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A Project Aimed to Increase Energy Efficiency of the Object Swimming Pool Universitetsky by Application of Hollow Mirrored Tubular Light Guides Under Trade Mark

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Abstract
The goal of the project is to increase the efficiency of the facility by using an energy efficient technology of delivering natural daylight to spaces with permanent presence of people. A special feature of the heat engineering calculation was a study of the options for locating anticondensation trays in hollow tubular light guides to find their most optimal position in terms of possible thermal losses. The results of lighting calculations inside the object are produced in the program DIALux, which in its tern has been improved due to the integration of the information on hollow tubular light guides of the applied diameter in it.

1. Introduction
The normative illumination level inside a swimming pool is 150 Lux (on the water surface) [1]. This value is achieved in various ways, first of all by mounting the lighting equipment of the "overhead light" [2], for example, halogen floodlights with IPX4 splash protection in accordance with GOST 14254-96 [3] with diffusers of direct or predominantly direct light installed on the ceiling or side walls above the lateral passages [4]. In the object of our investigation - Swimming Pool Universitetsky in the city of Ekaterinburg (Figure 1), which has a total swimming pool area of 733.96 sq.m, there are five windows with the surface of 19.74 sq.m each, the normative value of illumination is achieved by 20 halogen floodlights TDM ИО1000 SQ0301-0005 (10 devices on each opposite wall) with a power of 1 000W per piece.

Using the calculation technique of David Jenkins and Tarig Munir (Engineering School of Napier University, Edinburgh, UK, [5]), it is easy to calculate that to ensure 15 hours a day continuous operation of the above halogen floodlights, we are forced to pollute the environment with CO_2 emission = 84 tons / year, emission of $S0_2$ = 1.05 tons / year, emission of $N0_2$ = 357 kg / year. In addition, given the constant increase in the cost of energy resources and rapid reduction in their number, it is impossible to ignore the high prices of maintenance and service cost of such lighting systems. In connection with the foregoing, we propose to make changes to the standard design of the

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swimming pools and to apply 900 mm daylight emitting systems based on hollow tubular light guides (HLGs) of Solarspot International SRL company, which has the best in the world reputation and results [6] in the production of these systems and efficiency of the natural daylight delivery to rooms with permanent presence of people[1].

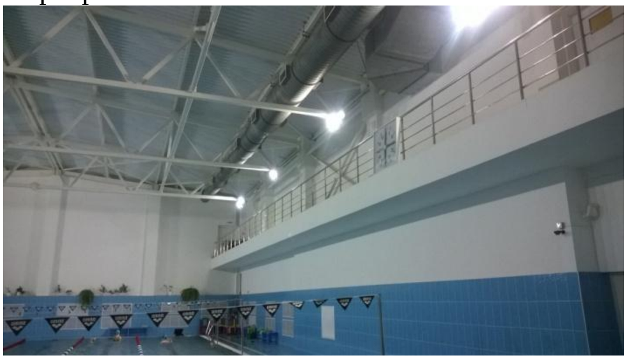

Figure 1. Photograph of the of the swimming pool interior where it is proposed to use energy efficient lighting systems based on hollow tubular light guides with a diameter of 900 mm of Solarspot International SRL company instead of halogen floodlights

HLGs of various configurations are installed and used in many developed and developing countries to deliver natural daylight to premises for quite some time. The leading scientific centers in Europe, Asia and the USA constantly conduct research in order to improve the design and efficiency of HLG systems; various tests of these systems in different conditions are being made. The results of the research are reflected in numerous scientific publications.

For an example, in articles by Jitka Mohelnikova [7], Jeong Tai Kim [8], Wang Shuxiao [9] and Stanislav Darula [10], results of evaluations of direct tubular light guides are presented, including those creating "tropical interiors", and a conclusion had been made that they "allow to improve the level of illumination in the interior parts of buildings", "to provide adequate visual comfort" and "huge potential for energy saving" provided that the design is carefully planned.

B. Malet-Damour in his article [11] states that "HLGs are innovative devices that can transport and distribute natural daylight without transferring heat in dark rooms." An overview of various programs for modeling the tubular devices also presented there.

In paper [12], characteristics and reflective properties of a hollow tubular light guide system equipped with two-component glazing in its base have been analyzed. Miroslav Kocifaj in his study [13] presented a theoretical derivation of the light flux model with its graphical representation in coordinate system taking into account the distortions of the bending of the inverse light ray in a bent HLG.

Seung Jin Oh considers "two different daylight systems: a light guide tube and a solar fiber-optic hub" that allow the light to be transported to the interior of a building with insufficient daylight; photometric model of the natural light system Photopia has been used [14]. In work [15], some predictions had been made regarding the energy saving potential thanks to use of passive tubular daylight systems in Romania, and in work [16] authors present a double light tube, an innovative technological device designed as a continuation of a traditional tubular light guides that distributes

[1] Report No. 280962 on the results of comparative tests of hollow tubular light guide systems (measurements of the transmittance of natural light by four different HLG systems of the world's leading manufacturers: Solarspot® D-38, two-layer light capturing units: dome and anti-condensation tray (Solarspot International SRL, Italy); Solarspot® D -38, single-layer light capturing unit, dome without anti-condensation tray (Solarspot International SRL, Italy), Sun Pipe® 450, double-layer diffuser (Monodraught, UK) Brighten Up® 290 OS, double-layer diffuser and reflective notch on the surface of the dome (Solatube International Inc, USA) conducted on August 14th, 2012, in BRE (Building Research Establishment) Office Building, Bucknalls Lane, Watford WD25 9XX Hertfordshire, United Kingdom.

daylight to underground areas of a building, illuminating simultaneously the passage zone between building floors because of the larger collector and the second transparent pipe attached to the first.

Friedrich Linhart, Stephen K. Wittkopf, Jean-Louis Scartezzini in their article [17] considered one of the most promising technologies for rooms lighting by means of natural light: the anidolic daylighting systems (ADS), which has not yet become widespread. The article explores the possibility of using such technology in Singapore, where the efficiency of use, according to the authors, can exceed 50%.

In article [18], the authors study the illumination given by curved HLGs. It is claimed that in some cases they are capable of collecting more sunlight than straight light guides, but the system collector should have a maximum directivity towards the sun.

Natural daylight systems with synthetic polymethylmethacrylate (PMMA) fiber are considered in article [19]. The experimental data on use of PMMA fibers presented in it and are aimed to help to optimize the illumination of premises' interior.

From the standpoint of the possibility of using vertical tubular light guides to deliver natural daylight to the central sectors of multi-level buildings where windows are not able to provide adequate illumination, the work [20] is of a particular interest, the method of extraction and distribution of an equal amount of light at each level has been investigated; design of collectors in order to increase the effectiveness of HLG systems when delivering low-level sunlight into the interior of buildings has been studied.

Simei Ji, Guanying Cao describe advantages and energy saving benefits of natural daylight illuminance in comparison with traditional electric artificial light sources by the example of underground parking at Dalian University of Foreign Languages, China [21]. In theoretical studies [22], [23] mathematical calculations have been carried out confirming the economic profitability of use of lighting systems based on HLGs in the specific climatic conditions of Russia. Research by Danny H.W. [24] includes field measurements in a corridor of a building illuminated by daylight using of several light guide tubes. Authors Thanyalak Taengchum, Surapong Chirarattananon [25] present the results of an experiment and modeling of transmission of light through rectangular light tubes.

As we can see, none of the named respected authors, nor other scientists, have made an attempt to calculate the natural daylight illumination level of premises by HLGs using a specifically adapted computer program. Modeling of heat exchange processes when using HLG aimed to study the application possibility of the technology to deliver daylight to rooms in cold climatic conditions has been carried out only in [22] and [26].

In view of the above, in this study we have set the following tasks to ourselves:

- calculation of illumination level inside the object of Swimming Pool Universitetsky in the city of Ekaterinburg (Russia) using lighting systems based on hollow tubular light guides under the methodology of Italian scientist, Dr. Gennaro Bracale [27], and its illustration in the augmented DIALux program;
- modeling of the heat exchange process when using HLGs with the variation of location of anti-condensation trays inside the tube, with simultaneous investigation of the effect of trays' location on the probability of water vapor condensation inside the tube, on its inner surface, on the surface of the anti-condensation trays, and also at the point of passage of a light guide through the outer panels of the building;
- analysis of the possibility of freezing of HLG joints with outer walls of a building in conditions of critical winter temperatures, depending on the location of anti-condensation trays;
- profitability calculation of the project "Illumination of Swimming Pool Universitesky" with the help of energy-efficient technology of natural daylight delivery to premises with constant presence of people.

2. Methods

To determine the required number of HLGs and calculate the illumination level, we used the technique of Dr. Gennaro Bracale [27]. Calculations of natural daylight levels have been made for the light climate of Moscow to which data from the European database of natural and sunlight "Satel-Light" are available [28]. Verification of the solution, as well as diagrams of the practical task completed have been made in augmented DIALux program, in which the information on LED Solarspot® systems with a diameter of 900 mm has been integrated.

Study of heat exchange processes in a hollow tubular light guide have been made in the calculation complex Ansys (Solid70 (Thermal mass)).

In the course of the project economic profitability calculating we have taken into account the energy savings thanks to use of the energy efficient lighting system for the delivery of natural solar and diffuse daylight to the pool room, average annual growth of electricity tariffs, inflationary processes in Russia and Western Europe, average bills discount rates.

3. Results and Discussion

3.1 Technical rationale for the application of innovative technology for natural daylight delivery

3.1.1 Calculation of natural illumination level inside the object "Swimming Pool Universitetsky" using lighting systems based on hollow tubular light guides and its visualization using the augmented DIALux program

As a result of the calculations, we obtained the following: optimal positions of HLGs[1] diffusers/scatterers of natural daylight and halogen floodlights in the swimming pool room (Figure 2), 3D-color visualization of the pool illumination (Figures 3, 4).

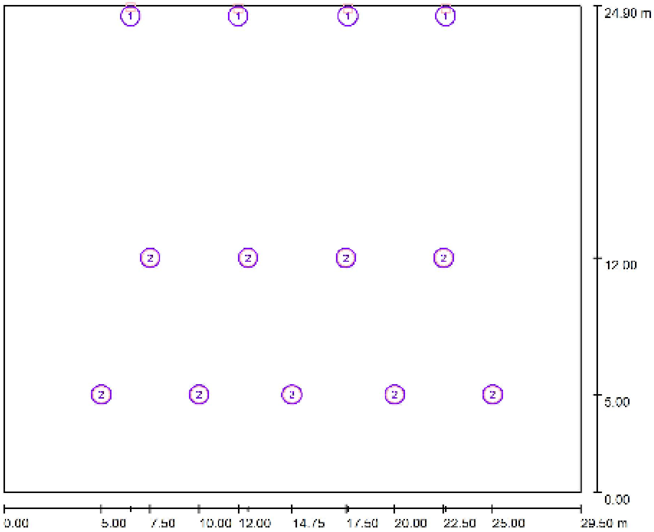

Figure 2. Positions of halogen floodlights TDM ИО1000 SQ0301-0005 (item 1) and HLGs LEDSolarspot® 900 (item 2). The calculation have been carried out in the augmented DIALux program

In Fig. 4 the illuminated working surface (water surface) in the color spectrum is indicated in white and thus is not visible, since its average illumination exceeds the norm (179 Lux). The numerical values of illuminance of the swimming pool in Lux can be seen in Fig. 5.

Analyzing the data in Fig. 5, we see very good light-engineering results, with a margin satisfying regulatory requirements:

total luminous flux 226038 Lm;

total luminous flux of 226038 Lm;

average illumination of the working plane: directly - 179 Lux, indirectly - 43 Lux, total - 222 Lux;

illumination uniformity on the working surface: $E_{min} / E_{average} = 0.166$; $E_{min} / E_{max} = 0.105$;

- specific connected power: 2.18 W / sq.m = 0.98 W / sq.m / 100Lux (base surface 733.96 sq.m).

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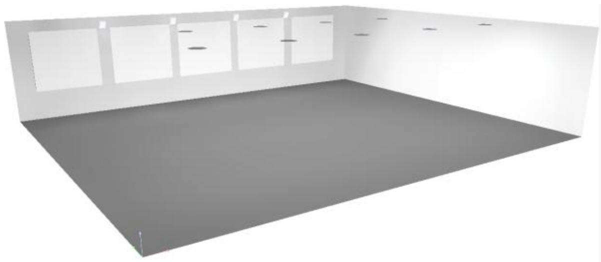

Figure 3. 3D-visualization of the swimming pool illuminated by 4 halogen floodlights TDM IO1000 SQ0301-0005 and 9 HLGs LEDSolarspot® 900. The calculation has been carried out in the augmented DIALux program

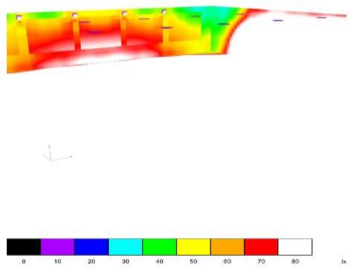

Figure 4. 3D-color visualization of the swimming pool illumination by 4 halogen floodlights TDM ИО1000 SQ0301-0005 and 9 HLGs LEDSolarspot® 900. The values are given in Lux. The calculation has been carried out in the augmented DIALux program

During periods of insufficient natural illumination, sensors build in the system LEDSolarspot® 900 will gradually activate LED-lights, allowing people inside to feel quite comfortable, the way they feel in the daytime.

24.88 m

44	58	76	96	86	114	145	133	104	121	148	138	108	123	158	123	92	95	88	58	40
69	82	118	126	138	163	212	199	181	182	220	207	188	188	218	185	147	128	126	88	66
79	109	146	162	165	213	267	264	219	241	282	278	229	253	275	242	176	164	156	121	76
98	131	162	175	191	240	285	280	262	277	311	295	277	279	296	254	211	182	174	136	94
112	136	163	169	193	232	273	268	270	276	302	289	283	272	260	245	211	179	172	142	108
118	132	151	160	188	218	247	253	266	270	280	278	275	261	251	229	202	173	162	139	115
122	133	149	162	189	214	237	251	264	268	273	274	271	259	242	223	202	176	160	140	120
125	132	148	168	192	215	235	255	267	272	275	275	272	262	242	224	205	181	163	141	124
123	131	150	172	198	223	241	261	274	280	282	282	278	267	249	232	213	187	166	143	123
125	135	157	184	214	242	261	279	294	301	302	301	298	285	269	253	233	203	176	150	127
127	137	161	192	227	258	276	294	310	317	317	317	315	300	285	269	248	214	183	154	132
130	141	168	205	247	280	298	315	333	339	337	338	337	323	307	292	271	232	194	160	135
133	144	174	214	257	291	310	327	344	350	347	348	348	335	319	304	283	243	201	165	140
136	147	179	220	263	298	314	331	347	352	349	350	349	338	323	308	287	249	206	169	145
139	150	182	222	262	293	312	328	342	347	345	345	344	334	321	305	285	249	209	172	148
142	157	190	228	262	290	308	323	334	339	338	337	334	326	316	300	282	252	216	180	152
146	161	196	233	264	289	307	321	330	334	334	333	329	322	313	299	281	255	222	185	158
150	166	206	243	271	293	310	324	331	334	335	332	327	321	315	302	288	263	233	195	164
150	172	212	249	275	295	312	325	331	334	335	331	325	321	316	303	288	268	239	200	165
151	173	214	251	275	293	309	321	325	328	329	324	318	315	312	300	286	268	241	202	167
146	168	207	245	267	284	298	310	314	317	318	313	307	304	302	290	278	260	235	195	162
137	155	188	221	240	255	267	277	281	283	283	279	275	271	269	260	250	234	213	179	150
129	146	173	201	219	234	243	252	256	259	258	255	252	248	246	238	228	213	194	166	139
114	127	147	170	186	198	205	213	217	219	218	216	214	210	208	201	193	180	165	141	121
117	127	143	163	172	181	187	193	197	199	199	197	195	192	189	183	176	164	159	139	121

0.00

0.00 29.50 m

Figure 5. Table of illumination of the swimming pool (working surface) by 4 halogen floodlights TDM IO1000 SQ0301-0005 and 9 HLGs LEDSolarspot® 900". The values are given in Lux, in scale 1: 211. The calculation has been carried out in the augmented DIALux program

3.1.2 Modeling and investigation of the heat exchange process via an HLG with variation of the anticondensation trays position

Having in mind the possibility of water vapor condensate falling inside the tube, on its surface and on the surface of anticondensation trays at certain outside air temperatures and air temperature inside the HLG, we considered and investigated three variants of the position of anticondensation trays along the light tube length (Fig. 6).

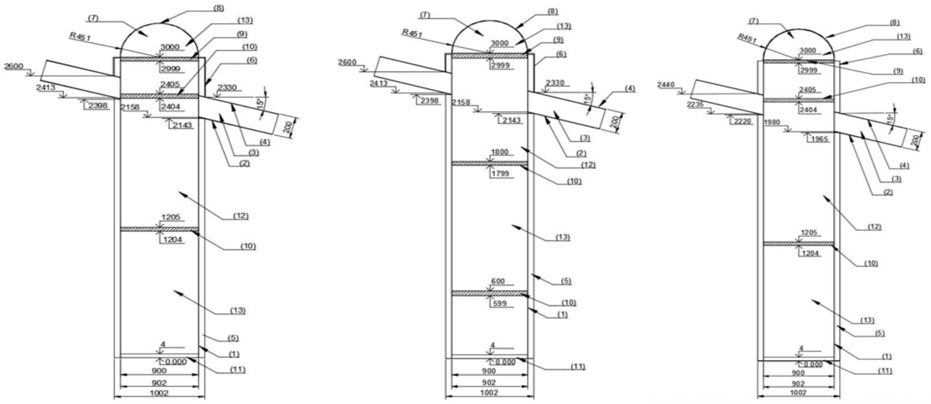

Figure 6. Variants: 1 (on the left, the model is divided into 3600044 elements); 2 (in the center, the model is divided into 3583675 elements); 3 (on the right, the model is divided into 3622075 elements) of the location of anticondensation trays.

The notation for
Fig. 6: 1 - HLG body (λ = 96 W / m · ºC); 2 - internal covering of the roofing sandwich panel (λ = 52 W / m · ºC); 3 - thermal insulation of the roofing sandwich panel (λ = 0.039 W / m · ºC); 4 - external covering of the roofing sandwich panel (λ = 52 W / m · ºC); 5 - thermal insulation of the light guide (λ = 0.035 W / m · ºC); 6 - roof adapter (λ = 0.48 W / m · ºC); 7 - closed air space between the roof adapter and the light guide (λ = 0.025 W / m · ºC); 8 - acrylic dome collector (λ = 0.21 W / m · ºC); 9,10 - anticondensation tray (λ = 0.29 W / m · ºC); 11 - tube diffuser (acrylic, glass, λ = 0.16 W / m · ºC); 12, 13 - the closed air space inside the HLG (λ = 0.025 W / m · ºC)

The adopted values of the thermal conductivity coefficients of the individual HLG structure elements are given in the notation to Fig. 6. For calculations we have taken the outside air temperature equal to -38 ºC, the indoor air temperature equal to +26 ºC; the heat transfer coefficient of the inner surface of the enclosing structure is 25.12 W / m2 · ºC.

For the first variant of the location of anticondensation trays, we have obtained the following scheme of temperature fields and temperature distribution along the central axis of the HLG (Fig. 7).

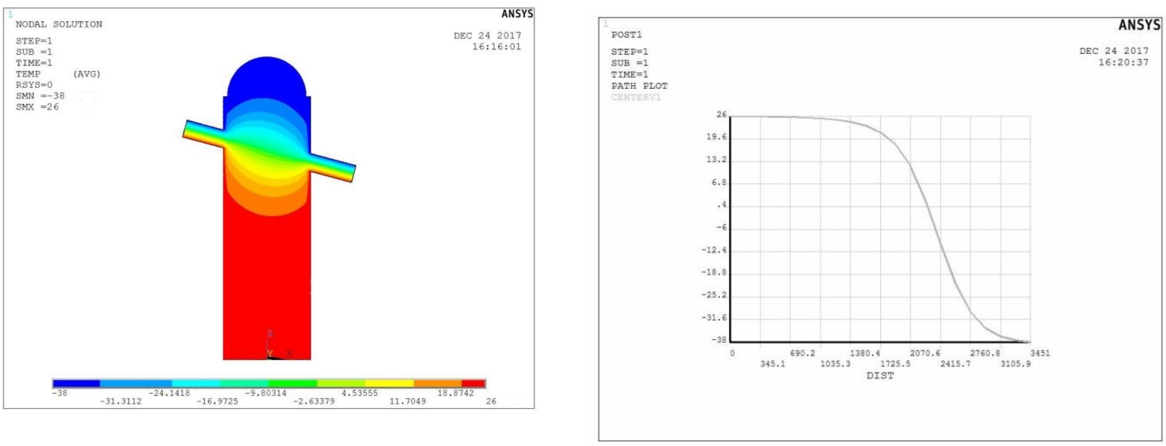

Figure 7. Temperature fields in the cross-section of the HLG (diagram on the left, ºC); graph of the distribution of temperatures along the central axis of the HLG (diagram on the right, the ordinate is temperature, ºC, abscissa is length of the HLG, mm)

The middle tray is located at the level of the roofing sandwich panel. The roof of the swimming pool building is pitched (slope 15 °), part of the anticondensation tray is outside the building in the low temperature region and cooled to -30.14 ° C; the second part is in the area of positive temperatures, inside the building. Temperature on the surface of the disk raises up to +11.625 ° C. In this case, the surface of the HLG from the inside of the building due to the thermal resistance of the HLG body and due to the presence of the roof insulation has a temperature of +10.179 ° C.

Analyzing the considered variant, we can state that the temperature on the surfaces of the anticondensation tray is much higher than the dew point temperature of the ambient air. Condensation should not occur. The temperature on the surface of the insulation in the point of conjugation with the enveloping structure of the roof (sandwich panel) +25.039 ° C, which also exceeds the dew point temperature of the ambient air, equal to +20.093 ° C for the pool, that is, the condensation of water vapor should not occur. The temperature at the surface of the light guide at the conjugation with the enveloping structure of the roof (sandwich panel) is + 10.179 ° C, which is substantially lower than the dew point temperature of the ambient air (+ 20.093 ° C). Though, in case of a loose fitting of the insulation to the roofing sandwich panel and the light tube, condensation of water vapor may occur.
Consideration of the second variant model of the anticondensation tray location has given us the following schemes, see Fig. 8.

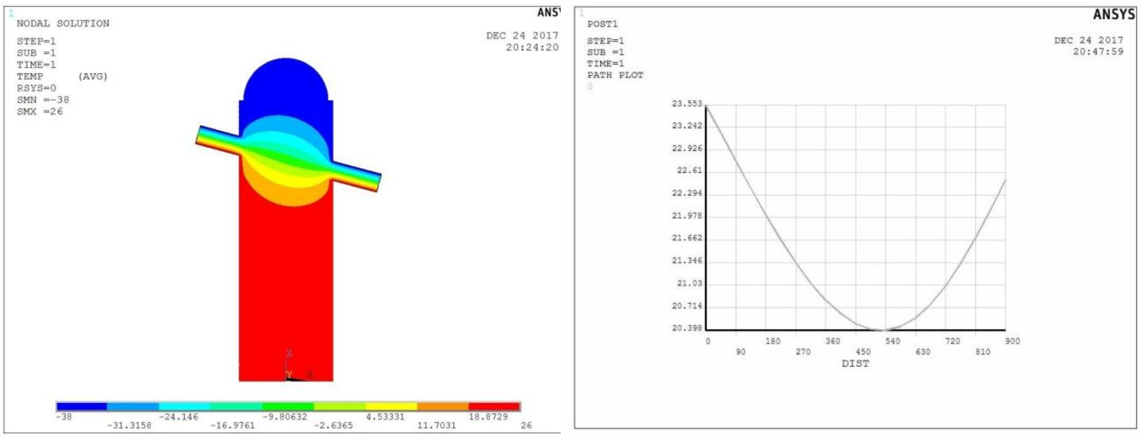

Figure 8. Diagram of the temperature fields in the cross section of the light guide for option-2 (Figure on the left) and the temperature distribution graph on the surface of the middle anticondensation tray (figure on the right, on the ordinate axis temperature is plotted, ºC, on the abscissa axis – HLG diameter, mm, Z coordinate = 1799 mm, see figure 6)

In absence of the middle anticondensation tray in the level of the roofing sandwich panel (option-2), the temperature at the surface of the HLG inside the building will be + 10.734 ° C, that is higher than in option-1. For the first and second options of the location of condensation trays, the temperature distributions along the central axis of the HLG practically coincide.

Temperature on the surfaces of the anticondensation tray is much higher than the dew point temperature of the ambient air (Figure 8, right). We can state that condensation should not occur. Temperature on the surface of the insulation at the conjugation with the enveloping structure of the roof (sandwich panel) +25.782 ° C, which exceeds the dew point of the ambient air (+20.093 ° C) in the swimming pool.

Temperature at the surface of the light guide at the conjugation with the enveloping structure of the roof (sandwich panel) is + 10.734 ° C, which is below the dew point of the ambient air (+20.093 ° C). Though, in case of a loose fitting of the insulation to the roofing sandwich panel and the light tube, the likelihood of condensation of water vapor is high.

In the third variant of tray location (the average anticondensation tray is located at the roof level, just above the sandwich panel, it does not border on the point of its contact with the HLG body inside the building), the temperature on the surface of the light guide inside the building is +11.153 ° C. In this case, the anticondensation tray, having its own thermal resistance, creates an air chamber above the roof panel, retains heat inside the HLG and reduces the possibility of freezing of its structures. Results of the heat fluxes motion are shown in Fig. 9.

Temperature on the surfaces of the anticondensation tray again significantly exceeds the dew point temperature of the ambient air. Condensation should not occur. Temperature on the surface of the insulation in the point of conjugation with the enveloping structure of the roof (sandwich panel) +25.79 ° C exceeds the dew point temperature of the ambient air, equal to +20.093 ° C in the swimming pool. Temperature at the surface of the light guide at the conjugation with the enveloping structure of the roof (sandwich panel) +11.153 ° C. This is below the dew point temperature of the ambient air (+20.093 ° C). Though, if the insulation is not adherent to the roofing sandwich panel and the light tube, there is a possibility of condensation of water vapor (see the diagram on the right in Figure 9).

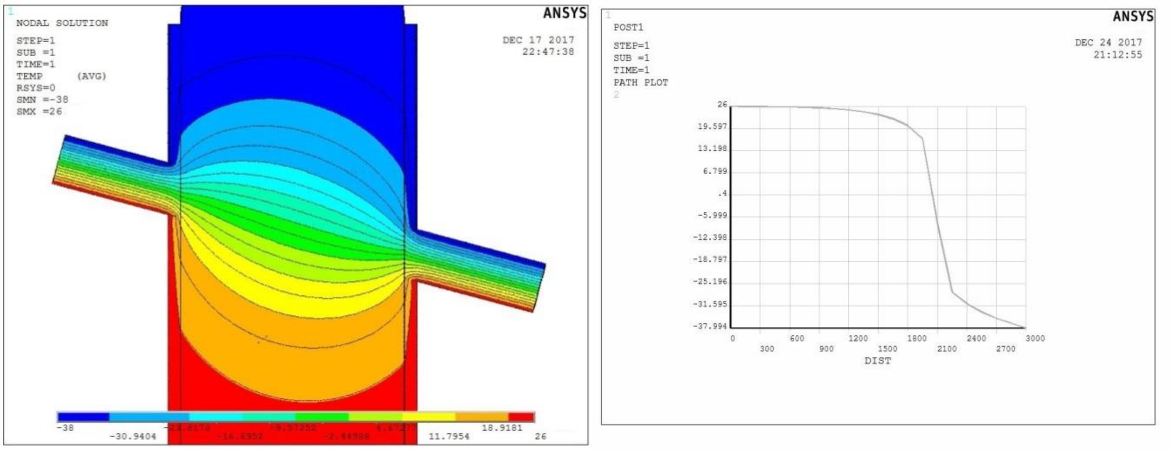

Figure 9. Diagram of temperature fields at the conjugation of the light guide and the sandwich panel according to the version-3 (figure on the left, ºC); the graph of the temperature distribution along the outer surface of the HLG (figure on the right, the ordinate is temperature, ºC, abscissa is length of the HLG, mm, the coordinate is X = 451 mm, Y = 0 mm)

3.2 Economic justification for the use of hollow mirrored tubular light guides

Increase in energy efficiency of a project can not be considered without a calculation of profitability. The payback dynamics of the additional costs incurred to improve the energy efficiency of the Swimming Pool Universittesky project is reflected in Fig. 10.

Analysis of the diagrams shows that by using only own funds and having additional investment for the project due to savings out of electricity bills, the return of funds spent on the acquisition and installation of lighting systems based on the HLG manufactured by Italian company Solarspot International SRL can be obtained approximately after 13-14 years. The attraction of borrowed funds from commercial banks will increase the repayment period by 3-4 years. Since the object Swimming Pool Universitesky is a state property [29], the financing system could be implemented on a preferential basis. Then the payback period of additional funds spent will be significantly reduced.

Analysis of previously published scientific papers on the subject shows that studies related to the adaptation of the natural light delivery system to rooms with constant presence of people in cold climate practically were not carried out. Only Prof. A. Soloviev and Assistant Prof. O. Tusnina [26] had performed calculations to compare the thermos-technical characteristics of zenith roof lights and HLGs. Authors of this work in 2017 had calculated similar systems, however, of a different diameter

[22]. In the proposed study the completed thermo-technical calculation is supplemented by a deep analysis based on the variation of the placement of anticondensation trays in the tube of HLG in order to optimize the possible loss of efficiency in connection with the probability of condensate formation on the tray surfaces. In this regard this work is unique.

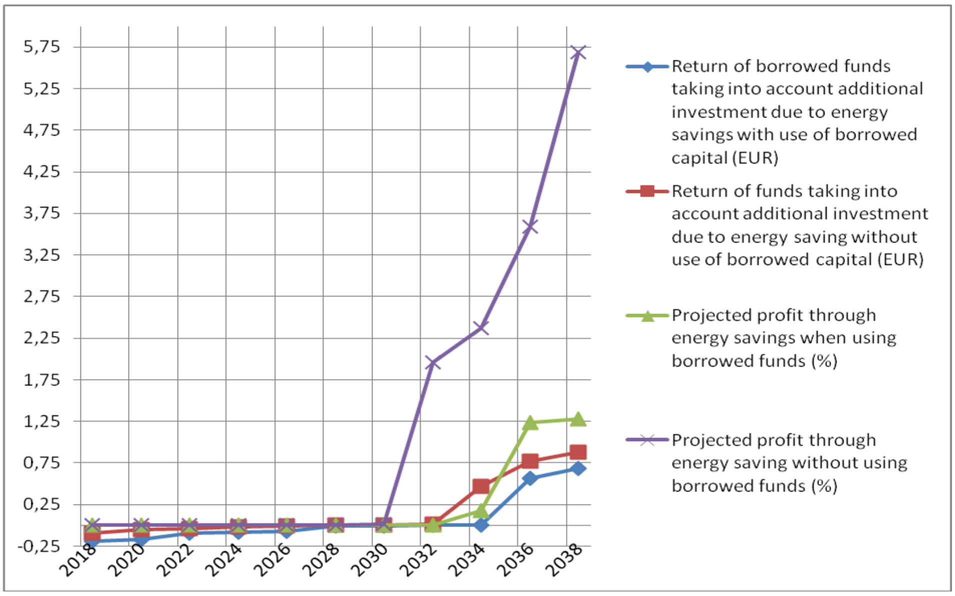

Figure 10. Dynamics of the return of additional extra (borrowed) funds with long-term investments in the Swimming Pool Universitetskiy project in order to increase its energy efficiency, taking into account additional investment through saved funds of payment for lighting (electricity bills)

Currently, there is no computer program in the open access that would allow not only to calculate the illumination of premises using HLG, but also effectively illustrate them. In this very fact we also see a fundamental difference between our research and all previously published scientific works.

4. Conclusions

1. Long-term investments in energy-efficient projects implemented through the use of lighting systems based on hollow tubular light guides are profitable in the climatic conditions of Russia.

2. The research performed has shown that energy-efficient lighting systems produced by Solarspot International SRL for the delivery of natural solar and diffuse daylight to rooms with permanent presence of people are not cold bridges for cold air currents in the climatic conditions of Russia.

3. Position of anticondensation trays of the lighting system affects the thermal state of the light guide. The temperature on the surface of the middle disc located in the room zone is lower than in case when the upper anticondensation trays are located closer to each other.

4. The study has made it possible to make a hypothesis about the possibility of HLG freezing at its junction with the outer fence of the building in conditions of critically low winter temperatures, depending on the location of the anticondensation trays. In this connection, the authors propose to add to the construction of HLGs a qualitative thermal protection that protrudes beyond the enclosing structure of the building, under the roof adapter (see figure 6, position 6).

In this paper, we considered the ideal coupling of anticondensation trays and the body of HLG, without taking into account the technological gaps. If they are available, the nature of the operation of this system from the point of view of heat engineering can significantly change. This will require additional research, which we will discuss in our subsequent scientific papers.

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