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Summary The Research Institute for Building Physics (NIISF) has developed a unique installation — a successfully functioning large 'Artificial sky'. The paper gives a detailed description of its structural features and facilities.

Artificial sky for use with large-scale architectural daylight models

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1 Introduction

In the last decade the possibilities of solving problems linked with the design of rational daylighting for multi-purpose premises have increased. This is mainly due to the progress in computer technology and in the methods of daylighting calculations.

However, there exists a whole category of problems which need more exact computations, existing methods failing to provide the required degree of accuracy. Some difficulties in the calculations of daylighting interiors are presented by buildings of complicated configuration, with relief-decorated facades, built in close proximity to other constructions or possessing directionally diffused reflection under clear sky. Also, there are currently no practical methods for calculating daylighting which allow for real interior situations. The main obstacle in the theoretical aspect of the problem is the necessity for either a complex, labour-consuming programme or a large number of approximations in creating a mathematical model which reduce accuracy. All of these problems may be easily solved with the help of physical models.

The installations in use in Russia, Czechoslovakia, Sweden, the United States of America, United Kingdom (Building Research Establishment) and a number of other countries are usually solid hemispherical or semi-elliptic constructions with interior surfaces illuminated by special luminaires installed at the base of the construction or in caissons distributed along the base perimeter. In such constructions the interior reflecting surface produces an imitation of the diffused natural light of clouded sky.

The common drawback of such installations is the difficulty of tuning the diffused light imitator to the light distribution conditions of clear or partially clouded sky; or 'horizon error' organic to such installations. The small size of these installations limits the scope of models; large-scale models cannot be used because of the 'scale error' which also results in a decrease in accuracy.

2 NIISF artificial sky

The tentative work of the scientists and engineers of the Research Institute for Building Physics has resulted in design and construction of a new generation of installation named the NIISF 'artificial sky' (Moscow, Russia). This installation is to a large degree devoid of all the drawbacks listed above.

It occupies a two-storey building with solid hemispherical roofing made of sheet aluminium and special profiles (Figure 1). The ground floor (Figure 2) houses the power installations and equipment, light adjustment controls, automatic devices for tuning the 'sky' to the light-distributing conditions and monitoring and measuring equipment.

Light-emitting equipment which imitates daylight and the turning work platform occupy the first floor. The platform is designed for the installation of models under consideration and for the imitation of sun travel trajectories. It also houses the outlets of a powerful ventilation plant, necessary because of the large amount of heat released by the installed lighting equipment. The upper portion of the hemisphere also contains an opening for natural ventilation.

In designing the new installation the imitation of all daylight components was taken into account: the diffused light of the sky, direct sunlight and reflected light from the underlying surface of the ground. The autonomous operation of each daylight imitator is provided for. The design also takes account of the need for large-scale models (1:50, 1:20, 1:10) to provide greater accuracy of computation.

In addition, the installation meets the basic requirement of wide-range continuous adjustment of light radiation of separate sectors of sky for tuning its luminance distribution qualities to any existing law, to any height of the sun, and to any geographical co-ordinates at any time of the day, month and year.

The installation is composed of three functional parts: 'artificial sky', 'artificial ground' and 'artificial sun'. From the point of view of technology and construction the most complicated part of the installation is the 'artificial sky'. It is designed for imitating daylight components produced by

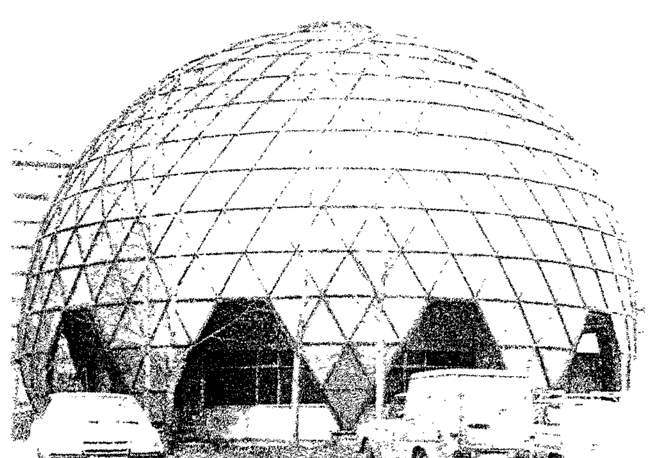

Figure 1 General view of the set-up from the outside

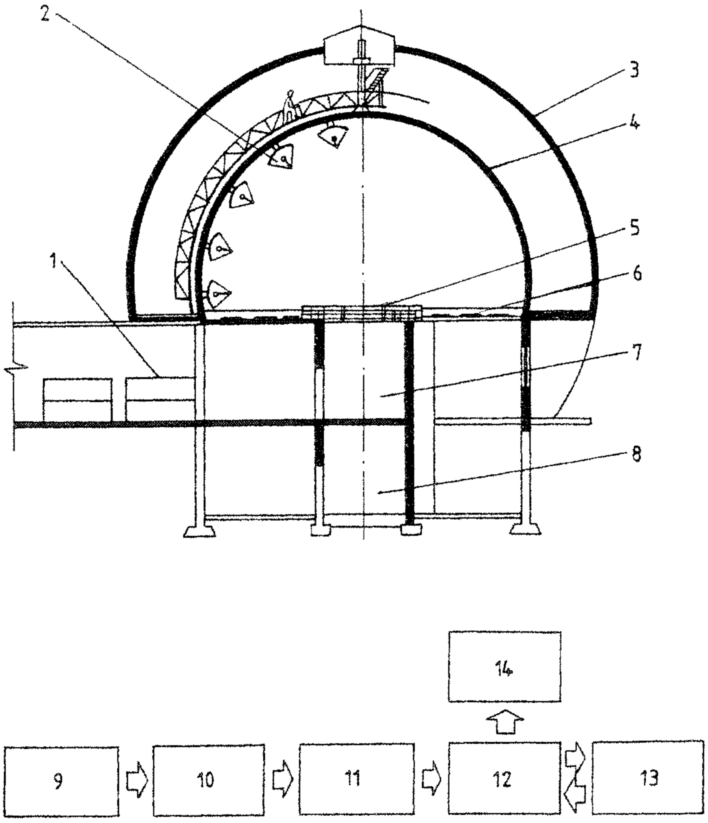

Figure 2 Diagrams of the arrangement of the set-up and conduction of measurements. 1 – measuring device, 2 – 'artificial sun' set-up, 3 – protective dome-like shell, 4 – 'artificial sky' set-up, 5 – rotating model platform, 6 – 'artificial ground' set-up, 7 – mirror chamber, 8 – photometric chamber, 9 – matching device, 10 – measuring system, 11 – recording devices, 12 – terminal, 13 – computer, 14 – processed data.

diffused sky light. Structurally, this part of the installation is a grid hemisphere, 16.8 m in diameter. The specially designed armature construction is fixed to the hemisphere so that each of the cells has two light-emitting sources: incandescent lamps, type 3Ш-300 (or 3Ш-500) and high pressure discharge lamps, type ДРИ-250† (Figure 3). The installation description has been published in Russian[1–4]. The surface of the hemisphere consists of 736 cells and, consequently 736 lamps of both types, forming two autonomous systems.

The high pressure discharge lamps system is designed for imitation of evenly-bright clouded sky and may be used for subjective perception study of different architectural forms and constructions. Its other purpose is to increase the possibilities of the incandescent lamp-type system by qualitative and quantitative (by the spectrum) changes of the light flux emitted by the 'sky'.

The incandescent lamp-type system is intended to reproduce the luminance distribution of the sky (clouded, partially clouded and clear), as well as special types of luminance distribution (for example, the one described by the Gousev[5] formula). Due to the fact that the luminance distribution of the sky is symmetrical in relation to the sun vertical, the cell light sources bearing the same calculated luminance are joined together in 117 separate groups.

The 'artificial sun' is used as a direct sunlight model. This part of the installation is designed for carrying out research on insulation and sun-protection of buildings, including shadow-forming processes in development and evaluation of qualitative and quantitative mechanisms of shadow formation in buildings illuminated by direct sunlight.

Structurally, the system consists of five projectors installed (Figure 2) on the interior surface of the hemisphere at angles of 13°, 26°, 40°, 55° and 70° relative to the working platform centre. Each of the projectors forms a directed light flux 2.5 m wide. The horizontal illuminance varies from 1000 to 6000 lux.

Discrete switching-on of the 'artificial sun' at a specific height and simultaneous turning of the working platform by a specific angle, corresponding to the azimuth of the real sun, imitates the visible trajectory of the sun and allows measurements to be taken for any geographical co-ordinates of the construction site location and for any period of the

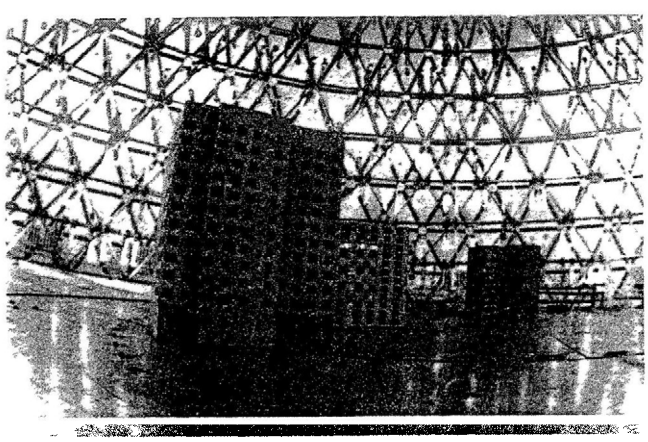

Figure 3 View of the set-up from the inside

† Note that 3Ш-300 and 3Ш-500 500 lamps correspond to the R-60 300 W and incandescent lamps respectively manufactured by Philips. The ДРИ-250 lamps correspond to HPI-250 lamps by Philips

day. As usual, the 'artificial sun' system operates in the autonomous mode and the obtained values of illuminance are corrected by an appropriate factor.

The 'artificial ground' system is designed to model the light flux reflected from the ground's surface. The construction is a circular recess surrounding the working platform with a built-in lighting system consisting of 435 radially mounted fluorescent lamps. These lamps are covered with opal glass, the exterior surface of which imitates the surface of the ground. The albedo model is created by direct radiance of the underlying surface and its value corresponds to the glass surface illuminance of the 'artificial ground' system for any concrete constructional situation, within the limits of 600 to 1000 $cd^2\ m^{-1}$, provided by the powering of lights from thyristor voltage limiters. Also, the 'artificial ground' surface may be screened by special sheets with a different reflection factor.

3 'Artificial sky' adjustment

The luminance adjustment of separate zones of the sky is obtained by changing the voltage applied to the existing groups of light sources. Each group of lamps is fed through a thyristor. The change of the check signal of each of the controls from 0 to −6.5 V drives to a change in the voltage of a certain group of lamps from 0 to 220 V by the thyristor opening angle variation each half-period of the powering voltage.

For the thyristor unit control a system of voltage dividers is used, their number corresponding to the number of the light sources to be adjusted. This system was installed in the 'artificial sky' installation instead of the standard control panel. Thus 117 dividers combined in one unit can provide a light program for 'tuning' the sky to a particular distribution of the luminance.

In order to change the 'sky'-tuning program an automatic device allows the required unit of dividers to be introduced into the circuit and so obtain the required conditions of luminance distribution. The programmed units are connected to the automatic control panel containing seven sets of dividers, providing seven 'sky-tuning' programs. With the help of detachable units the number of programs may be considerably increased.

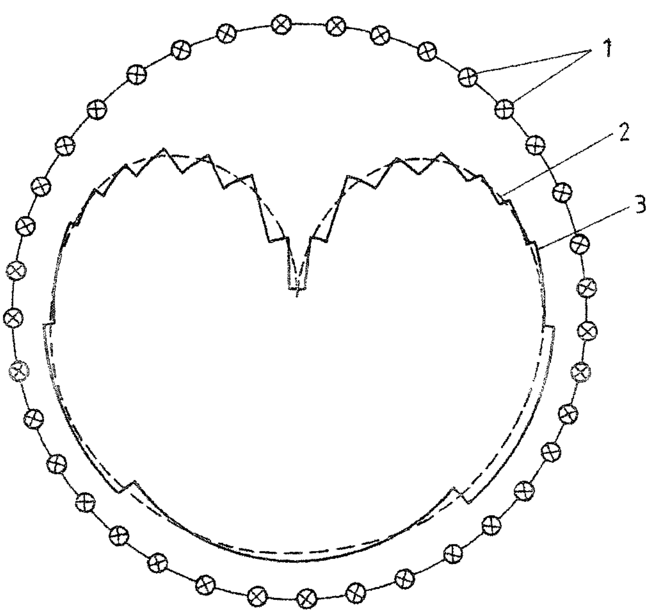

Figure 4 Distribution of luminance of light sources located in one of the horizontal chords of the set-up. 1 – light sources, 2 – theoretical distribution of luminance, 3 – factual distribution of luminance

One of the programs is designed to imitate the clouded sky, in which case the law of luminance distribution can be presented by the following equation:

$$L_\theta = \text{const.} \tag{1}$$

where L_θ is the luminance of the sky at the point located at the angle θ to the horizon.

Another program provides for 'tuning' to the CIE clouded sky and is represented by the Moon–Spenser equation[6]:

$$\frac{L_\theta}{L_z} = \frac{1 + 2\sin\theta}{3} \tag{2}$$

where L_z is the zenith sky luminance.

For imitating the clear sky five programs are used that correspond to different heights of the sun. Here, the distribution of luminance responds to the conditions of the Kittler formula[6]:

$$\frac{L_\theta}{L_z} = \frac{(1 - e^{-0.32\sec\varepsilon})(0.91 + 10e^{-3\delta} + 0.45\cos^2\delta)}{0.274\,(0.91 + 10e^{-3z_0} + 0.45\cos^2 z_0)} \tag{3}$$

where L_θ is the sky luminance at the required point, L_z is the sky luminance in zenith, ε is the angular zenith distance to L_θ, δ is the angular distance of the Sun from L_θ, z_0 is the angular zenith distance of the sun.

Light programs appropriate to intermediate sky have also been worked out. Average and mean sky programs will be presently introduced. These types of programs are within the framework of CIE TC 3-09 with refinements by Professor Nakamura[7].

The first sky model requires horizontal illuminance of 6000 lux on the working platform. In the clear sky model the luminance of certain zones of the sky corresponds to 10% of the natural sky luminance. This luminance ratio facilitates the calculation of daylight illuminance from the model. In this case the illuminance of the working platform varies from 9000 to 35 000 lux depending on the height of the sun.

Imitation of skylight radiation is obtained using specific light sources with a wide curve of radiant intensity. This results in a maximum experimental error of 3% caused by the replacement of the diffused radiant surface by pointwise radiation.

Joining the lamps into groups results in the light distribution along the surface of the 'artificial sky' changing stepwise. The actual luminance distribution at the height of the sun equal to 26° is illustrated in Figure 4. The NIISF 'artificial sky' is provided with the correction system of luminous flux decrease of light sources during operation time.

4 Measurement complex of the installation

In designing the NIISF 'artificial sky' system much attention was paid to the method of illuminance measurement inside the model and to the methods of tuning the system to the present luminance distribution.

A special, very high-speed automatic measurement complex was designed to carry out experiments on models with the purpose of determining their illuminance. This consists of photocells, a matching device, a measurement signal switchboard, a digital measuring device, a UPH 3200 microcomputer, and a digital printer. This measuring complex provides measurement results in actual values of illuminance. The matching device comprises a voltage divider and exterior load for each photocell so that the output voltage digital value of the illuminance is measured, excepting the order of number. The measurement system allows adequate data to be received from 100 check points within 5 s. Installation and measurements are controlled automatically from an isolated room. The accumulated results obtained with the help of the 'artificial sky' have proven the adequacy of the construction and the efficiency of the installations power and measuring complexes.

5 Applications of the NIISF 'artificial sky'

The installation designed by the Research Institute for Building Physics helps to solve many lighting problems:

(*a*) predicting the lighting environment in multi-purpose premises (apartments, industrial and social premises, etc.) under the conditions of clouded or clear sky with different light characteristics of the interior

(*b*) evaluating the influence of different parameters of fenestration and skylights on the illuminance of the premises

(*c*) determining the lighting characteristics of skylights in industrial and social premises

(*d*) studying the shadow-forming processes in development areas and influence of sun-shading devices on the lighting environment of the premises

(*e*) studying luminance distribution inside the accommodation blocks, taking account of a large number of factors (number of storeys, space between buildings, separate construction and whole district orientation, etc.)

(*f*) studying the subjectives of different architectural structures under daylighting and electric lighting conditions

(*g*) predicting rational changes in the number of storeys of reconstructed buildings in accommodation blocks.

6 Conclusions

The Research Institute for Building Physics is able to carry out all the programmes listed above as well as any other type of research according to the requirements of Russian and foreign companies. The authors also consider it important to emphasise that any experiments undertaken on this highly expensive installation should be included in the International System of Co-operation. At present the Institute is carrying out installation certification and thereafter the authors expect an International Research Centre on Daylighting Problems to be founded. Finally, it should be noted that the authors have not yet fully realised all the facilities of this unique installation, and would welcome joint research initiatives.

Acknowledgement

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