PLC

Fig. 11. Energy analyser

For both our country and other countries of the world, the lighting energy consumption is at very high levels. And with population growth, it can be foreseen that these levels will rise even high-

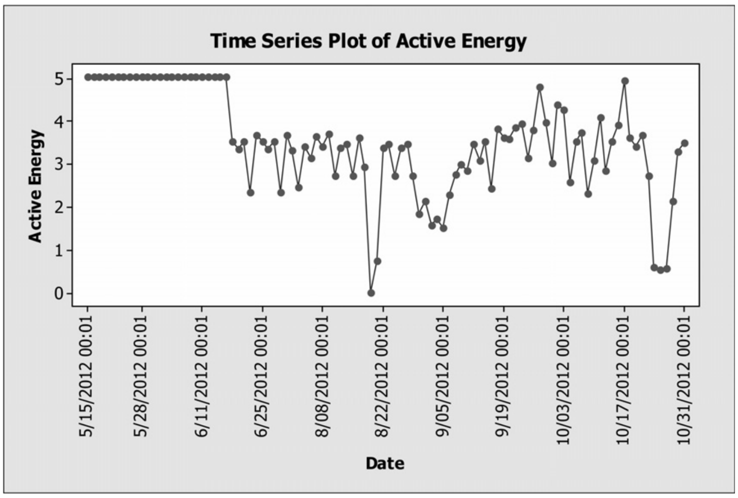



Fig. 12. Daily Active Energy Consumption

**One-way ANOVA: Active Energy versus BA**

```
Source  DF       SS      MS       F      P
BA       1   72,018  72,018  102,56  0,000
Error   98   68,817   0,702
Total   99  140,836

S = 0,8380   R-Sq = 51,14%   R-Sq(adj) = 50,64%


                             Individual 95% CIs For Mean Based on
                             Pooled StDev
Level    N    Mean   StDev   ---------+---------+---------+---------+
After   76  3,0489  0,9579   (--*-)
Before  24  5,0360  0,0000                            (----*----)
                             ---------+---------+---------+---------+
                                   3,50      4,20      4,90      5,60

Pooled StDev = 0,8380
```

Fig. 13. ANOVA Analysis before and after, Active Energy Consumption

er. Therefore, in order to save energy in interior lighting, lighting conditions of the existing structures need to be improved. Also new buildings must be planned and built with energy-efficient lighting assembly.

One of the most serious methods is to change the lighting systems of existing buildings with energy-efficient lighting equipment and to integrate with "daylight-dependent lighting control" where possible. Previous studies show that 35 to 42% of lighting energy saving is possible just by using daylight control systems [14, 15].

On the other hand daylight is very important for people or indoor users' psychology. Various studies show that the presence or absence of daylight affects human behaviours in different ways. People need to see in order to detect many environmental stimuli. And people need the daylight to achieve the best visual conditions [2].

Considering the lighting energy consumption ratios, it is decided to carry out a study that aims to design energy saving and flexible lighting system by using imaging techniques.

## 3. CURRENT-BASE ANALYSIS AND APPLICATION

### 3.1. System structure

In the experimental implementation is a computer connected to the network, control and input-output units connected to network, a camera connected to the computer, energy analyser. The hardware structure is shown in Fig. 1.

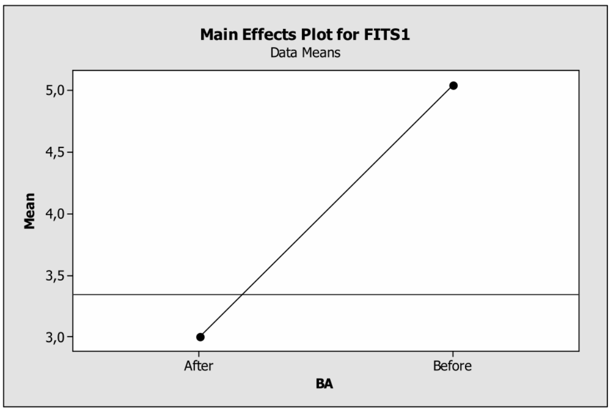



Fig. 14. Main Affect Graph for Before and After

### 3.2. The Principle of system operation

In the detecting areas of the office, the lighting is switched on and off. The lighting of the Office is divided into three parts. 7 fluorescent fixtures are switched on and off depending on the motion-sensitive area assets of 2, 2 and 3.

### 3.3. Prototype research and instalment

The equipment that is used for installing the prototype is determined and the installation is carried out. Necessary materials are provided and the system installation is completed. First of all, daylight illumination installation of the office is carried out. The application of daylight illumination can be seen in Fig. 2 and Fig. 3.

Then, the installation of fluorescent luminaires is completed by using DALI ballast, Figs. 4, 5.

Camera mounting and monitoring system installation is carried out as in Figs. 6, 7 and 8.

### 3.4. Developing the interface program

The control of illumination system is carried out by a PLC. PLC is corresponded with camera monitoring system via connection in series and illuminations are switched on by input signals reaching at PLC after motion circumstances. Energy consumption of the system is followed up by PAC 3200 energy analyser. The data obtained on PLC through PROFIBUS is stored on the server via SCADA software. The control system, the hardware structure of PLC, and energy analyser can be seen in Figs. 9, 10, 11.

It is recorded in such a manner to follow up the total energy consumption and total harmonic distortions from the energy analyser.

## 4. RESULTS OF THE EXPERIMENT

The results obtained from the new method, the illumination on-off via sensing only by camera, are given below. Before developing the method, daily consumption was known as 5040 Wh considering the situation that 7 luminaires are operating for 10 hours. The amount of reduction in the consumption of 5 kWh before the application can be seen in Fig. 12.

When the diffraction of energy consumption is observed in time, it is found out that the dispersion in daily electricity consumption increased af-

**One-way ANOVA: Active Energy versus Month**

```
Source  DF      SS      MS      F      P
Month    4   57,479  14,370  16,38  0,000
Error   95   83,356   0,877
Total   99  140,836

S = 0,9367   R-Sq = 40,81%   R-Sq(adj) = 38,32%

                                   Individual 95% CIs For Mean Based on
                                   Pooled StDev
Level       N    Mean   StDev   ---------+---------+---------+---------+
Agust      23  2,8635  0,9335   (----*----)
June       21  4,2027  0,9578                   (-----*----)
May        13  5,0360  0,0000                              (-----*-----)
October    23  3,0565  1,1868     (----*----)
September  20  3,1350  0,8840      (----*----)
                                ---------+---------+---------+---------+
                                      3,20      4,00      4,80      5,60

Pooled StDev = 0,9367
```

Fig. 15. ANOVA Analysis on monthly basis for Active Energy Consumption

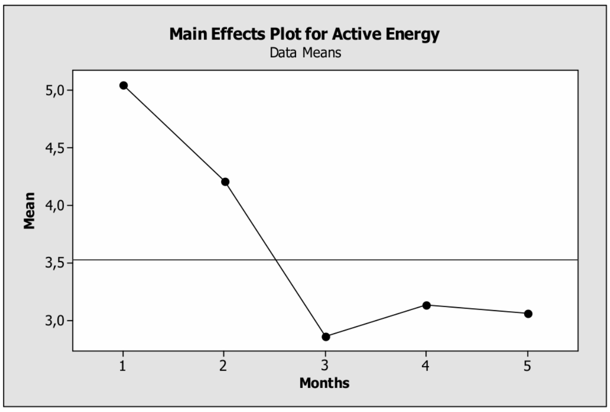



Fig. 16. Main Affect Graph amongst months

ter the date 15.06.2012 and the energy consumption decreased. In order to reflect statistically if there is a difference or not, ANOVA analysis is used –one of the tools of the 6 sigma [14].

Since the value is P<0.05 according to that analysis, it is accepted that there is $H_a$ (difference between before and after values). There is actually a difference between before and after values, and the average energy utilization for after values is 40% less. In order to show that visually, a main affect graph is shown in Fig. 14.

While checking if there is a difference on monthly basis, the data below given in Fig. 15 is analysed.

Since the value is P<0.05 according to that analysis, it is accepted that there is $H_a$; i.e. the values for at least one of the months is different from the others. In order to show that visually, a main affect graph on monthly basis for 5 months (June, July, August, September and October) is figured in Fig. 16.

In the period that the energy efficiency studies are carried out, the system is analysed daily and it is found that there is no difference (Fig. 17).

## 5. CONCLUSION

As seen on the power consumption graphics light pipe equipped and camera integrated PLC lighting control system saves 40% of lighting energy compared to the present conventional lighting system. Compared to previous studies [14,15,17] that use direct daylight enters through windows in the approximate geography and daylighting conditions, 40% is a promising achievement for this type of hybrid system which does not use daylight directly but mostly transports it. Use of such systems in industrial environments can be an alternative energy saving solution to systems work with stand-alone motion sensors and also can accompany to daylight based control systems. This type of systems also can be realized by using 1–10 V on-off control instead of using DALI ballasts to reduce the costs. For further study, the next applications below shall be maintained by decreasing luminous intensity in case of daylight illumination is sufficient through luminance level measurements: monitoring energy conservation, monitoring current and voltage harmonics.

## ACKNOWLEDGEMENTS

This study is an outcome of a Sakarya University Scientific Research Projects Unit project, Project number 2012–50–02–043.

**One-way ANOVA: Active Energy versus Day**

```
Source  DF      SS    MS     F      P
Day      4    0,85  0,21  0,14  0,965
Error   95  139,99  1,47
Total   99  140,84

S = 1,214   R-Sq = 0,60%   R-Sq(adj) = 0,00%

                                 Individual 95% CIs For Mean Based on
                                 Pooled StDev
Level       N   Mean  StDev  ---------+---------+---------+---------+
friday     20  3,545  1,152       (--------------*---------------)
monday     19  3,372  1,271  (--------------*---------------)
thursday   20  3,480  1,290     (--------------*---------------)
tuesday    20  3,573  1,173        (--------------*--------------)
wednesday  21  3,646  1,183          (--------------*--------------)
                             ---------+---------+---------+---------+
                                   3,15      3,50      3,85      4,20

Pooled StDev = 1,214
```

Fig. 17. Anova Analysis on daily basis for Active Energy Consumption after Energy Efficiency Studies

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# PULSATION OF LUMINOUS FLUX OF LIGHT EMITTING DIODES AND FEATURES OF THEIR MEASUREMENT AND RATIONING

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## ABSTRACT

Some features of luminous flux pulsation of light emitting diodes caused by their characteristics and by their power supply devices are considered in this article. It is shown that the pulsation of radiation of luminaires with light emitting diodes and with gas-discharge lamps can differ essentially from each other by its intensity, waveform and frequency. Therefore, it is concluded that the luminous flux pulsation measurement methods accepted today and their standards developed in the middle of the twentieth century for gas-discharge illumination, in some cases cannot be used for light-emitting diode illumination and should be revised.

**Keywords:** light emitting diodes, luminous flux ripple, stroboscopic effect, power supply devices, current linear stabilizers, pulse-width control

## INTRODUCTION

Luminous flux pulsation first presented at the end of the nineteenth century, when incandescent lamps supplied with alternating current appeared. However, due to an incandescent filament's thermal inertia, the pulsation was insignificant and did not influence visual perception.

The issue of light source luminous flux pulsation became challenging from around the 1950s in connection with a mass introduction of gas-discharge light sources supplied with alternating current of 50 Hz frequency using electromagnetic ballasts. Because of the small inertia of discharge and phosphor, the curve of the discharge lamp's luminous flux is close in waveform to the current straightened curve and therefore, has a considerable alternating component of 100 Hz frequency (Fig. 1).

This pulsation was noticed at once because of two harmful consequences: the first one was discomfort, headache and increased fatigue; the second one was the possibility of an optical illusion because of a stroboscopic effect, which consisted in an apparent change of rotation speed of observable objects, down to their stop or reverse rotation. In connection with this, lighting engineers together with physicists conducted studies to research the illuminance pulsation [1–5]. As a result, methods of pulsation measurement were developed, and their admissible limits were established depending on the conditions of visual work. It should be noted that these methods and standards were developed for pulsation waveforms close to that represented in Fig.1 for a power supply frequency of 50 (60) Hz.

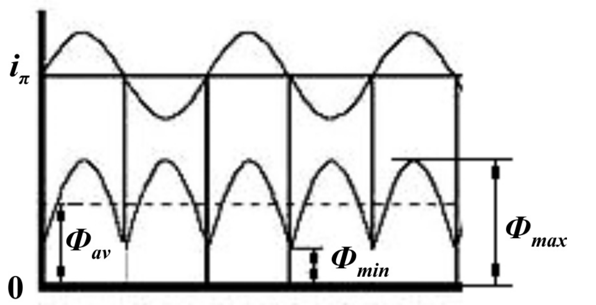


Fig.1. Typical waveforms of current and luminous flux of a discharge lamp when working with electromagnetic ballast using a 50 Hz network

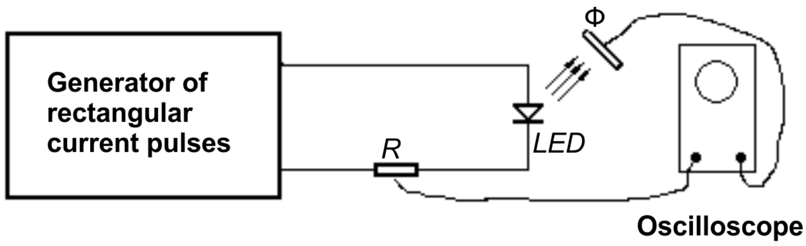


Fig. 2. Layout of the LED inertia measurements. R is the measuring resistor; LED is measured light emitting diode; Φ is silicon photo cell

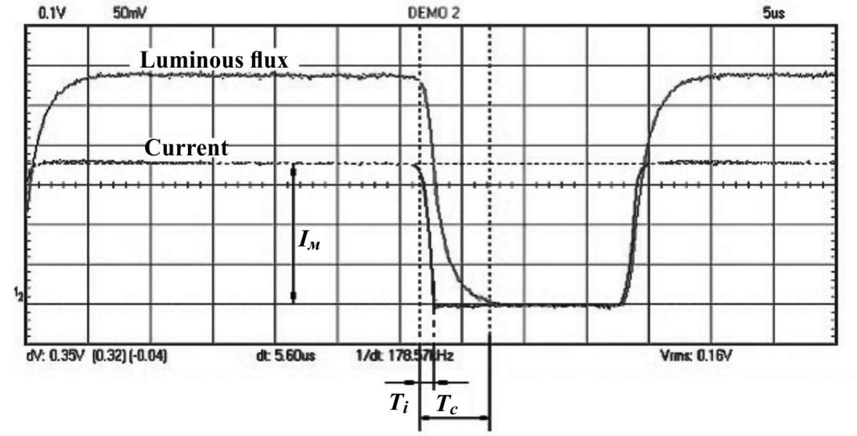


Fig.3. Oscillograms of light emitting diode current and luminous flux. $T_i$ is front of current decrease; $I_M$ is current amplitude; $T_c$ is luminous flux decrease front

However, operational experience available today has shown that value, waveform, and frequency of pulsation of light-emitting diode light sources can essentially differ from those given in Fig.1.

**Features of LED luminous flux pulsation**

The pulsation of luminous flux of light sources depends on two factors: inertia of the radiation source of and on its power supply network (current waveform and frequency).

LED inertia

LEDs' inertia depends on their luminous flux Φ increase time (from 0.1 to 0.9) and decrease time (from 0.9 to 0.1) of $F_{rate}$ when switching voltage on and off. Modern LEDs, without phosphor, have the inertia time from 10 to 50 ns [6]. For white LEDs with phosphor, this time theoretically (because of phosphor inertia) can be even higher. In order to determine this time, we measured inertia of several types of widespread LEDs. The measurement description and results are given in Figs.2, 3 and in Table 1. The measurements were performed at a frequency of 20 kHz.

It can be seen from Table 1 that LED luminous flux is behind current by no more than 0.2–3.8 µs. It follows, therefore, that at frequencies no more than several tens kHz, one can consider all LEDs (both colour and white) to be inertialess, because at these frequencies the curve of LED luminous flux change practically coincides with their current curve, i.e. it is only determined by the current waveform set by the power supply equipment.

Waveform of output current of the most widespread modern LED power supply equipment (and accordingly LED luminous flux waveform)

1. Direct current with pulsation from several deciles percent to several tens percent at a frequency of 100 Hz (waveform of the pulsation is close to sinusoidal). Such a waveform is typical for non-controllable electronic and electromagnetic supply devices operating with a 50 Hz network. And it practically coincides with pulsation waveform of gas-discharge light sources with electromagnetic ballasts (Fig.1). Therefore, to evaluate them, effective standards and methods of pulsation measurement are applicable.

2. Pulsing rectangular current with alternating filling coefficient (Fig. 4). Such current waveform

**Table 1. Results of measurement of light emitting diodes inertia of different types**

| № | LED type | Iм (A) | Ti (μs) | Tc (μs) |
|---|---|---|---|---|
| 1 | Osram "LUW-W5AM" | 0.35 | 1.2 | 1.5 |
| 2 | SEOUL W42182 | 0.35 | 1.2 | 5.9 |
| 3 | Nichia NS2W157ART | 0.075 | 1 | 1.6 |
| 4 | Nichia STS-DA1–1459 | 0.02 | 1.2 | 2.2 |
| 5 | Nichia NSPR310S (red) | 0.02 | 1.2 | 1.2 |
| 6 | Nichia NSPW300DS (white) | 0.02 | 1.2 | 1.2 |
| 7 | BRIDGELUX BXRA | 0.3 | 1.5 | 5.7 |
| 8 | SEOUL KWT801-S | 0.02 | 1.2 | 5 |

is typical for linear stabilizers co-sworking with 50 Hz networks, and for electronic supply devices adjusted by pulse-width modulation (PWM) method and working both with alternating and with direct current.

For linear stabilizers, $f = 100$ Hz, $\gamma = 0.7–0.9$. For supply devices adjusted by the PWM method, $f \geq 100$ Hz; $\gamma = 0.01–1$.

3. Pulsing half-sine current with pauses between pulses (Fig. 5). Such waveform is typical for a wide class of light-emitting diode modules of Acrich type promoted by South Korean company Seoul Semiconductor, which are directly connected to networks of alternating current without supply devices.

As pulsation waveform and frequency in Figs. 4 and 5 essentially differ from pulsation waveform and frequency for gas-discharge light sources with electromagnetic ballast, then effective pulsation standards are not applicable for their evaluation.

The evaluation of the pulsation features of luminous flux from light emitting diodes given above, is confirmed by studies performed by CIE Pub. 205:2013 (TC3-50) "Review of lighting Quality Measures for Interior Lighting with LED Lighting System", TC1-83 "Visual Aspects of Time-Modulated Lighting Systems", and by Committee PAR1789 of the Institute of Electrical and Electronic Engineers (IEEE). In these works [7–12], significant attention is given to the research of pulsation depth and frequency influence on comfort of visual perception and on a possibility of the emergence of stroboscopic effect. It is shown that stroboscopic effect can be manifested with pulsation frequencies of up to 1000–10000 Hz. Besides, it is noted in these works that existing methods of measuring pulsation are not acceptable for light emitting diodes, the waveform and frequency of which can change over a wide range.

**Features of measuring pulsation ratio of LED luminous flux**

At present, three measurement methods of luminous flux pulsation ratio (Rr) are known.

Method 1. Amplitude ratio method

Pulsation ratio calculation is performed using the formula:

$$K_{p1} = [(\Phi_{max} - \Phi_{min})/(\Phi_{max} + \Phi_{min})]100\%$$

Method 2. Method of amplitude relation to an average value

Pulsation ratio is calculated using the formula:

$$K_{p2} = [(\Phi_{max} - \Phi_{min})/2\Phi_{av}]100\%$$

Method 3. Average values method

Pulsation ratio is calculated using the formula:

$$K_{p3} = [\Delta\Phi_{av}/\Phi_{av}]100\%,$$

where $\Delta\Phi_{av}$ is an average value of luminous flux deviation for a half-cycle from the average value for this period ($\Phi_{av}$).

This method was proposed by Eastman and Campbell in 1952 and considered in detail [1] in

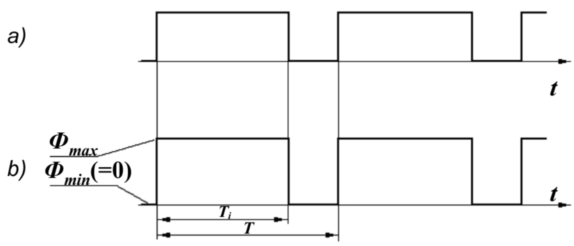


Fig.4. LED current (a) and luminous flux (b) waveforms when working with current linear stabilisers and with supply devices adjusted by the PWM method
$T_i$ is current pulse duration; T is pulse repetition interval;
$f = 1/T$ is impulses repetition frequency;
$\gamma = T_i/T$ is impulses filling factor

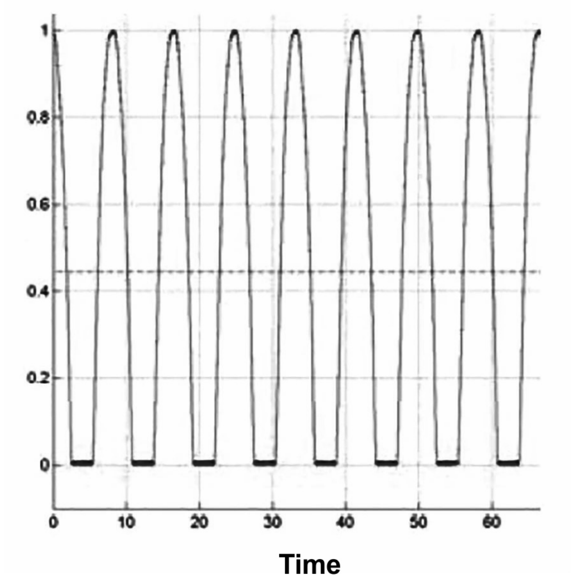


Fig. 5. Ripple waveform of Acrich light-emitting diode modules

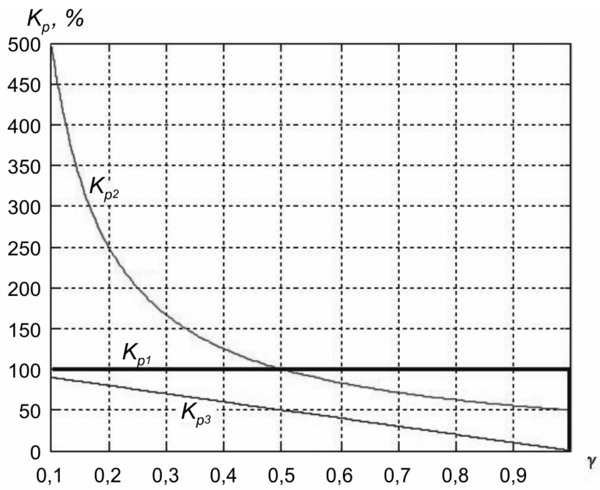


Fig.6. Results of $K_p$ measurement obtained by methods 1–3 at rectangular waveform current with filling factor γ changing from 0.1 to 1

1955 as one, which most accurately reflects eye reaction to the pulsation [2].

When evaluating gas-discharge illumination pulsation characterised with a constant frequency and waveform close to sinusoid, all three methods give results well correlated with each other. In our country, the first and the second methods have been accepted as most easily implemented.

However, for light-emitting diode illumination with pulsation waveforms essentially different from sinusoidal and with a frequency different from 100 Hz, all these methods give different results. So, for example, for luminous flux presented in Fig. 5, pulsation ratios computed using different methods, have the following values: $K_{p1}$ = 100%, $K_{p2}$ = 114%, $K_{p3}$ = 42%.

Still more differences take place for pulsation ratios computed by different methods for rectangular waveform current with filling factor γ, which changes from 0.1 to 1 (Fig. 6).

It is seen from Fig. 6 that the first and the second methods, which are used for the measurements, give unreasonable results: the first method doesn't respond to the change of the pulse waveform, and the second method gives jumps at the edges of the γ change interval. The third method reflects waveform change properly, but to use it is also impossible as correlation of its results with the accepted standards is not obvious and requires further checks.

## CONCLUSIONS

1. Light emitting diodes at frequencies to tens kHz can be consider practically inertialess elements. Therefore, the pulsation of their luminous flux is completely determined by the pulsation of the power unit output current.

2. When operating with non-controllable electronic and electromagnetic power supply devices of a 50 Hz network, the luminous flux pulsation of light emitting diodes practically coincides by the waveform and frequency with pulsation of gas-discharge light sources with electromagnetic ballast. Therefore, in these cases, effective standards of pulsation and methods of their measurement are applicable for them.

3. The pulsation of luminous flux for a large number of light-emitting diode luminaires (with electronic supply devices controlled by the PWM method, with linear current stabilisers and directly connected to an alternating current network without power supply equipment) essentially differ from the pulsation of gas-discharge lamps by waveform and frequency. So, existing measurement methods and standards are inapplicable for their measurement and rationing. In these cases, the creation of new standards and methods for measuring pulsation is required. And for this purpose, the collaborations of light engineers and physicists is needed, similar to collaborative research performed in the fifties for gas-discharge illumination.

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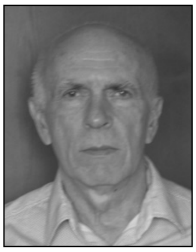


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# COMPARISON OF A SINGLE PHASE LINEAR AND A BUCK-BOOST LED DRIVER

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## ABSTRACTS

This paper presents a comparison of LED driver topologies that include linear and buck-boost converters. Both topologies are connected to grid over a single-phase diode rectifier and designed for 8 W power. Further, buck-boost converters work on a discontinuous conduction mode (DCM) with 63 kHz switching frequency. Finally, power factor and total harmonic distortion (THD) of current and voltage, power LED voltage and current are shown for both topologies over implementations, and a comparison is made. Furthermore, voltage-current characteristic, current and voltage- illuminance characteristics are derived.

**Keywords:** LED driver, single phase buck-boost converter, linear regulator, power factor, THD

## 1. INTRODUCTION

The power LEDs using in lighting is more common nowadays and receives much attention due to their high efficiency. Besides, power LEDs need *dc* power in order to operate, and obtaining *dc* power is possible using a battery, solar cells and grid. To use a single-phase grid for *dc* voltage, rectifier circuits are needed. After rectification, linear and switch mode topologies are used to obtain variable *dc* voltage feeding power LEDs. However, a diode rectifier can effect the grid negatively in terms of power factor and THD. Therefore, to avoid these effects, international institutes define standards like IEC/EN 61000–3-2 and these standards need to be taken into account when designing LED driver circuits. Furthermore, using a *dc-dc* converter after uncontrolled LED single phase rectifier can avoids these problems. That's why this kind of converters is called as power factor corrected (PFC) converters. Especially, operating buck-boost derived topology at DCM can reduce switching losses and for power factor correction, buck-boost converter is the most appropriate converter.

LED driver using buck, buck-boost converter is designed in [1]. Cuk converter based LED driver is implemented in [2]. In [3–4] LED driver with flyback sepic-derived converter carried out. Combined buck and flyback LED driver is realized as in [5]. In paper [6] *ac-dc* and *dc-dc* converters are used as an LED driver. Advantages and disadvantages of basic *dc-dc* converter using as PFC converters are analysed as in [8–10]. In [11], designs, analyses and operation of *dc-dc* converters are describing.

In this paper, the comparison of LED driver topologies that include linear and buck-boost converters is presented. Both types are connected to grid over a single-phase diode rectifier and designed for

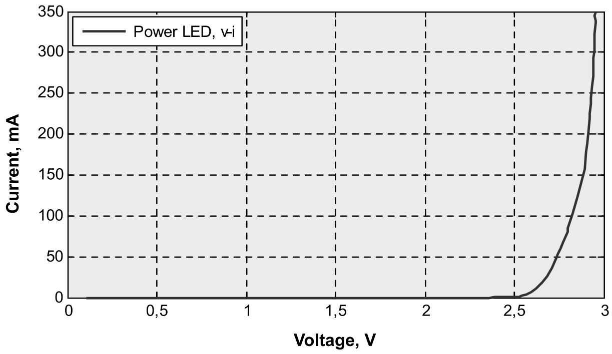


Fig. 1. Voltage-current characteristic of power LED

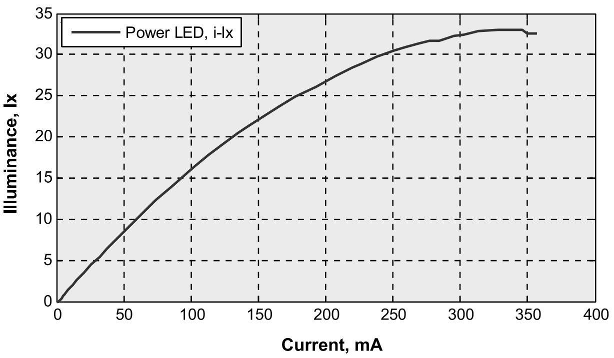


Fig. 2. Current-illuminance characteristic of power LED

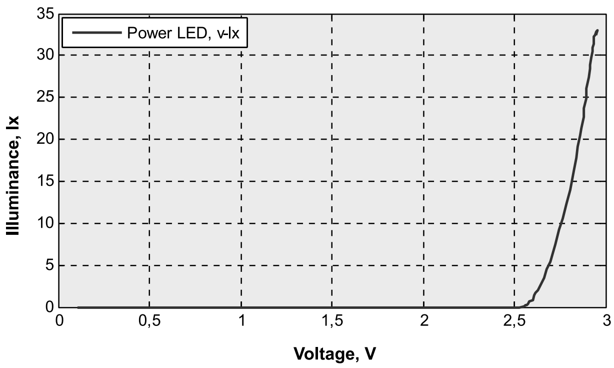


Fig. 3. Voltage-illuminance characteristic of a power LED

8 W power. Besides, buck-boost converters work on discontinues conduction mode (DCM) with a 63 kHz switching frequency. Furthermore, the power factor and total harmonic distortion of grid current and voltage, LED current and voltage are shown for both types over multiple implementations.

This paper is organised as follows. Power LED characteristics are derived in Section 2. The applied LED driver topologies are reviewed in Section 3. Applications of LED drivers are presented in Section 4. THDs and power factors of each type are illustrated in Section 5. Some conclusions are given in Section 6.

## 2. POWER LED

In this chapter, current- voltage, current-illumination and voltage-illumination characteristics of power LEDs used for this paper are derived with using Fluke 15 B, Fluke 17 B and Lutron LX1102.

Fig. 1. shows the voltage-current characteristic of a power LED. It can be seen from the fig. that LED voltage and current has an exponential relationship and LED current increases extremely after the LED turns on. Also, LED voltage doesn't change much after and up to 340 mA current on LED.

Fig. 2. shows the illumination level of power LED versus current and it can be seen from this fig. that the illumination level is reducing when a higher current is obtained until that time it is at the saturation level of the power LED.

Fig. 3. shows the illumination level of the power LED versus its voltage. This curve is similar to the voltage-current characteristic of an LED.

## 3. LED DRIVER

In this chapter, the usage of the linear regulator and buck–boost converter as the LED driver are introduced. Both drivers are connected to grid over a single-phase diode rectifier.

### A. Linear Regulator

Fig. 4. shows the linear regulator that provides the continuous desired voltage for load.

The working principles of the linear regulator are as follows; control circuit sense the output voltage on a negative terminal of op-amp and adjust the current source that is realised by controlling darlington connected transistors to hold the output voltage at the desired value defined by a positive terminal of op-amp [12]. However, the linear regulator works as a buck converter.

### B. Buck-Boost Converter

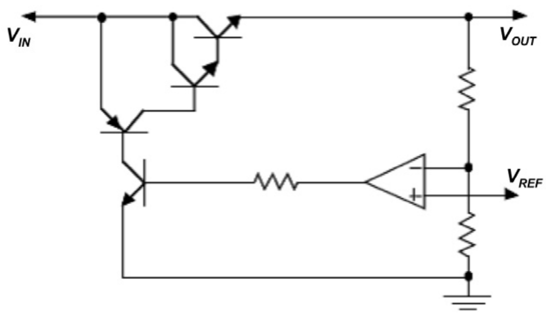


Fig. 4. Linear regulator principles

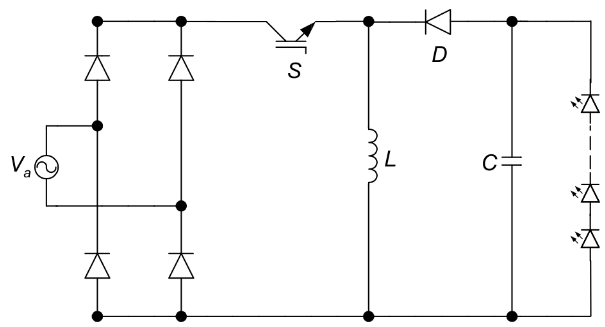


Fig. 5. PFC buck-boost converter

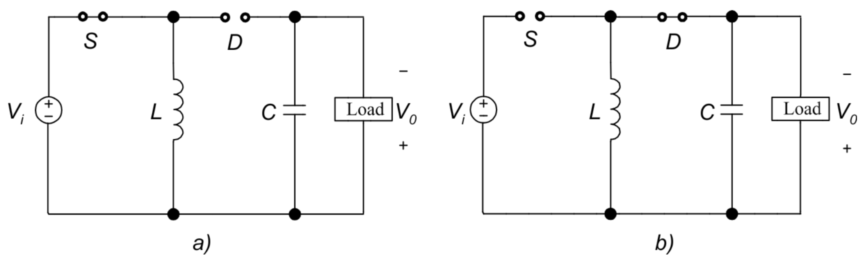


Fig. 6. Switching state a) open, b) closed

Fig. 7. Application setup

Fig. 5. shows the PFC buck-boost converter circuit.

The buck-boost converter is also connected to grid over a diode bridge and high frequency operation of the switch *dc* voltage that feeds power to the LEDs is obtained. This converter works on the principle of transferring energy of inductance and can be analysed by the state of the switch that is shown in Fig. 6. If the switch is turned on, inductance stores energy and when the switch turns off, inductance transfers its energy to the load.

A mathematical model of the PFC buck-boost converter can be derived as a *dc-dc* buck-boost converter; the only difference is the changing input voltage [11]. After using the Kirchoff voltage and current law to the each state of the switch that is seen in Fig. 6, Equation (1–2) is obtained for the open and closed states respectively.

$$\begin{bmatrix} \dot{i}_L \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -1/RC \end{bmatrix} \begin{bmatrix} i_L \\ V_o \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_i . \quad (1)$$

$$\begin{bmatrix} \dot{i}_L \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/RC \end{bmatrix} \begin{bmatrix} i_L \\ V_o \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} . \quad (2)$$

Then, equation (1–2) is combined and PFC buck-boost state space representation is obtained for operation CCM and BCM.

$$\begin{bmatrix} \dot{i}_L \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} 0 & -1/L + d/L \\ 1/C - d/C & -1/RC \end{bmatrix} \begin{bmatrix} i_L \\ V_o \end{bmatrix} + \begin{bmatrix} d/L \\ 0 \end{bmatrix} V_i . \quad (3)$$

Furthermore, the voltage on power LEDs can be adjusted to less or more with respect to input voltage by the duty cycle of the pulse width modulation

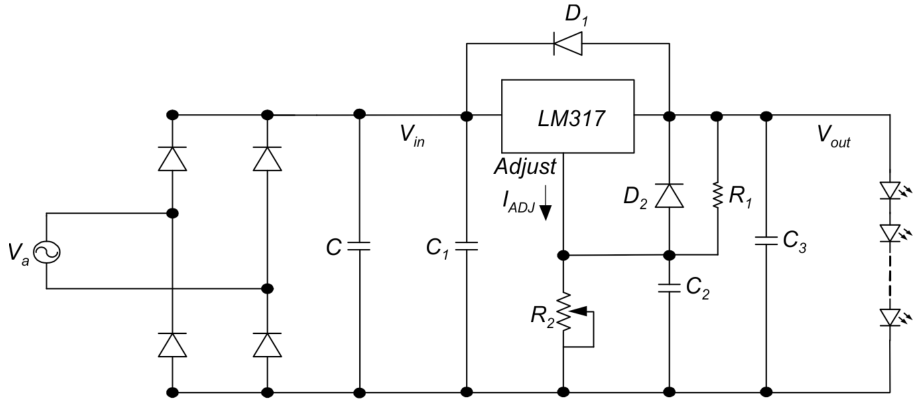


Fig. 8. Linear regulator application circuit

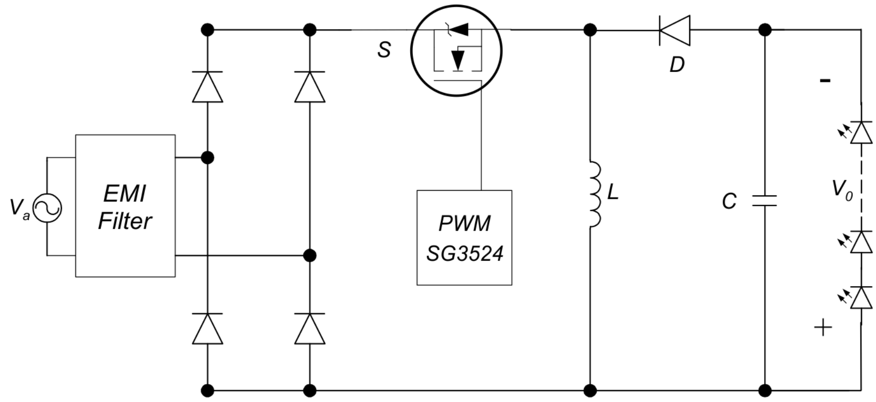


Fig. 9. Application circuit of PFC buck-boost converter

(PWM). High frequency operation also provides a high power factor [8]. However, the *dc* voltage on power LEDs are at reverse polarity with input voltage and to avoid high frequency noise, an input filter needs to be added.

## 4. APPLICATION

In this chapter the application of LED drivers that use linear regulator and PFC buck-boost as converters is realised. Fig. 7. shows the experimental setup. Both converters are connected to grid over a step down transformer 220/24 50 Hz. Furthermore, as a power LEDs, three series connected power LEDs tied two parallel branch. It was understood from Fig. 1,2 and 3 that single power LED voltage must be set to 3 V for optimal operation: therefore, in the applications, power LEDs is set to 9 V.

### A. Linear Regulator

The application circuit of the linear regulator is shown in Fig. 8. LM317 IC is used as a linear regulator.

Firstly, single-phase *ac* voltage is rectified by a diode bridge then with a capacitor *dc* voltage is obtained. Using LM317 and varying its potentiometers, variable *dc* voltage is acquired. In this application 8 W power LEDs are used. Diodes on LM317 provide the safe operation of the linear regulator [13]. $V_{out}$ is set to the desired level as shown in equation (4) and output voltage can also be adjusted by using $R_2$ as a variable resistor.

$$V_{out} = 1.25V\left(1 + {R_2}/{R_1}\right) + I_{ADJ}R_2 \,. \tag{4}$$

The values of elements, which are used in linear regulator application circuit, are defined in Table 1.

### B. Buck-Boost Converter

Fig. 9. shows the application circuit of the buck-boost based LED driver. SG3524 IC is used for PWM signals. It is understood that an open loop operation is realised.

The duty can be changed by the potentiometer connected to SG3524 and PWM frequency is 63 kHz. The same load is used with the linear regulator.

The maximum value of L for DCM operation that provides less power loss on switch can be found by using equation (5) and the calculation of the capacitor value is given in equation (6) [11].

$$L_{max} = {R_{Lmin}(1 - D_{max})^2}/{2f_s} \,. \tag{5}$$

**Table1. Values of elements**

| $D_1$ | $D_2$ | $C$ | $C_1$ | $C_2$ | $C_3$ | $R_1$ | $R_2$ |
|---|---|---|---|---|---|---|---|
| 1 N4001 | 1 N4001 | 2200 μF | 0.1 μF | 10 μF | 1 μF | 240 Ω | 5 kΩ pot |

**Table 2. Values for calculation of $L_{max}$ and $C_{min}$**

| $R_{Lmin}$ | $D_{max}$ | $f_s$ | $V_o$ | $V_{cpp}$ | $L_{max}$ | $C_{min}$ |
|---|---|---|---|---|---|---|
| 20 Ω | 0.107 | 63 kHz | 12 V | 20 mV | 126 μH | 4 μF |

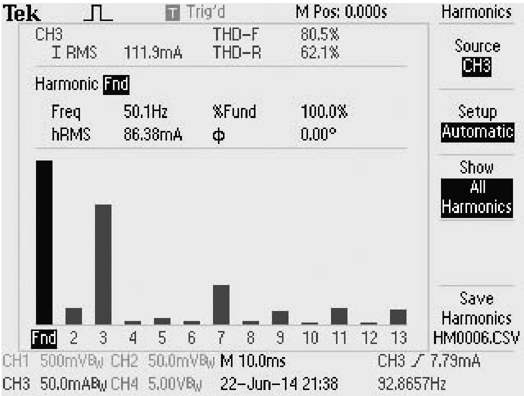


Fig. 10. THD of grid current

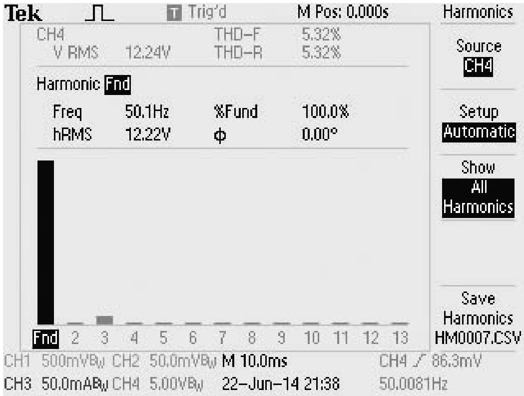


Fig. 11. THD of grid voltage

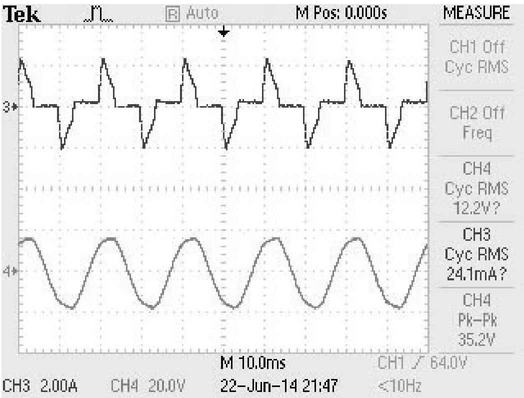


Fig. 12. Grid current and voltage

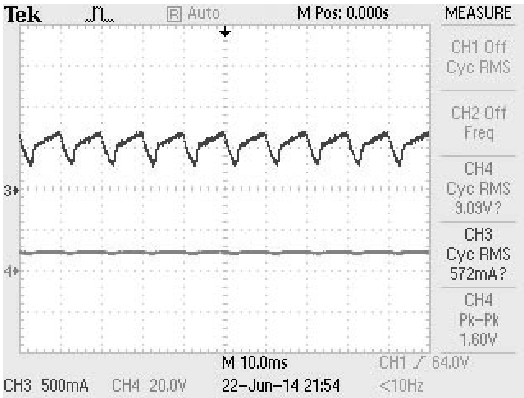


Fig. 13. Power LED voltage and current

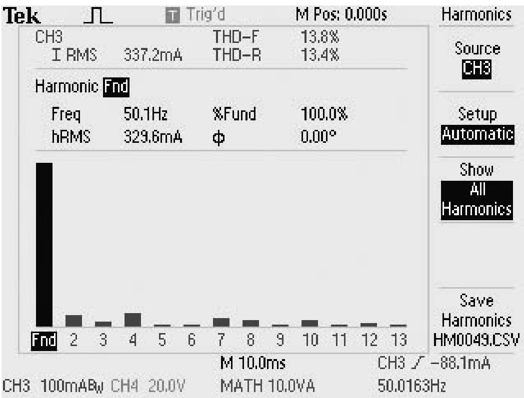


Fig. 14. THD of grid current

$$C_{min} = {D_{max} V_o}/{f_s . R_{Lmin} . V_{cpp}} \ . \qquad (6)$$

It can be is seen in Fig. 9 that the input EMI filter is used in order to reduce high frequency noise of switch, peak voltage on grid and provide continuity of grid current. Besides, Table 2 shows the values which are used in calculating maximum inductance $L_{max}$ and minimum capacitor $C_{min}$. $R_{Lmin}$ is the minimum load resistance, $D_{max}$ is the maximum duty cycle, $f_s$ is the switching frequency, $V_o$ is output voltage, $V_{cpp}$ is the ripple voltage across the filter capacitance $C$ [11].

In Fig. 9, for switch S and diode D, IRF540 N Mosfet and Mur460 fast diode are used, respectively. To drive IRF540 N, an IR2117 high side Mosfet driver is added. Furthermore, $L$ must be smaller than $L_{max}$ to provide DCM operation so $L$ is chosen as 113.4 µH. $C$ needs to be higher than 4 µF, therefore, $C$ is chosen as 1000 µF in application circuit [14–17].

## 5. MEASUREMENT RESULTS

In this section, THDs of grid current and voltage, power factors, power LEDs voltage and current are measured for both linear and buck boost converters. For the measurement, a TPS2024 B oscilloscope and TPS2 PWR1 power application software were used.

### A. Linear Regulator

Fig. 10 shows the THD of grid current at 80.5% while using a linear regulator as an LED driver. Power factor is measured as 0.701.

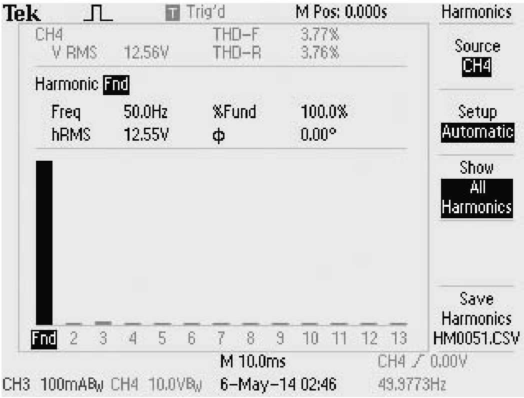


Fig. 15. THD of grid voltage

THD of grid voltage is shown in Fig. 11 as 5.53%.

Grid current and voltage are shown in Fig. 12. It can be seen from the fig. that the grid voltage is sinusoidal but the grid currents is not and that is why grid current is needed to make its shape sinusoidal in order to have a higher power factor and less harmonics.

The power LED's voltage and current are shown in Fig. 13.

### B. PFC buck-boost converter

Fig. 14 shows the PFC buck-boost converter circuit's THD of grid current. P.F. is measured as 0.958 and THD is 13.8%.

THD of grid voltage is shown in Fig. 15, and it is equal to 3.77%.

Grid current and voltage are shown in Fig. 16. The shape of grid current is similar to that of the grid voltage, and they are both sinusoidal.

The power LED's voltage and current are shown in Fig. 17, and it can be seen that LED current is not dc and has peak values.

## 6. CONCLUSIONS

This paper compares LED drivers that include linear regulator and buck-boost PFC converters. Also, voltage-current, current illuminanace and voltage-illuminanace characteristics of the power LED are obtained. By means of the applications, THDs of the grid current and voltage, power factor, power LED's current and voltage are measured. Application of a linear regulator as an LED driver gives THDs of grid current and voltage at 80.5% and 5.32% respectively, PF is 0.701 as a result. The results of the buck-boost PFC converter are 13.8% and 3.77% grid current and voltage THD, respectively, 0.958

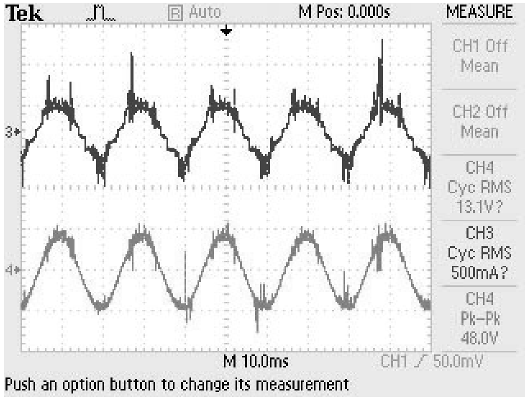


Fig. 16. Grid voltage and current

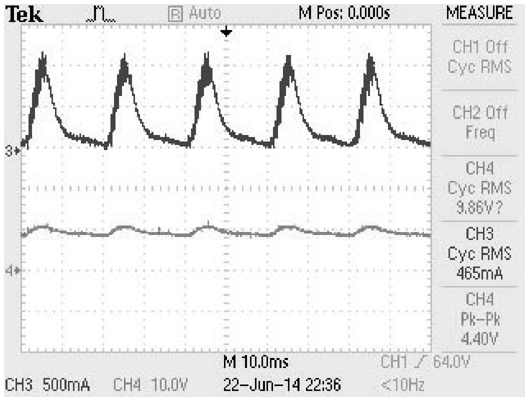


Fig. 17. Power LED voltage and current

PF. Besides, PFC buck-boost converter provides IEC61000 3–2 standard C.

It is understood that according to grid, the buck-boost PFC converter gives better results. Although, both LED drivers can supply comparatively smooth *dc* voltage, the linear regulator based LED driver can provide better current for power LEDs compared to the buck-boost PFC based driver. However, it can also be concluded that linear the regulator is getting hotter than the buck-boost PFC. Also, an input filter is required when using a buck-boost PFC to avoid high frequency noise.

Future work could include the addition of a current control algorithm in order to avoid increasing the LED current above the limited value that destroys an LED due to the higher temperature.

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# NEW CIRCUIT SOLUTIONS FOR THERMAL DESIGN OF CHANDELIERS WITH LIGHT EMITTING DIODES

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## ABSTRACT

A new approach to the design of energy efficient chandeliers with light emitting diodes (LEDs) to illuminate rooms is proposed. The essence of this approach is manufacture of elements of chandelier decorative frame as thermal tubes (TT) and use of light-emitting diode modules (LEDM) installed within them as light sources. TT application allows removing heat from the LEDMs and dissipating it by means of a heat exchange extended surface, which is provided in the TT cooling area. Due to the increase of heat removal efficiency, LEDM power and luminous flux can be increased at least twice in comparison with the correspondent light-emitting diode lamps of direct replacement (DRLEDL).

**Keywords:** inner illumination, chandelier, light emitting diode, light-emitting diode module, thermal tube, heat removal

## INTRODUCTION

Between 19% and 22% of electric energy generated globally is consumed for illumination [1]. The introduction of energy saving technologies into illumination systems of domestic and public buildings allows for a significant saving in electrical energy. Light-emitting diode light sources (LEDLS) present excellent opportunities for use in systems of indoor illumination. The luminous efficacy and power of LEDLSs increase every year [2]. The main challenge associated with the use of powerful LEDLSs is methods of effective heat removal released in crystals of the light emitting diodes (LED). A rise of the crystal temperature above 85 º C leads to a decrease in service life and luminous flux and to changes in the chromatic characteristics of the LED's radiation. Therefore, the problem of supporting a normal thermal mode of LEDLSs as a part of a lighting device (LD) is very topical.

## TRADITIONAL TECHNICAL SOLUTIONS FOR SUPPORTING A NORMAL THERMAL MODE OF LEDs IN LDs FOR INDOOR ILLUMINATION

Usually, LDs for illumination of rooms in domestic and public buildings were pendant luminaires in the form of chandeliers with decorative elements in the frame and with incandescent lamps installed in light diffusers. Since the emergence of DRLEDLs of 3–5 W power with standard socle *E14* [3] and of 7–16 W power with socle *E27* [4], it has become possible to use these instead of incandescent lamps both in traditional, and in newly designed pendant chandeliers. Heat removal from LEDs in the DRLEDLs is achieved by means of a built-in radiator [5]. The geometrical and structural limitations of the radiator surface result in its temperature reaching (51.7–80.7)ºC [4], and LED crystal temperature is higher still. Radiator heating also leads to a rise in temperature of the elements located inside the radiator (electrolytic capacitors are especially sensitive to temperature), and this reduces the reliability of the DRLEDL as a whole.

To increase the efficiency of heat removal, DRLEDLs [6–8] were developed with built-in thermal tubes (TTs), the heat conduction of which is higher than heat conduction of metals [9]. TT installation between the LEDLSs and the radiator slightly reduces the temperature difference between them. However, this cannot essentially influence the general temperature difference between LEDLSs and the surrounding air, which to a greater degree is determined by the temperature difference between the radiator heat-dissipated surface and air. Besides, the problem of heating ballast elements by the radiator is not eliminated either.

To further increase the efficiency of heat removal from powerful LEDLSs, a new unconventional approach is needed to the design of indoor illumination LDs.

## A NEW APPROACH TO THE USE OF TT IN LDs AND TO THE DESIGN OF POWERFUL CHANDELIERS WITH LEDs

The thermal problem can be solved when designing powerful chandeliers with LEDs by using TT as elements of the decorative frame of a chandelier and by manufacturing LEDLSs as LEDMs installed in the TT heating area, providing a thermal contact [10]. In Fig. 1, a simplified picture of such a chandelier with two LEDMs is presented. In real structures, it is desirable to have at least 3–5 LEDMs for greater uniformity of room illumination. Basic elements of the chandelier frame are made as bent TTs 7 and 8. The inner surface of the TT case is covered with a capillary structure (CS) layer 9 in the form of longitudinal microgrooves (Fig. 1 b). The TT case is partly filled with a heat-carrier compatible with the material of the TT case from the point of view of corrosion. The questions of TT manufacture, operating principles and calculation methods have been discussed in detail: see, for example [9]. An electric fan 14 is only installed in case of high power LEDM use.

When the chandelier is switched on, heat from powerful LED 5 crystals of each LEDM 2 and 4 is transmitted via a thermal contact to heating areas 10 of TT 7 and 8, and further via TTs – to cooling ribs 12 and 13, which dissipate the heat to the environment. Due to the high heat conduction of the frame elements working through the closed vapour-condensation cycle, the thermal flow essentially raises and dissipates in the environment. The thermal flow is also increased due to rather extended surface of the cooling ribs. This allows using chandelier LEDMs of power at least twice greater than with DRLEDLs, and to increase chandelier luminous flux and reliability accordingly. The latter is because of the normal thermal mode of the LEDs and of the ballast elements placed over a distance from the LEDMs releasing heat.

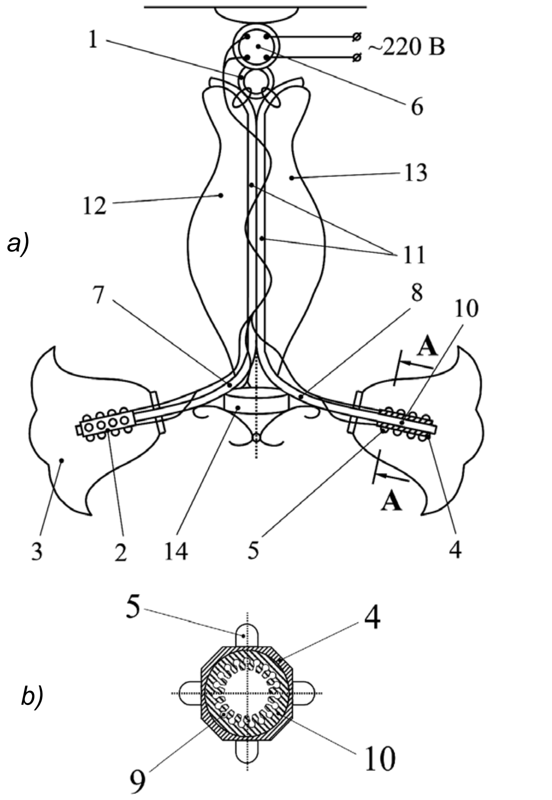


Fig. 1. *Light-emitting diode chandelier with TT frame:* a – general view; b – cross-section by A-A line: 1 – frame part; 2, 4 – LEDMs; 3 –light diffuser; 5 – powerful LED; 6 – ballast; 7, 8 –TTs; 9 – CS layer; 10 – TT heating area; 11 – TT cooling area; 12, 13 – cooling ribs; 14 – electric fan

To increase the uniformity of scattering light radiation in space for large premises with high ceilings and rooms in public buildings [11, p. 581], a light-emitting diode chandelier [12] is proposed, a simplified picture of which is given in Fig. 2. The third group public buildings, which would benefit from this design, are as follows: libraries, assembly halls, foyers, halls, couloirs, entrance halls and metro stations, etc. This chandelier differs by the configuration of the TTs, which provides for vertical LEDM placing. Their powerful LED light-radiating surfaces are directed to the lateral sides. Because of this, and

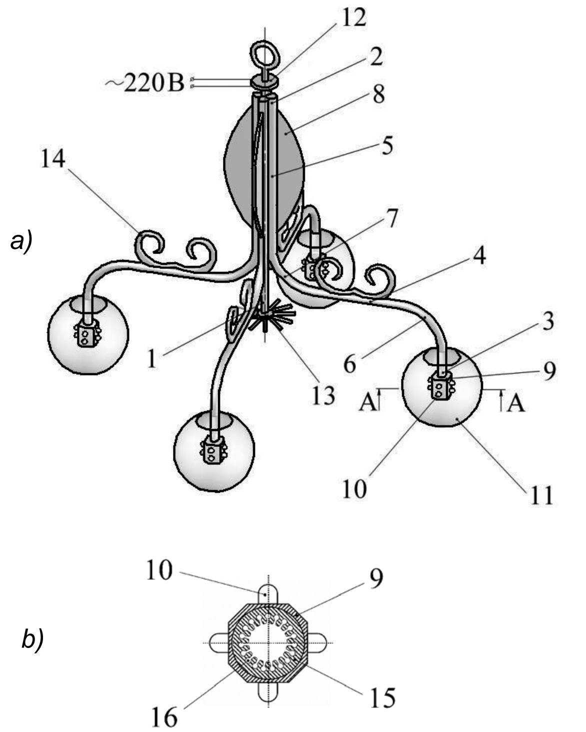


Fig. 2. *Light-emitting diode chandelier with vertically placed powerful LEDMs:*
*a – general view; b – cross-section by A-A line: 1 –supporting frame; 2 – TT; 3 – TT heating area; 4 – TT transport area; 5 – TT cooling area;; 6 – TT first bend; 7 – TT second bend; 8 – cooling rib; 9 – LEDM; 10 – powerful LED; 11 –light diffuser; 12 – ballast; 13 – electric fan; 14 – decorative element; 15 – TT case; 16 – CS layer*

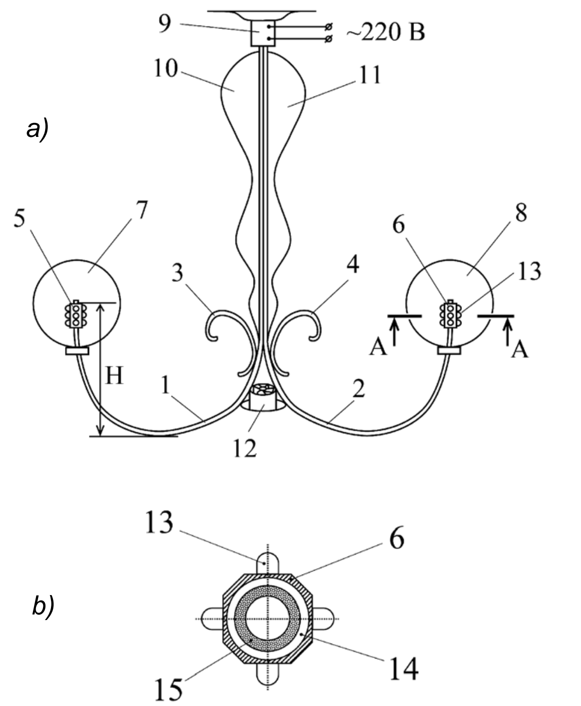


Fig. 3. *Light-emitting diode chandelier with top LEDM placing:*
a – general view; b – cross-section by A-A line: 1, 2 – TTs; 3, 4 –decorative elements; 5, 6 –LEDMs; 7, 8 – light diffuser; 9 – ballast; 10, 11 – cooling ribs; 12 – electric fan; 13 – powerful LED; 14 – TT case; 15 – MFCS layer

the spherical diffusers 11, the chandelier illuminates a room more uniformly. The procíple of operation of the chandelier in terms of heat removal and dissipation is not too different from its previous version given in Fig. 1.

In other manufactured versions, the chandelier can have a greater number of TTs with LEDMs on them, which are placed at different heights, forming many-tier chandeliers for large rooms.

These circuit solutions of LED chandeliers have some limitations due to the implementation of the design solutions, which use U-type bent TTs in the frame. This is due to the poor capillary-transport properties of the CSs in the form of longitudinal microgrooves, which cannot provide transport of a heat-carrier against gravity to the heating area of TTs located overhead with LEDMs.

This disadvantage can be overcome by using a more perfect CS in TTs, which provides transport of a liquid heat-carrier against gravity, for example of the metal fiber capillary structure (MFCS) [13]. A structural scheme of a chandelier with LEDs using U-type bent TTs with MFCS is given in Fig. 3 [14].

In this case, height H installation of the LED top end face shouldn't exceed a maximum height $H_{max}$ of capillary balance of a heat-carrier in the MFCS layer.

This height is determined as:

$$H_{max} = \frac{4cos\theta \cdot \sigma}{D_{ef} \cdot \rho \cdot g},$$

where θ is MFCS material contact angle of wetting by liquid heat-carrier of the TTs; σ is the surface tension coefficient of the heat-carrier; $D_{ef}$ is the effective diameter of the MFCS layer pores; ρ is the density of a liquid heat-carrier; g is gravity constant.

If this requirement is observed, capillary forces provide a constant saturation of the MFCS layer with a liquid heat-carrier in the TT heating area, where corresponding LEDMs with powerful LEDs are installed. This occurs despite the counteraction of gravity at the transport area ascending part, and thus the reliable work of TTs is ensured.

## CONCLUSION

A new approach to the design of energy efficient chandeliers with LEDs for inner illumination is proposed, the essence of which consists in manufacturing TTs as decorative frame elements of a chandelier and in the use of LEDMs installed on the TTs as light sources.

TT application allows heat removal from LEDMs over a distance and heat dissipation by means of an extended heat exchange surface formed in the TT cooling area.

Due to the increase in heat removal efficiency, the LEDM power and their luminous flux can be increased at least twice in comparison with DRLEDLs.

This allows reducing the number of the chandeliers required to illuminate big domestic and public rooms (halls, libraries, entrance halls, metro stations, etc.).

Further research should be focused on manufacturing functional models of the proposed chandeliers with LEDs and on experimental determination of their thermal and light characteristics.

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