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IMPACT OF THERMAL BRIDGES ON THERMAL PROPERTIES OF THE NEW-TYPE PIGGERIES STRUCTURES

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ABSTRACT

Pig production has high energy consumption thus the energy efficiency of a building is very important. The objective of this paper is a qualitative and quantitative evaluation of thermal properties and thermal bridges in the structure of a newly constructed piggery. The results prove unsuitable thermal properties of the majority of structures. Characteristic thermal properties: external walls (UT=0.470 $W\cdot m^{-2}\cdot K^{-1}$), flooring (UT=1.356 $W\cdot m^{-2}\cdot K^{-1}$), ceiling (UT=0.229 $W\cdot m^{-2}\cdot K^{-1}$), windows and doors (UT=1.70 $W\cdot m^{-2}\cdot K^{-1}$). Qualitative detection of thermal defects with utilization of infrared thermography claimed the most significant thermal bridges on uninsulated socle and flooring, steel concrete straining band of the wall, bearing steel roof frames and window and door frames. The energy efficiency of buildings is significantly affected by the built structure properties and some structures of the measured buildings had low thermal insulation and caused high heat losses.

Introduction

Pig production highly depends on the ambient conditions inside environment of the piggery. For regulation of the inside environment conditions, thermal insulation of external envelope elements and technical equipment for heating and ventilation are used. This is one of the reasons of high energy consumption of pig production. (Theodosiou and Papadopoulos, 2008) state that the European Directive 2002/91/EC on the Energy Performance of buildings (EPBD) is probably the most important single action towards the improvement of energy efficiency in the building sector throughout Europe since 1970s when, in the aftermath of the energy crisis, most national building regulations introduced mandatory thermal insulation requirements. The implementation of the European Directive 2002/91/EC in the form of national laws by each Member State, gradually leads to the need to adopt advanced standards, techniques and technologies while designing and constructing new buildings, but also to apply energy renovation measures in existing ones, in order to comply with the updated energy efficiency requirements. (Déqué et. al., 2001) state that insulating walls represent one of the simplest solutions for decreasing heat losses of the building. However, although quite obvious in the energy balance, the ever improving insulation implies that the relative proportion of heat losses by cold bridges in the wall has relative influenced thermal bridges in the overall heat losses. The other major improvement in the study of thermal bridges is this recent possibility for engineers to use infrared thermography instruments. This technique allows visualization of heat losses in situ, at a distance (without contact) at the scale of the building and without intrusion in the building walls as non-destructive technique (Zalewski et al., 2010).

Bucklin et al. (1992) states that livestock buildings housing young animals need addition of heat during cold weather periods. The most significantly heated livestock building, housing early-weaned piglets is a swine nursery. Autonomic and behavioral thermoregulatory mechanisms play important role in the adaptation of the pig to its environment (Ingram, 1976). Piglets are homeothermic animals and continuously try to keep their body temperature at 39ºC through the thermal exchanges with the surrounding air. (McCracken, 1984) states that for early-weaned piglets, 3-4 weeks old when weaned, housed under real farm conditions, growth parameters are optimized when temperatures vary between 21ºC and 29ºC. For pigs especially in the weaning phase, a critical parameter is room temperature, which must be maintained around 26ºC (Whittemore, 1993). The thermal equilibrium in the body is achieved through a balance between the metabolic heat production and heat loss from the body. Pigs heat production has a diurnal rhythm depending on the feed intake and activity level, and is influenced by the ambient temperature (Henken at al., 1993). Climatic conditions in pig housing, primarily ambient temperature are monitored and automatically adjusted based on the set point temperature. However, the thermal environment is not only determined by the dry-bulb temperature, but is also influenced by the wet-bulb temperature, radiant temperature and air velocity (Sällvik and Walberg, 1984). If the thermal environment does not satisfy the current thermal need of the pigs, it can lead to hygiene (Aarnink et al., 2006) and welfare problems (Hillmann at al., 2004). (Gálik and Karas, 2004) claimed that the difference between the average air temperature in the house and that of interior wall surfaces is 3.44ºC and resulted in the bedewing of circumferential construction.

The objective of this paper is a qualitative and quantitative characterization of thermal bridges on the walls of a new -built piggery. In the first step, the proposed methodology involves an infrared camera employed to locate the thermal bridges on the walls. Experimental part of the paper consists of thermograms of the envelope with their interpretation. The next step is calculation of the thermal characteristics and heat losses caused by thermal bridges.

Material and methods

The analyzed piggery is located at Suchohrdly u Miroslavi (lat 48º56´50´´N, long 16º22´26´´E) Znojmo region, Czech Republic. This new-building piggery is a part of facilities for livestock production and was built in 2008. Capacity of piggery is designed for 350 sows and 1300 piglets. Piggery has forced ventilation with the electronic system of measurement and regulation, warm-water heating. A continuous winter duct pit ventilation centrifugal fan is integrated with variable speed axial fan to cover the summer ventilation rates.

The floor is slatted and the slurry collected in the pit underneath is continuously removed into a farm biogas station. The interior air temperature is maintained between 20-30°C. The piggery consists of two integrated parts. The building is overall 25.0 m wide, 95.0 m long and 6.0 m high (exterior sizes). The external walls of the piggery are 40 cm thick (including plasters) and are made of light clay brick block plastered on both sides. The roof structure is made of prefabricated steel beams, with a ceiling in large trapezial galvanized steel plates layered with rock wool (about 16 cm thick). The roof sheeting is made of fibrous concrete. The inner rooms are divided by brick block walls (30 cm and 12.5 cm in thickness including plasters) plastered on both sides. The doors, gates and windows are made of plastic (PVC) profile with thermal double glazing. The parameters of the doors and gates are – width 1.10 m, height 2.10 m and width 2.10 m, height 2.10 m. The parameters of the windows are – width 1.00 m, height 1.00 m and 1.50 m.

For this study FLIR E320 thermal infrared camera was used. For thermal imaging measurement purposes the air temperature, air humidity, distance from the monitored walls and material emissivity were measured. Determination of material emissivity was performed by creation of measuring points on the materials for thermal analyses. On these points temperature with using OMEGA HH11 contact thermometer (accuracy of temperature measurement: ±0.1°C) was measured. The most significant prerequisite was to prevent fluctuation of temperature in the course of time. The afore-mentioned point was also monitored using FLIR E320 thermal camera. In case the temperature values proved to be different, the temperature in the thermal camera was calibrated by means of setting up the emissivity value in the user interface of this device. The final emissivity value was determined at the time when the temperature values on both devices were balanced.

The air temperature and humidity were measured using OMEGA RH81 thermo-hygrometer featuring the temperature measurement accuracy of ±1°C and humidity measurement accuracy of ±4% (at the temperature of 25°C and relative humidity within the range of 10-90%). The temperature and humidity were measured in the close vicinity of the thermal camera and measured equipment, and the arithmetic mean was subsequently calculated on the basis of these values. The reflected temperature was not measured because no heat sources were in the surroundings, which could influence the measurement. The measurement was performed in cloudy conditions.

The measurement was conducted at a constant distance from the measured objects. The distance of the camera from the measured objects was determined using Leica DISTO^{tm} A5 laser EDM device (measurement accuracy: ± 1.5 mm at a distance between 0.2 and 200 m). The thermal imaging measurement as such was conducted using FLIR ThermaCAM E320 thermal camera (FOV: 25°). The average temperature of the surface was calculated using ThermaCAM QuickReport software in which each pixel of the video recording was allocated to one temperature value. An arithmetic mean was subsequently created on the basis of all values.

The Standard EN ISO 10211:2007 describes the calculation method for linear thermal bridges and superficial temperatures.

If we consider a multi layered construction with a simplified index to represent the total heat-transfer processes, the total thermal transmittance U_T is given by (EN ISO 6946) according to the following equation:

$$U_T = \frac{1}{R_T} \quad (\mathrm{W \cdot m^{-2} \cdot K^{-1}}) \tag{1}$$

where:

R_T – the total thermal resistance ($\mathrm{m^{-2} \cdot K^{-1} \cdot W^{-1}}$)

The total thermal resistance is given by (EN ISO 6946) according to the following equation:

$$R_T = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se} \quad (\mathrm{m^{-2} \cdot K^{-1} \cdot W^{-1}}) \tag{2}$$

where:

R_{si} – the internal surface resistance ($\mathrm{m^{-2} \cdot K^{-1} \cdot W^{-1}}$),

R_1, $R_2 \ldots R_n$ – the thermal resistance of each layer,

R_{se} – the external surface resistance ($\mathrm{m^{2} \cdot K \cdot W^{-1}}$).

Thermal resistance R for multilayer homogenous building elements is calculated according to the following equation (EN ISO 6946:2008)

$$R = \frac{d}{\lambda} \quad (\mathrm{m^{-2} \cdot K \cdot W^{-1}}) \tag{3}$$

where:

d – the thickness of layer (m),

λ – the thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$).

Total heat losses of object Q were calculated according to the following equation

$$Q = S \cdot (I + q_t) \ (\mathrm{W}) \tag{4}$$

where:

I – the intensity of grey-body radiation ($\mathrm{W \cdot m^{-2}}$),

q_t – the heat losses due to convection ($\mathrm{W \cdot m^{-2}}$),

S – the outer surface of construction ($\mathrm{m^{-2}}$).

Heat losses due to convection were calculated with the use of the convective heat transfer coefficient. This coefficient was determined according to the following equations (Bašta 2000): Cihelka

$$\alpha_k = 0.48(t_1 - t_2)^{0.33} \ (\mathrm{W \cdot m^{-2} \cdot K^{-1}}) \tag{5}$$

McAdams

$$\alpha_k = 1.78 \cdot \Delta t^{0.12} \quad (\mathrm{W \cdot m^{-2} \cdot K^{-1}}) \tag{6}$$

Hencky-Hottinger

$$\alpha_k = 1.67 \cdot \Delta t^{0.27} \quad (\mathrm{W \cdot m^{-2} \cdot K^{-1}}) \tag{7}$$

where:

t_1 – the temperature of atmosphere out of thermokinetic layer (°C, K),

Δt – the difference of air temperature and surface temperature (°C, K).

Then specific heat fluxes were calculated according to the equation

$$q_t = \alpha_k (t_1 - t_2) \quad (\mathrm{W \cdot m^{-2}}) \tag{8}$$

where:

α_k – the convective heat transfer coefficient ($\mathrm{W \cdot m^{-2} \cdot K^{-1}}$),
t_1 – the temperature of air (°C, K),
t_2 – the temperature of surface (°C, K).

Heat losses due to radiation are calculated with the help of Stefan–Boltzmann law. At first total intensity of a grey body radiation is calculated. Then the total intensity of an environment radiation was subtracted from the total intensity of a grey body radiation.

The equation for calculation of specific heat fluxes due to radiation is following

$$I = (\sigma \cdot \varepsilon_s \cdot T_s^4) - (\sigma \cdot \varepsilon_t \cdot T_t^4) \ (\mathrm{W \cdot m^{-2}}) \tag{9}$$

where:

ε_s – the emissivity of grey-body,
ε_t – the emissivity of environment
T_s – the thermodynamic temperature of grey-body (K),
T_t – the thermodynamic temperature of environment (K),
σ – the Stefan-Boltzmann constant ($\mathrm{W \cdot m^{-2} \cdot K^{-4}}$).

The boundary conditions for calculation hypotheses are given in Table 1.

Table 1
Boundary conditions used to calculate thermal resistance and thermal transmittance of the construction

Parameter	Symbol	Value	Unit
External surface thermal resistance	R_{se}	0.04	$\mathrm{m^2 \cdot K \cdot W^{-1}}$
Internal surface thermal resistance	R_{si}	0.13	$\mathrm{m^2 \cdot K \cdot W^{-1}}$
Indoor temperature	Θ_i	+22	°C
Outdoor temperature	Θ_e	-15	°C

Results and discussion

This survey aims at thermal defect detection of new-building piggery structures with the use of the IR thermography system. Boundary conditions of infrared thermography measurement are presented in table 2.

Next part of the paper consist in calculation of the thermal characteristics of the envelope construction (presented in Table 3 and 4) and heat losses caused by thermal bridges (presented in table 5). Piggery is heated at temperature 20-30°C. Interior relative air humidity is about 75%. Temperature depends on the age group category of animals. First thermogram represents first part of the south façade of piggery. Construction of the wall is from light clay brick with external and internal plaster. This construction has only average thermal properties (U_T=0.470 $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$) but it is not the most problematic part of the construction.

Table 2
The boundary conditions for evaluation of the infrared thermography survey

No.	Object	Emissivity (-)	Atm. temperature (°C)	Relative humidity (%)	Distance from measuring point (m)	Measured surface (m^2)	Average temperature of the surface (°C)
1	Steel concrete straining band of the wall	0.92	- 8.8	83	28	40	- 2.8
2	Bearing steel roof frame	0.86	- 8.7	82	32	215	- 4.9
3	Frame of the window	0.88	- 8.8	83	13	0.4	0.8
4	Frame of the door	0.88	- 8.8	83	12	0.8	1.2
5	Uninsulated socle	0.95	- 8.7	83	24	43	0.5

Table 3
Characteristic thermal properties of the new-building piggery constructions

Specification of the structure	Material of the structure layer	Thickness (m)	Thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^{-3}$)	Calculation of the total thermal resistance R_T ($m^2 \cdot K \cdot W^{-1}$)	Calculation of the total thermal transmittance U_T ($W \cdot m^{-2} \cdot K^{-1}$)
Outside wall	Internal plaster	0.015	0.99	2000	0.015	66.66
	Light clay brick	0.365	0.19	720	1.921	0.52
	External plaster	0.020	0.99	2000	0.020	50
	Total thermal properties of the structure				2.126	0.47
	Required value according to standard CSN 73 0540-2:2011				-	0.30
Flooring	Concrete	0.100	1.36	2300	0.074	13.51
	Bitumen sheet	0.07	0.21	1400	0.033	30.30
	Steel concrete	0.100	1.58	2400	0.063	15.87
	Gravel	0.150	0.58	1650	0.259	3.86
	Total thermal properties of the structure				0.796	1.356
	Required value according to standard CSN 73 0540-2:2011				-	0.45

Surface temperature of the brick wall is about -5.2ºC. As we can see in Figure 1 there is increased heat flow in socle parts (height 0.7 m) of the structure because socle and foundations are from uninsulated steel concrete and also flooring has no thermal insulation. A comparable problem with heat transfer over uninsulated foundations is presented in (Al-Anzi and Krarti, 2004). The warm water floor heating system without thermal insulation of flooring is an unsuitable solution for this structure. The average surface temperature of the socle is about 0.5ºC. Significant detail there is steel concrete straining band of the wall. It is bearing structure with poor thermal insulation.

This layer (height 0.25 m) is placed under steel roof frame. Next thermal bridge related to the straining band is the bearing roof frame with external brickwork with insufficient thermal resistance. This thermal defect of the envelope caused by the bearing steel frames is similar to the results of (Höglund and Burstrand, 1998; Juárez et al., 2012; Al-Sanea and Zedan, 2012). How we can see that there is a layer in the top part of the wall (height 0.5 m), where apparent heat fluxes are visible. The average surface temperature of the brickwork is about -4.9ºC. The next problematic detail there are the door and window frames mainly at the pass between the frame and the wall. Probably it is caused by poor thermal parameters of the frames and unsuitable construction design of this detail. The surface temperature at the door frame is about 1.2ºC. The surface temperature at the window frame is about 0.8ºC. A similar case study of thermal bridges by window framework is presented in (Ben-Nakhi, 2002; Cappelletti et al., 2011). Thermal bridges caused by steel reinforcement of the wall are presented in (Fukuyo, 2003). Figure 2 and figure 3 represent the second part and the third part of the south façade of the piggery. As we can see the same situation is with the existence of thermal bridges in critical structure details. Figure 4 and Figure 5 represent a west façade (gable wall). Most problematic there is the straining band again. The surface temperature at the straining band is about – 5.2ºC. A socle part of the wall has only 0.2 m height but has not thermal insulation. Figure 6 and figure 7 (east façade of piggery) and figure 8 (north façade of piggery) represent thermograms with similar situation which confirm unsuitable solution of structure details.

Figure 1. South façade of piggery (part 1)

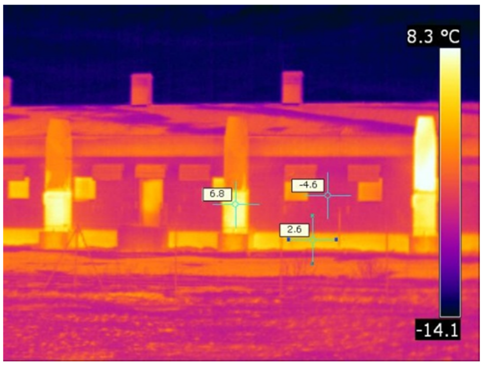

Figure 2. South façade of piggery (part 2)

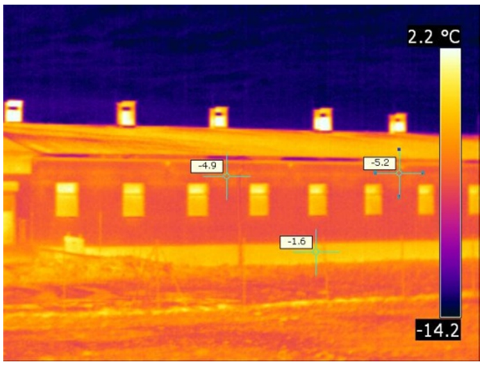

Figure 3. South façade of piggery (part 3)

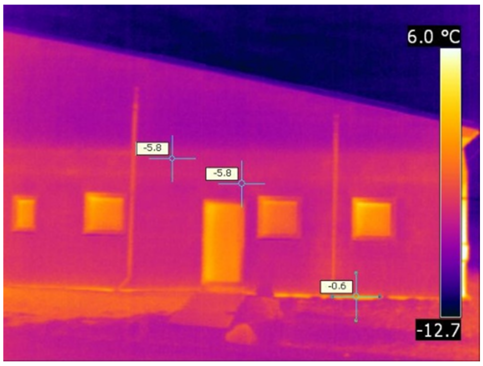

Figure 4. West façade of piggery (part 1)

Figure 5. West façade of piggery (part 2)

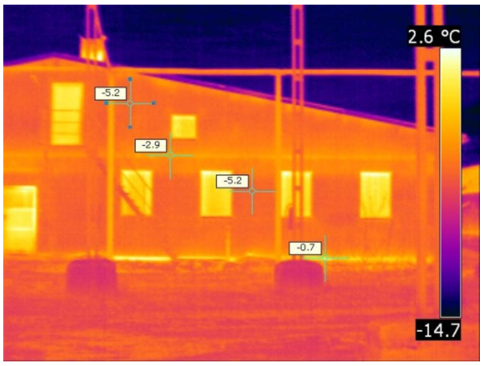

Figure 6. East façade of piggery (part 1)

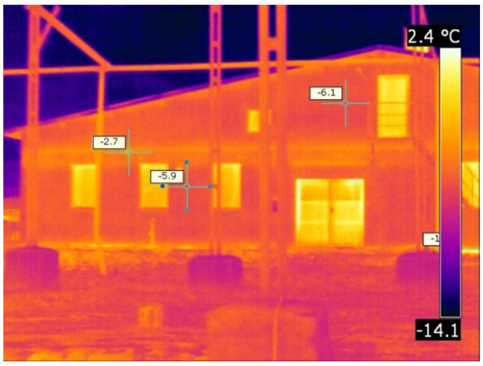

Figure 7. East façade of piggery (part 2)

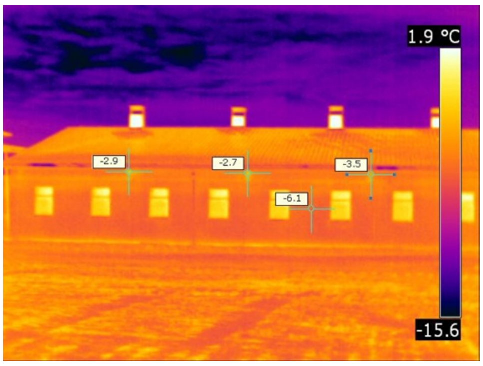

Figure 8. North façade of piggery

Table 4
Characteristic properties of the new-building piggery structures

Specification of the structure	Material of the structure layer	Thickness (m)	Thermal conductivity λ (W·m^{-1}·K^{-1})	Density (kg·m^{-3})	Calculation of the total thermal resistance R_T (m^2·K·W^{-1})	Calculation of the total thermal transmittance U_T (W·m^{-2}·K^{-1})
Ceiling	Fiber-cement roofing	0.007	0.45	1800	0.016	62.5
	Aeration space	0.040	0.250	1.275	0.160	6.25
	PES sheet	0.002	0.16	1400	0.013	76.92
	Rock wool integrated with bearing steel frame	0.160	0.0040	100	4.0	0.25
	PE vapor barrier	0.001	0.35	1470	0.003	333.33
	PVC board	0.005	0.16	1400	0.031	32.25
	Total thermal properties of the structure				4.363	0.229
	Required value according to standard CSN 73 0540-2:2011				-	0.24
Original door	PVC frame	0.075	0.16	1400	-	-
	Total thermal properties of the structure				-	1.70
	Required value according to standard CSN 73 0540-2:2011				-	1.50
Original window	PVC frame (+ heat insulating glazing)	0.075 (0.001)	0.16 (0.71)	1400 (2500)	-	-
	Total thermal properties of the structure				-	1.70
	Required value according to standard CSN 73 0540-2:2011				-	1.50

Calculation of heat fluxes and heat power of all thermal bridges is presented in the Table 5. Coefficient of free convection along vertical walling was calculated according to the equations developed by three different authors. Coefficient of free convection calculated by Hencky-Hottinger equation presented the maximal value of the total heat power. Next is the result of calculation by McAdams and the last is calculation by Cihelka. The calculation of heat fluxes and heat thermal bridges is approximate. The difference between calculated values is given by boundary conditions under which equations were determined.

Table 5.
The calculated values of heat fluxes and heat losses

No.	Object	McAdams		Hencky-Hottinger		Cihelka	
		Heat Fluxes ($W \cdot m^{-2}$)	Heat Losses (W)	Heat Fluxes ($W \cdot m^{-2}$)	Heat Losses (W)	Heat Fluxes ($W \cdot m^{-2}$)	Heat Losses (W)
1	Steel concrete straining band of the brickwork	7.47	298.90	8.50	339.81	2.64	105.44
2	Bearing steel roof frame	7.93	1704.70	9.71	2087.10	5.09	1093.39
3	Frame of the window	8.32	3.33	10.81	4.33	8.66	3.46
4	Frame of the door	8.45	6.76	11.19	8.96	10.26	8.21
5	Uninsulated steel concrete socle	13.71	589.37	17.94	771.29	9.18	394.83

Conclusion

The energy efficiency of buildings is significantly affected by right structure design. A farm building for animal production (piggery) is a heated building with high energy consumption. Modern structures have possibility for well technological solutions and energy performance of a building. Our study confirms that not only modern materials but also well technological solutions of critical structure details are very important because thermal bridges cause high heat losses, a risk of condensing of air humidity and mildew growing. The most problematic are thermal bridges at the uninsulated socle and flooring, the straining band of the wall, the bearing steel roof frame and the window and door frames. The results of this paper confirm these claims.

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WPŁYW MOSTÓW CIEPLNYCH NA WŁAŚCIWOŚCI TERMICZNE KONSTRUCJI NOWYCH BUDYNKÓW CHLEWNI

Streszczenie. Chów trzody chlewnej związany jest z wysokim poborem energii, dlatego też wydajność energetyczna budynku jest bardzo ważna. Celem niniejszego artykułu jest jakościowa i ilościowa ocena właściwości cieplnych oraz występowania mostków cieplnych w konstrukcji nowo wybudowanej chlewni. Charakterystyczne właściwości termiczne: ściany zewnętrznej (UT = 0,470 $W{\cdot}m^{-2}{\cdot}K^{-1}$), podłogi (UT=1,356 $W{\cdot}m^{-2}{\cdot}K^{-1}$), sufitu (UT=0,229 $W{\cdot}m^{-2}{\cdot}K^{-1}$) oraz okna i drzwi (UT=1,70 $W{\cdot}m^{-2}{\cdot}K^{-1}$).Wyniki potwierdzają nieodpowiednie właściwości termiczne większości konstrukcji. Jakościowa ocena wad cieplnych z wykorzystaniem termografii w podczerwieni umożliwia identyfikację najbardziej znaczących mostków cieplnych, występujących przede wszystkim na nieizolowanych cokołach i podłogach. Nasze badania potwierdzają, że nowoczesne konstrukcje umożliwiają wprowadzanie nowych rozwiązań technicznych oraz technologii, które poprawiają charakterystyki energetyczne budynków inwentarskich.

Słowa kluczowe: chlewnia, nowa chlewnia, właściwości termiczne, mostki termiczne, wydajność energetyczna, termografia w podczerwieni