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Cost analysis at different energy sources for heating of an air-supported dome for indoor tennis

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Abstract. Numerical analyses of the energy supply for heating of air supported structure for indoor tennis in Sofia via district heating, gas and liquid fuels are performed. The computational procedures are implemented through thermal balances of the structures, calibrated on the base of in situ measurements of the indoor temperature and the amount of the fuel, consumed at heating of an air supported balloon for tennis in University of Chemical technology and Metallurgy. The profitability of the different heating variants is estimated using the price of the energy and the systems.

1 Introduction

The wholly air-supported structures, also known as air supported domes (ASD), are lower cost alternatives to the traditional building, suitable for covering areas for indoor sports as soccer fields, large swimming pools, tennis and multisport facilities [1, 2]. They are mobile and semi-permanent as can be taken down and set up every season. The walls are made by fabric membranes (i.e. PVC coated polyester), anchored to the ground around their perimeter, without needs of supporting beams or columns. The dome access points include revolving doors, pedestrian airlocks for barrier free access, and vehicle airlocks for maintenance and lift equipment.

A higher air pressure inside the dome according to the local meteorological pressure supports the entire structure. This gauge pressure has to compensate the gravity force of the membrane, the wind loads and the snow loads during the winter periods. It is a function of the expected wind speed and snow intensity for the region at a given mass of the envelope. The practice shows that a gauge pressure of 250 Pa in the indoor space is enough to counteract the loads, mention above [3]. It is maintained by continuous fresh air supply into the structure in order to compensate the leakages and to ensure the necessary fresh air for the people in the dome [3, 4].

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The supply airflows are provided by ventilation and heating/cooling units. Their temperature and volumetric flow are regulated by the automation system, based on a differential pressure gauge and temperature sensors. A recirculation of the return air can be maintained in order to prevent inlet temperatures higher than 40 °C. Temperatures above that value are dangerous for the polyester membranes and the people. However, the ventilation system have to ensure 100 % fresh air, if it is necessary. According to [3 and 4] the blower capacity of the ventilation unit should be designed to allow:

- a compensation of the maximal air leakage at the base, around the doors and through the vents. The experience indicates that the leakage losses at a gauge pressure 250 Pa in the dome can reach 57 m^3h^{-1} per linear meter of base perimeter, 340 m^3h^{-1} per door assembly, and 43891 x A m^3h^{-1} for vents (A is the total vent area in square meters);
- a fresh airflow of at least 60 m^3h^{-1} per person according to [5];
- a satisfactory initial inflation time specified by the design requirements.

The temperature and the relative humidity of the indoor air at sport halls have to be in the ranges of 14 - 16 ºC and 30 - 60 % respectively, [6]. The optimal air velocity is 0.3 - 0.4 ms^{-1}. The Bulgarian regulation [5] imposes more précised parameters for covered sport halls in universities and schools: temperatures of 18 ºC at the winter, 22 - 27 ºC in the summer. The maintaining of these indoor parameters is connected with relatively high energy needs due to the low thermal resistance of the dome envelopes and the relatively high air exchange rate per hour.

The estimation of the heating and the cooling power at the air supported domes depends on solar gains. They are difficult for computation at the complex geometry of the walls, causing complicated solar ray tracing and infrared radiation heat transfer into the structure [7]. Comprehensive investigations of these related processes have not been published so far. The estimation of the energy needs and the relevant cost analysis at air supported domes are actual and open problems.

This paper presents a cost analysis at different energy sources for heating of an air-supported dome for tennis. The assessments are based on a calibrated thermal balance, based on a model for solar energy gains estimation.

2 Assessment of the energy inputs and outputs at heating

2.1 Object of investigation

The ASD for indoor tennis cover 3 tennis courts on the territory of University of Chemical Technology and Metallurgy (UCTM) in Sofia (fig. 1 and 2). Parameters of the structure are given in Table 1. The wall area is obtained based on the geometrical model of the construction (fig. 2). It is overestimated with 5 % for the thermal losses computation to reflect the surface relief, obvious from fig. 1.

Fig. 1. Air supported dome for indoor tennis at UCTM.

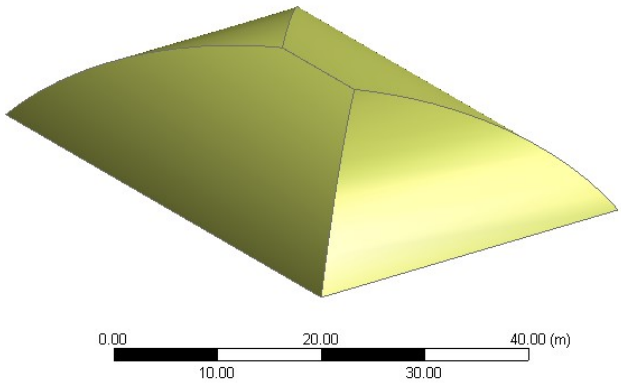

Fig. 2. Geometrical model of ASD.

The air-supported structure is set in the middle of December 2020 with an idea to be taken down in the end of the heating period in Sofia (23 April).

Table 1. Geometrical and thermal parameters of ASD.

Parameter	**Dimension**	**Value**
Width	m	37.10
Length	m	48.10
Maximal height	m	10
Floor perimeter	m	170.40
Floor area, A_f	m^2	1784.51
Wall area A_w	m^2	2259.59
Wall area + 5%	m^2	2372.46
Indoor volume V	m^3	10424
Supply fresh air flow $\dot{V}$ (over 90% of the time)	m^{3}h^{-1}	11400
Air exchange rate per hour (ARCH)	h^{-1}	1.09

The ventilation and heating unit (VHU) is type K-140 D, made by Gustav Nolting GmbH. It is consisted of a main blower (volumetric flow 11400 m^{3}h^{-1}, gauge pressure 300 Pa, power of 4 kW), a stand-by engine (volumetric flow 11000 m^{3}h^{-1}), and a burner coupled with a heat exchanger for heating of the supply airflow. The stand-by engine is used as a reserve power. The used fuel is diesel oil. The nominal heating capacity of the unit is 181 kW, the nominal heat output is 163 kW (10% thermal losses). The burner is switched on during the occupation periods of the ASD. The rest of the time the dome is not heated up – only the main blower is working.

There is a possibility for recirculation, but it is not used because of the relatively small capacity of the unit - it support the structure at a lower indoor gauge pressure than recommended. Additional blower with frequency inverter and a maximal power of 15 kW is used to supply additional fresh air in order to keep the gauge pressure at chilly nights and snow loads. The electrical energy consumption of the blowers (minimum 2976 kWh/month if the additional blower is not working) is not taken into account in the present study. It does not influence on the thermal balance for the heating as the blowers are outside the dome and the heat, released by the engines, is dissipating in the outdoor environmental. In addition, this energy consumption is the same at the different variants of the primary thermal energy.

2.2 Thermal balance of air supported domes for tennis

The thermal balance according to the system boundary on figure 3 is:

$$\dot{Q}_{in} = \dot{Q}_w + \dot{Q}_f + \dot{Q}_l - \dot{Q}_s - \dot{Q}_h, \text{ kW} \tag{1}$$

where $\dot{Q}_{in}$ is the input heat flow, $\dot{Q}_w$, $\dot{Q}_f$, $\dot{Q}_l$ are respectively the thermal losses through the wall, floor and the air leakage, $\dot{Q}_s$ represents the solar gains and $\dot{Q}_h$ are additional thermal sources (lighting, people, electrical equipment). The last are relatively small at the covered tennis courts and can be neglected.

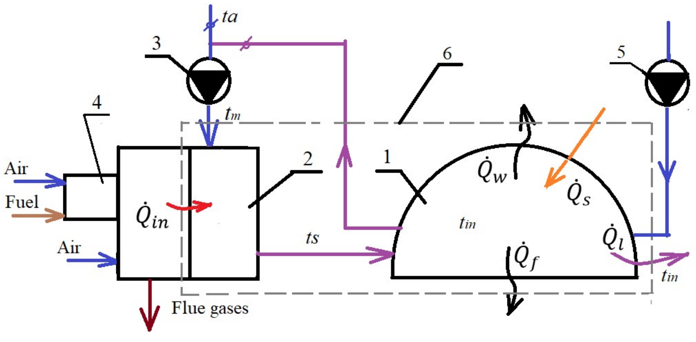

Fig. 2. System, consisted of an air dome for tennis and VHU. 1 - air dome; 2 - heat exchanger of VHU; 3 – main blower of VHU; 4 –burner of VHU; 5- additional brower; 6 - system boundary.

The input heat flow, necessary to heat the supply air with a mass flow $\dot{m}_l$ from the ambient temperature t_a to temperature t_s (fig. 1), is:

$$\dot{Q}_{in} = \eta_g \dot{Q}_g = \dot{m}_l c_{air} (t_s - t_a), \text{ kW} \tag{2}$$

where: η_g = efficiency of the heat generator; $\dot{Q}_g$ = the output heat flow of the generator, kW; c_{air} is the specific heat capacity of the air at constant pressure, kJkg^{-1}K^{-1}.
At a case of combustion, $\dot{Q}_g$ is obtained via the lower heating value LHV [kJkg^{-1}] and the mass flow $\dot{B}$ [kgs^{-1}] of the fuel:

$$\dot{Q}_g = \dot{B}.LHV, \text{ kW} \tag{3}$$

The mass flow of the fresh supply air is equal to the mass flow of air leakage. Usually it is higher than the necessary fresh air for the people (maximum 4 per court).

$$\dot{m}_l = \frac{ARCH.V\rho}{3600} \tag{4}$$

where ρ=air density at the indoor temperature, kgm^{-3}.

The thermal losses through the balloon walls are computed by the equation:

$$\dot{Q}_w = \frac{1.1 U_w A_w (t_{in} - t_a)}{1000}, \text{ kW} \tag{5}$$

where U_w = thermal transmittance of the walls, $Wm^{-2}K^{-1}$. It is computed by the thermal resistances of the membrane envelope R_m, internal and external thermal boundary layers R_{si} and R_{se} respectively, [m^2KW^{-1}]. U_w is increased with 10% in the equation above to reflect the thermal bridges [8].

$$U_w = \frac{1}{R_{si} + R_m + R_{se}}, \text{ Wm}^{-2}\text{K}^{-1} \tag{6}$$

The thermal resistance of one layer membrane is:

$$R_m = \frac{\delta_m}{K_m}, \text{ m}^2\text{KW}^{-1} \tag{7}$$

where δ_m=membrane thickness, m; K_m=thermal conductivity of the material, $Wm^{-1}K^{-1}$.
The heat flow, exchanged with the ground, can be obtained by the equation, used at the floor of greenhouses [9]:

$$\dot{Q}_f = 0.001 A_f \left[k_e (t_{in} - t_a) - \frac{1.2}{h_k} (t_{gw} - t_a) \right], \text{ kW} \tag{8}$$

where h_k = underground water depth, m; t_{gw}=underground water temperature, °C; k_e = equivalent coefficient of thermal transmittance, $Wm^{-2}K^{-1}$, function of floor area A_f and h_k [9].
The thermal losses due to the air leakage are computed according to:

$$\dot{Q}_l = \dot{m}_l c_{air} (t_{in} - t_a), \text{ kW} \tag{9}$$

The heat flow, expressing solar gains $\dot{Q}_s$ in equation (1) is non-zero at the daily time. It is difficult for computation due to the changeable and transient solar incident angle at the curved balloon envelopes (fig. 1 and 2). The polyester membranes are transparent, absorb part of the solar irradiation and have relatively high emissivity in the infrared spectrum [7]. Therefore, the solar heat gains are consisted of the directly transferred solar energy and the absorbed one, which is transferred by convection and radiation in the infrared spectrum to the indoor space. In the present paper the amount of the solar energy, utilized in the dome, is obtained by the monthly energy balance, knowing the fuel consumptions and the other amounts of heats:

$$Q_{in} = Q_w + Q_f + Q_l - Q_s, \text{ kWh/month} \tag{10}$$

The input amounts of heat are computed based on the known monthly fuel consumptions B [kg/month]:

$$Q_{in} = \eta_g B.LHV, \text{ kWh/month} \tag{11}$$

The monthly amounts of heat in the right side of equation (10) are computed with the averaged heat flows $\dot{Q}_w^{av}$, $\dot{Q}_f^{av}$ and $\dot{Q}_l^{av}$:

$$Q_w = \tau_m \dot{Q}_w^{av} = \tau_m \frac{1.1 U_w A_w (t_{in}^{av} - t_a^{av})}{1000}, \text{ kWh/month} \tag{12}$$

$$Q_f = \tau_m \dot{Q}_f^{av} = 0.001 \tau_m A_f \left[k_e (t_{in}^{av} - t_a^{av}) - \frac{1.2}{h_k} (t_{gw} - t_a^{av}) \right], \text{ kWh/month} \tag{13}$$

$$Q_l = \tau_m \dot{Q}_l^{av} = \tau_m \frac{ARCH.V\rho}{3600} c_{air} (t_{in}^{av} - t_a^{av}), \text{ kWh/month} \tag{14}$$

where τ_m=number of the hours of the correspondent month; t_a^{av} = monthly average ambient temperature, °C; t_{in}^{av} = time average indoor temperature, °C, computed by the part *d=n/24* of the operating hours *n* per day of the heating system:

$$t_{in}^{av} = d.t_{in} + (1-d) t_a^{av}, \text{ °C} \tag{15}$$

The monthly solar gains are accepted as part ***k*** of the real sky solar energy $Q_{s,m}$, incident on a horizontal plane with floor area A_f:

$$Q_s = k Q_{s,m}, \text{ kWh/month} \tag{16}$$

$$Q_{s,m} = q_{s,m} A_f D_m, \text{ kWh/month} \tag{17}$$

where $q_{s,m}$= specific amount of solar energy on a horizontal plane, $kWhm^{-2}day^{-1}$; D_m = number of the days per months at the heating period according to [8].
The coefficient k is obtained by equation (10). This approach is applicable as there is enough information about the solar energy, incident on the horizontal planes [10].

2.3 Calibration of the thermal balance

January and February are the first full months of the operation of the ASD. The average ambient temperature for these months, obtained via meteorological database [11] and the established indoor temperature during the time intervals with switched on heating are given in Table 2. The time duration of the heating correspond to the occupation periods that are initially smaller than the predicted one (12h/day) and increase gradually.

Table 2. Indoor and outdoor temperatures.

Month	t_a^{av}	**Heating time**	**Measured t_{in}**	t_{in}^{av}
-	°C	h/day	°C	°C
01. 2021	1.3	6	12	3.98
02. 2021	4.2	8	15	7.80

The daily amounts of the solar energy, incident on a horizontal plane at the location of the tennis courts is obtained by [10] as averaged values for 37 years period (1984-2019). They are used to compute the monthly solar gains in Table 3. The solar gains for January and

February are used in the energy balance (10) to obtain the part k of the utilized solar energy in the dome (Table 4).

Table 3. Incident solar energy on a horizontal plane

Month	January	February	March	April	October	November	December
$q_{s,m}$ kWhm^{-2}day^{-1}	1.706	2.476	3.414	4.263	2.840	1.801	1.448
D_m Days/month	31	28	31	23	17	30	31
$Q_{s,m}$ kWh/month	94397	123694	188886	174949	86148	96393	80075

The monthly amounts of heat, participating in the balance, are computed at the established monthly fuel consumptions and the parameters: LHV=9.7525 kWhl^{-1}; R_{si}=0.1 m^{2}KW^{-1}; R_{se}=0.043 m^{2}KW^{-1}; U_w= 6.51Wm^{-1}K^{-1}; η_g =0.1; k_e=0.5 Wm^{-2}K^{-1}; h_k = 6 m; t_{gw} =10°C. It is obvious that the thermal losses through the dome walls are the higher than the other, but they are compensate by the solar energy.

Table 4. Monthly amounts of heats.

Month	Diesel consumption	Q_{in}	Q_w	Q_f	Q_l	k	$Q_s=kQ_{s,m}$
-	l/month	kWh/month	kWh/month	kWh/month	kWh/month	-	kWh/month
01.2021	1000	8777	33830	-534	13561	0.345	32586
02.2021	1000	8777	41123	767	16260	0.346	42786
					Average	0.346	

The average k= 0.346 is the part of the solar energy, incident on a horizontal plane with floor area A_f, utilized in the investigated air supported dome. It is used in the next analyses at different energy sources.

3 Thermal and cost analyses at different energy sources

The 3-month experience show that the present heating capacity of the existing HBU is not enough to maintain the necessary indoor temperature at negative ambient temperatures. The solution of equation (1) in the absence of sunshine at minimal accepted temperature for Sofia (-16 °C) according to [12] gives a design (maximal) heat flow Q_{in}= 666.132 kW. It is several times higher according to the existing one. This fact and the established insufficient power of the main blower of VHU impose increasing of the capacity of the installation or a new one at the same or different primary energy.

Three options of energy sources for heating are analyzed: thermal energy from combustion of diesel oil (present variant), natural gas and from cogeneration power plants in Sofia (district heating). The monthly thermal balances are implemented at the average ambient temperatures in 7-th climatic zone (where Sofia is). A time occupation of the dome 12h/day and an indoor temperature of 15 are accepted. The necessary input amounts of heat are given in Table 6. The negative values of the necessary input energy for April and October show that the solar energy gains are enough to heat the dome to the desired temperature during these months.

Table 5. Technical and financial data at the investigated variants

Type	Thermal losses	LHV	Actual cost with VAT	Additional data
-	%	kWh/unit	BGN/unit	-
Diesel oil	10	11.75kWh/kg	1.82 BGN/l	Density: 0.83 kg/l
Natural gas	8	9.305 kWh/m^3	1.20 BGN/m^3	The m^3 are at Normal physical conditions
Thermal energy from district heating	8	-	0.1 BGN/kWh	The generator of the VHU is a heat exchanger

The primary energy, obtained at the thermal losses at the different generators, fuel consumptions and the subsequent actual financial costs for the period of November to March are systematized in Table 7.

Table 6. Monthly amounts of solar gains and input amounts on heat.

Month	D_m	t_a^{av}	$Q_s=kQ_{s,m}$	Q_{in}
-	day/month	°C	kWh/month	kWh/month
1	31	-0.4	32,619	89,317
2	28	0.2	42,743	63,149
3	31	4.6	65,270	17,865
4	23	10.4	54,408	-26,628
10	17	11.2	26,792	-9,707
11	30	5.1	33,309	43,326
12	31	0.4	27,670	88,663

Table 7. Necessary energy consumptions and costs.

Month	Diesel oil			Natural gas			District heating	
	Necessary amount of heat Q_g	Amount of fuel	Cost with VAT	Necessary amount of heat Q_g	Amount of fuel	Cost with VAT	Necessary amount of heat Q_g	Cost with VAT
-	kWh	l/month	BGN	kWh	m^3/month	-	kWh/month	BGN
1	99,241	10176	18520	97,083	10433	12520	97,083	9563
2	71,760	7358	13392	68,640	7377	8852	68,640	6762
3	20,301	2082	3789	19,419	2087	2504	19,419	1913

11	49,234	5048	9188	47,093	5061	6073	47,093	4639
12	100,754	10331	18803	96,373	10357	12429	96,373	9494
Sum	**341,289**	**34995**	**63691**	**328,608**	**35315**	**42378**	**328,608**	**32371**

The necessary thermal energy at the cases of natural gas and district heating are equal because of the same thermal losses. But their cost is different. The cost of the thermal energy for the heating of the ASD is maximal at the use of a diesel oil. It is approximatively twice in comparison with the heating option at district heating. The financial payback times of the energy costs per heating season at the investigated variants are given in Table 9. The computations are implemented at the assumption for a full occupation of the covered tennis courts 12 h/day and a cost of 30 BGN with VAT per hour per court.

Table 8. Financial payback time of the energy consumption for heating of ASD

Type	Payback time of the thermal energy cost	Payback time of the overall energy cost
-	Days per heating period	Days per heating period
Diesel oil	59	65
Natural gas	39	54
Thermal energy from district heating	30	36

If the cost of the electrical energy consumption of the blowers is taken into account (approximatively 30 MWh/year x 200 BGN/kWh), the payback time will increase (third column of Table 8).

4 Conclusions

The suggested approach for estimation of the solar energy gains at the heating of air-supported domes, based on inverse thermal balance at operating installations, is easy for implementation. It is tested and applied at balance assessment of the thermal energy inputs for heating of a covered tennis courts in Sofia at different energy sources. As results of the case study, it was found that:

- the solar energy cover significant part of the thermal losses at the chilly months and it is enough for the heating of the air dome during April and October;
- the energy supply by the district heating of Sofia is the more cost-effective variant for the heating.

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