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Material and design analysis of external baffles in inventory buildings with consideration of optimization of usable energy consumption

Key words: piggery, heat transfer coefficient, usable energy, energetic performance

Introduction

Technical and technological development in livestock breeding prompts to seek new solutions in forming of external baffles which would guarantee constant conditions of animals keeping and – above all – optimization of microclimate inside of an inventory building. In case of piggeries, it is crucial to maintain an appropriate temperature and humidity in the building. In aim to ensure the aforementioned conditions, it is inevitable to design the external baffles in appropriate way in terms of thermal conditions as well as material and constructive solution. Good insulating capacity of the external baffles is desired for technological reasons, on account of animal welfare as well as reduction of production costs (heating in low temperature period). In the agricultural building construction, there are several technologies of building erection in use; the basic ones contain: the traditional modernized technology, the frame technology and industrialized technology. The erection in the industrialized technology has been well known since 1970s. It constituted an important contribution in construction of big farms. Nowadays the industrialized technology is gaining interest on account of the pace of construction and it is an alternative for other technologies. The solutions of the industrialized technology contain also steel frame constructions which require to design filling walls and roof, simultaneously satisfying the coefficient of optimum heat transfer in aim to ensure minimum consumption of usable energy UE (Lenard, 1993).

Material and methods

The basic problem is that the external baffles of fattener piggeries must be adapted to requirements concerning animals' breeding, above all keeping the internal temperature within the range 18–20°C. A way of keeping the animals on litter or on cavity floor is of the greatest importance, what has been taken into consideration during fixing the range of the investigations. The proper design of well heat-insulated external baffles is also connected to the condition of prevention of water damp condensation inside the baffle or on its surface. The good heat insulating capacity of the baffles, apart of ensuring a proper microclimate of insides, affects reduction of demand of energy needed for heating of production spaces and transforms into higher production profitability.

In aim to determine an optimum solution on account of insulating capacity of baffles, a methodology of making an energetic performance of buildings and requirements of heat insulating capacity of building baffles were used as well as evaluation of baffles on account of heat and humidity was performed (Regulation of the Minister of Infrastructure and Development of 27 February 2015).

Two options of wall baffles were selected to the analysis, i e. made in traditional and monolithic technology, as well as two options of roof coverings, i.e. solid non-ventilated flat roof and wooden lattice girders were selected to the analysis. In the first option it was assumed a solution with non-ventilated flat roof made as a closely-ribbed ceiling on prestressed beams with the thickness 24 cm and consisting of layers: heat insulation made of Styrofoam boards with the thickness of 25 cm, panel layer made of concrete with the thickness 5 cm and thermo-weldable tar board. The external baffles in the first option were analysed in two variants: (a) masonry, two-layered wall, made of calcium-silicate blocks 2NDF and insulated with Styrofoam boards with the thickness of 10 cm (the most commonly used in practice); (b) three-layered wall consisting of a ferroconcrete load-bearing layer with the thickness of 7 cm, a heat insulation layer made of polyurethane (PUR) foam with the thickness of 8 cm and a ferroconcrete panel layer with the thickness of 5 cm. The basic difference in the second option consists in replacement of the solid flat roof with a wooden lattice girder. It has a sheet metal roofing tile covering, an initial covering wrap layer with high water vapour permeability, heat insulating layer made of mineral wool boards with the thickness of 25 cm, a vapour barrier foil and a finishing panel layer made of a trapezoidal shallow-profiled metal sheet. The external walls in the second option remained the same. In the investigations it was pursued to check whether the commonly applied solutions are capable to ensure good heat protection and low usable energy demand.

Microclimate in piggery and thermal insulating capacity of baffles

It is a big problem both for designers and for farmers to ensure an appropriate microclimate in inventory buildings. One of more important factors affecting the microclimate of building insides is the thermal insulating capacity of external baffles. The thermal insulating capacity of external baffles of buildings is usually associated to protection against excessive cooling of the inside during low temperature periods. The properly designed external baffles protect the inside against excessive increase of temperature in summer as well. Special attention is currently paid on very good heat insulation of roof which is directly subjected to the solar radiation, thus it can be a source of excessive increase of temperature inside of the inventory building.

The piggery buildings have been chosen for the investigations because they are very special object due to the heat and humidity requirements, diversified on account of breeding technology and animal herd structure in the building. The highest heat requirements concern the pig breeding on a cavity floor and, depending on a stage of development, they are as follows: dried sows 18–20°C, farrowing sows 18–22°C, piglets 22–30°C, fatteners 18–20°C keeping the air humidity 60–70%. If the animals are kept on litter, the temperature range is slightly lower (Table 1). It is very important to keep the heat and humidity conditions in the piggery on almost constant level because they directly transform into rapid pace of change of feed in animal body mass, thus in the production profitability. On this account, very good insulating capacity of baffles in fattener piggeries is the factor affecting reduction of consumption of energy needed to cover losses caused by heat transfer through the baffles as well as losses connected to air change, but also an important factor affecting the production profitability (lower feed consumption per a unitary increase of animal body mass).

The base for a profitable pig production is a minimization of costs associated to heating of inside areas – in this case, minimization of losses connected to heat transfer through external baffles. Limitation of these losses plays an important role – the losses connected to the ventilation can be limited only by ventilation heat recovery and heating of delivery air.

Calculation of annual demand of heating usable energy

The evaluation of usable energy demand for heating, ventilation and cooling is being performed with the monthly balance method (PN-EN ISO 13790:2009). The heat demand is calculated with assumption of normative conditions of use, i.e.:

- temperatures in areas provided in the regulation on technical conditions to be met by buildings and their location (Romaniuk & Overby, 2004; Technical Conditions WT2019);
- the least advantageous external temperatures established for a given climate zone in the standard PN-EN 12831-1:2017-08. Key changes in the methodology of building design heat load calculations;
- average monthly external temperatures and solar radiation for individual months – according to average multiannual data determined for the closest meteorological station;
- ventilation air flux quantity according requirements for pigs (Romaniuk & Overby, 2004);

TABLE 1. Recommended maximum and minimum ventilation and additional heating (for insulation of 0.8 $W \cdot m^{-2} \cdot K^{-1}$) (Romaniuk & Overby, 2004)

Group of pigs, maintenance system, feeding system		Body mass [kg]	Maximum ventilation [$m^3 \cdot h^{-1} \cdot animal^{-1}$]	Minimum ventilation [$m^3 \cdot h^{-1} \cdot animal^{-1}$]		Additional heating [$W \cdot animal^{-1}$]	
				$t_{ex} = -5°C$	$t_{ex} = -10°C$	$t_{ex} = -5°C$	$t_{ex} = -10°C$
Dried sows $t_{in} = 20°C$	–	–	100	15	15	12	42
Farrowing sows incl. 10 piglets	–	200	–	52	47	107	145
Piglets, empty area / full area							
Dry feeding $t_{in} = 30 > 22°C$	grate	7–30	37	3	3	28	34
Dry feeding $t_{in} = 24 > 16°C$	straw	7–30	37	3	3	12	18
Fatteners, continuous production							
Dry feeding $t_{in} = 15°C$	straw	40	40	13	11	–	–
Dry feeding $t_{in} = 15°C$	straw	70	70	18	14	–	–
Dry feeding $t_{in} = 15°C$	straw	100	100	25	20	–	–
Fatteners, empty area / full area							
Dry feeding $t_{in} = 16 > 14°C$	straw	30–100	100	10	8		
Dry feeding $t_{in} = 22 > 18°C$	grate	30–100	100	7	7	10	20
Dry feeding $t_{in} = 22 > 18°C$	grate	30–100	100	8	8	25	35

t_{in} – internal temperature, t_{ex} – external temperature.

- quantity of heat emitted to environment by fatteners of various age groups (Lenard, 1993).

The research methodology takes into consideration the assumptions presented in the work concerning heat balance in pregnant sow piggery (Suszanowicz, 2012). Until recently, a so-called WWT method, developed in 1970s, has been a standard method for thermal dimensioning of inventory buildings. It has been very simple and universal, yet very imprecise method. Due to this fact, the methodology of making an energetic performance of buildings according to the Technical Conditions WT 2019 was adapted for realization of thermal dimensioning of fattener piggery.

Due to lack of assumptions concerning specific heating systems, preparation of heat usable water and efficiency of these systems, the final energy and primary energy were not defined. The usable energy proves the quality of building construction and, above all, its heat insulating capacity; as it has been mentioned above, it is the main optimization factor for pig farms.

Variant of a fattener piggery building with non-ventilated (solid) flat roof

The temperature coefficient is a parameter which serves to determine the threat of mould fungi on surfaces of building baffles and it should fulfill a condition: $f_{Rsi} \geq f_{Rsi,\max}$.

The temperature coefficient (f_{Rsi}) is a difference between the temperature on a surface of an internal baffle and the outside air temperature ($\theta_{si} - \theta_e$), divided by the difference between the inside and outside air temperature ($\theta_i - \theta_e$).

The solid, non-ventilated flat roof is – as mentioned above – an alternative for traditional rafter framings and it can be performed in the industrialized technology.

The effective value of f_{Rsi} on the internal surface of the baffle and arrangement of layers are presented in Table 2.

In aim to determine the risk of humidification and appearance of mould, a limit value of f_{Rsi} was defined.

The total heat resistance of the baffle amounts R_c = 6.858 $m^2 \cdot K^{-1} \cdot W^{-1}$, whereas the heat transfer coefficient of the baffle (without accounting additions for thermal bridges ΔU_k) $U_c = 0.146$ $W \cdot m^{-2} \cdot K^{-1}$.

Check of the temperature coefficient:

– value of the temperature coefficient for the baffle: $f_{Rsi} = 0.981$,

– value of the temperature coefficient for the critical month: $f_{Rsi,\max} = 0.718$, $f_{Rsi} \geq f_{Rsi,\max} \Rightarrow 0.981 \geq 0.718$.

The condition is satisfied – the baffle has been designed properly with respect to avoid development of mould.

Variant of a fattener piggery building with roof on wooden lattice girders

The effective value of f_{Rsi} on the internal surface of the baffle and arrangement of layers are presented in Tables 3 and 4. According to the performed heat

TABLE 2. Construction of solid flat roof baffle

Layer	d [m]	λ [$W \cdot m^{-1} \cdot K^{-1}$]	μ [-]	R [$m^2 \cdot K^{-1} \cdot W^{-1}$]	S_d [m]
External side R_{se}				0.040	–
Double tar board without graveling	0.01	0.180	20 000	0.056	200.0
Ordinary concrete with stone aggregate 2400	0.05	1.700	24	0.029	1.2
Styrofoam board EPS 100-038 DACH	0.25	0.038	60	6.579	15.0
Ordinary concrete with stone aggregate 2400	0.24	1.700	24	0.141	5.8
Internal side R_{si}				0.100	–

TABLE 3. Construction of baffle – part A

Layer	d [m]	λ [W·m^{-1}·K^{-1}]	μ [-]	R [m^2·K^{-1}·W^{-1}]	S_d [m]
External side R_{se}				0.100	–
Ventilating layer	0.03	0.000	1	0.000	0.0
Pine and spruce wood cut along fibres	0.16	0.160	12	1.000	1.9
Mineral wool boards	0.09	0.037	1	2.432	0.1
Polyethylene foil	0.00	0.200	1	0.005	0.0
Trapezoidal galvanized metal sheet	0.00	50.000	100 000	0.000	100.0
			Internal side R_{si}	0.100	–

TABLE 4. Construction of baffle – part B

Layer	d [m]	λ [W·m^{-1}·K^{-1}]	μ [-]	R [m^2·K^{-1}·W^{-1}]	S_d [m]
External side R_{se}				0.100	–
Ventilating layer	0.00	0.000	1	0.000	0.0
Mineral wool boards	0.25	0.037	1	6.757	0.3
Polyethylene foil	0.00	0.200	1	0.005	0.0
Trapezoidal galvanized metal sheet	0.00	50.000	100 000	0.000	100.0
			Internal side R_{si}	0.100	–

and humidity calculations, the most critical months with respect to the risk of humidification and development of mould are January and February.

The total heat resistance of the baffle amounts $R_c = 4.573$ W·m^{-2}·K^{-1}, whereas the heat transfer coefficient of the baffle (without accounting additions for thermal bridges ΔU_k) $U_c = 0.219$ W·m^{-2}·K^{-1}.

Value of the temperature coefficient for the baffle amounts $f_{Rsi} = 0.971$, whereas value of the temperature coefficient for the critical month: $f_{Rsi,\max} = 0.852$.

Check of the temperature coefficient f_{Rsi}: according to the inequality $f_{Rsi} \geq f_{Rsi,\max}$ one obtains $0.971 \geq 0.852$. The condition is satisfied – the baffle has been designed properly with respect to avoid development of mould.

Heat and humidity conditions of external baffles

Humidification of external baffles evoked by condensation of the water vapour from the air is a very inconvenient phenomenon, especially for multi-layer baffles which are more prone to it. The acceptability of the water vapour condensation is defined depending on a place of its appearance – on the surface or inside the baffle. The surface condensation (retting) is unacceptable whereas the interlayer condensation can appear but only in a limited extent (it should not cause any excessive increase of humidification of a baffle material). In aim to avoid the surface condensation of water vapour, a minimum temperature of the baffle surface is determined. For building baffles, it is also required the thermal insulating capacity, defined with use of the heat transfer coefficient.

In case of fatteners' piggeries, the heat transfer coefficient for external baffles should be assumed according to the requirements defined in technical conditions with respect to internal temperatures over 16°C. The mentioned heat transfer coefficients should amount $U_c \leq 0.23 \text{ W·m}^{-2}\text{·K}^{-1}$ for walls and $U_c \leq$ $\leq 0.18 \text{ W·m}^{-2}\text{·K}^{-1}$ for roofs and flat roofs. Such thermal insulating capacity level of the baffles by periodically increased air humidity reduces the risk of arising the dew point temperature on the internal surface and thus – its humidification.

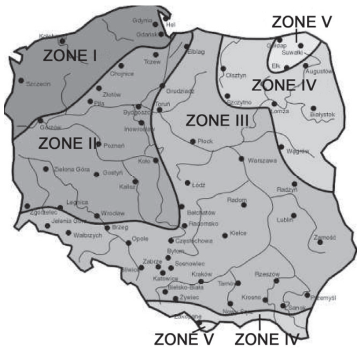
Check of the "dew-point condition" does not bring more serious calculation problems (with exception of places which require solving the two- or three-dimensional heat transfer problem). It is more problematic to assess a risk of occurring of condensation inside a baffle – especially for multi-layer baffles.

The design of a building baffle requires consideration of a local climate (cf. Fig. 1) in the building vicinity and an inside microclimate. The factors most affecting heat and humidity features of baffles are: temperature, relative humidity, degree of solar radiation.

Variant I – three-layer wall made of ferroconcrete and PUR foam

- for the climate zone II – there is no condensation of water vapour on the internal surface of the wall: $t_s + 1 =$ $= 11.69°\text{C} < t_{surf.} = 18.59°\text{C}$;
- for the climate zone III – there is no condensation of water vapour on the internal surface of the wall: $t_s + 1 =$ $= 11.69°\text{C} < t_{surf.} = 18.66°\text{C}$;
- for the climate zone IV – there is no condensation of water vapour on the internal surface of the wall: $t_s + 1 =$ $= 11.69°\text{C} < t_{surf.} = 18.73°\text{C}$.

Basing on the heat and humidity calculations for one-year period, for the designed baffle having the layer arrangement presented in Table 5, one condensation zone was found on the interface of the ferroconcrete panel wall and PUR foam heat insulation for November, December, January and February as well as one evaporation zone in each of these places for March, April and May. Hence, the baffle has been designed properly.



Zone	t_e [°C]	t_e* [°C]
I	–16	7.7
II	–18	7.9
III	–20	7.6
IV	–22	6.9
V	–24	5.5

t_e – designed external temperature
t_e* – average annual external temperature

FIGURE 1. Design temperatures of external air in Poland (modified KPOIIB, 2013)

TABLE 5. List of materials in Variant I

Material	λ [$W \cdot m^{-1} \cdot K^{-1}$]	μ [-]	d [m]	R [$m^2 \cdot K^{-1} \cdot W^{-1}$]	S_d [m]
Ordinary concrete with stone aggregate 2400	1.700	150.00	0.05	0.029	7.5
PUR foam	0.022	80.00	0.08	3.636	6.4
Ordinary concrete with stone aggregate 2400	1.700	150.00	0.07	0.041	10.5

$\Sigma R_i = 3.707\ m^2 \cdot K^{-1} \cdot W^{-1}$; $U = 0.258\ W \cdot m^{-2} \cdot K^{-1}$.

There is no water damp in the analysed baffle after the reference period.

Figure 2 presents the temperature distribution through the baffle thickness in the climate zone IV (the most difficult with respect to the temperature distribution) drawn to scale for the layers' thickness as well as the pressure distribution through the baffle thickness in the zone IV drawn to scale for the equivalent thickness of air layer.

Variant II – two-layer wall made of calcium-silicate blocks 2NDF and Styrofoam

- for the climate zone II – there is no condensation of water vapour on the internal surface of the wall: $t_s + 1 = 11.69°C < t_{surf.} = 18.59°C$;
- for the climate zone III – there is no condensation of water vapour on the internal surface of the wall: $t_s + 1 = 11.69°C < t_{surf.} = 18.66°C$;

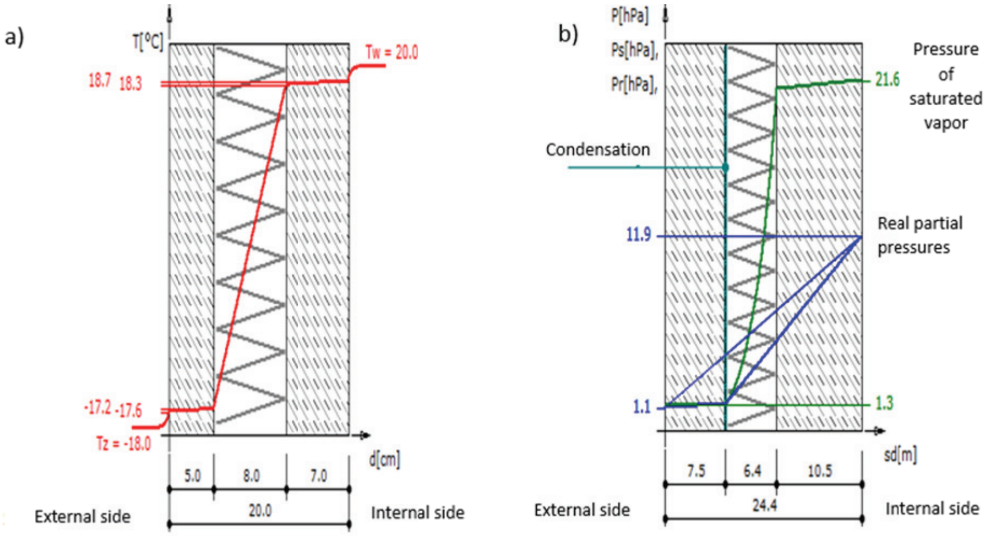


FIGURE 2. Graph of temperature distribution through the baffle thickness (zone IV) drawn to scale for the layers' thickness (a); graph of pressure distribution through the baffle thickness (zone IV) drawn to scale for the equivalent thickness of air layer (b)

- for the climate zone IV – there is no condensation of water vapour on the internal surface of the wall: $t_s + 1 = 11.69°C < t_{surf.} = 18.73°C$.

Basing on the heat and humidity calculations for one-year period and temperatures for multi-year period, for the designed baffle having the layer arrangement presented in Table 6, no condensation zone was found. No possibility of evaporation of water vapour on the baffle surface was stated either. Hence, the baffle has been designed properly. There is no water damp in the analysed baffle after the reference period.

Figure 3 presents the temperature distribution through the baffle thickness in the climate zone IV drawn to scale for the layers' thickness. This zone is characterized by the most inconvenient temperature conditions if compared to other zones. Longer period with lower temperatures in the IV zone affects the temperature distribution and risk of water vapour condensation between the layers in the baffle under consideration – especially on the interface of the heat insulation and external wall. As mentioned before, neither condensation inside the baffle nor

TABLE 6. List of materials in Variant II

Material	λ [$W \cdot m^{-1} \cdot K^{-1}$]	μ [-]	d [m]	R [$m^2 \cdot K^{-1} \cdot W^{-1}$]	S_d [m]
Styrofoam (15-40)	0.360	80.00	0.1	2.778	8.0
Calcium-silicate blocks 1.5-2NFD	0.800	7.50	0.25	0.313	1.875

$\Sigma R_i = 3.090\ m^2 \cdot K^{-1} \cdot W^{-1}$; $U = 0.307\ W \cdot m^{-2} \cdot K^{-1}$.

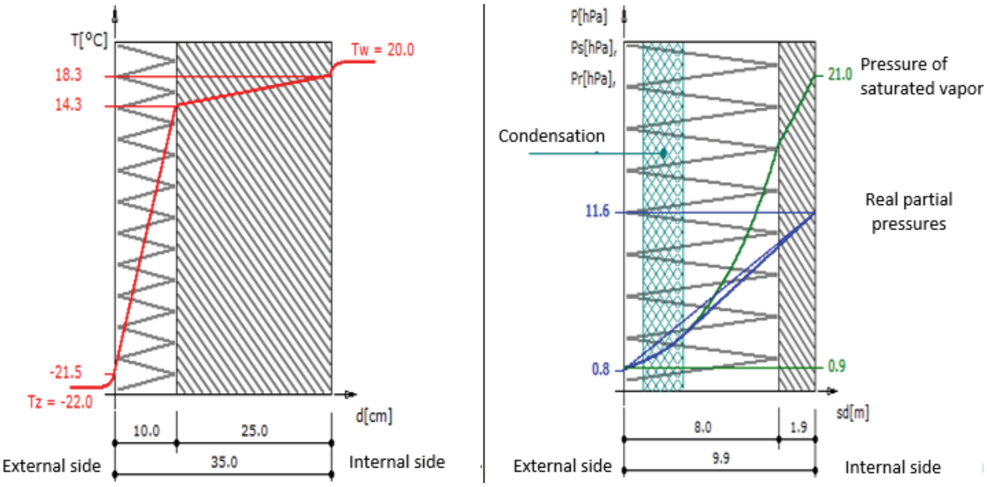


FIGURE 3. Graph of temperature distribution through the baffle thickness (zone IV) drawn to scale for the layers' thickness (a); graph of pressure distribution through the baffle thickness (zone IV) drawn to scale for the equivalent thickness of air layer (b)

possibility of condensation on the internal surface of the baffle has been found.

For calculations in all variants, the natural (gravitational) ventilation was assumed which is commonly used in such inventory buildings (Table 7).

TABLE 7. Energy losses for ventilation

Variant	Piggery with solid flat roof	Piggery with wooden lattice girder
	kWh·year^{-1}	
1.1 zone II	379 643.24	386 921.767
1.2 zone II	379 643.24	386 921.767
1.1 zone III	385 820.86	393 217.817
1.2 zone III	385 820.86	393 217.817
1.1 zone IV	416 874.76	424 867.081
1.2 zone IV	416 874.76	424 867.081

Basing on the obtained results, one can state that the usable energy demands for the climate zones II, III and IV differ from each other for various variants of heat insulations and baffle constructions (Table 8).

TABLE 8. Usable energy demand for heating during heating season

Variant	Piggery with solid flat roof		Piggery with wooden lattice girder	
	kWh·year^{-1}	kWh·year^{-1}·animal^{-1}	kWh·year^{-1}	kWh·year^{-1}·animal^{-1}
1.1 zone II	147 225.775	61.99	154 225.436	64.94
1.2 zone II	150 349.538	63.31	160 104.024	67.41
1.1 zone III	148 970.817	62.72	150 388.553	63.32
1.2 zone III	149 662.000	63.02	157 959.703	66.51
1.1 zone IV	177 745.544	74.84	187 428.867	78.92
1.2 zone IV	181 867.373	76.58	193 598.136	81.52

Discussion of results of investigations

The investigations were made for a building with dimensions 9.6 × 200 m and height $h = 2.80$ m. For such area parameters it was assumed a theoretical livestock quantity equal to 2,375 fatteners, continuous production, litter-free breeding system. For establishing the livestock density, it was assumed a conversion factor equal to 0.8 animal per 1 m^2 and workers' room with total area 20 m^2. In the second variant, assumed for investigations, the basement layout remained unchanged, merely the roof covering was replaced by a wooden lattice girder with span equal to 9.60 m.

Calculations of total and specific usable energy demand were made for three climate zones II, III and IV assuming data from meteorological stations for main cities in these zones, i.e. Poznań, Warsaw and Białystok. Calculations of usable energy demand were made for the internal temperature t_{in} = 20°C which favours optimum mass growth during pigs' breeding in the cavity floor system. For calculations of usable energy demand, the temperatures for multi-year period in heating seasons as well as insolation parameters appropriate for the given climate zone were assumed, according to the standards and data from meteorological stations.

Basing on the obtained results, one can state that the usable energy demand for the climate zones II and III is similar for various variants of heat insulations and baffle constructions (Table 8). However, a significant change in the usable energy demand is noticeable for the zone IV, hence in this case a correction of heat insulation thickness should be made, mainly for external load-bearing walls. The improvement of heat insulation of walls should contribute to the reduction of heat transmission losses. Basing on the losses connected to the ventilation of the piggery inside, one can easily notice (Table 7) that along with change of the climate zone from II to III and IV a significant increase of the usable energy demand arises. The reduction of the ventilation energy loss is possible through introduction of mechanic ventilation with heat recovery what should bring positive effects manifesting themselves as the lower usable energy demand because in the gravitational ventilation system significant quantities of heat energy are being irrevocably lost. All the variants of the walls are designed properly with respect of heat and humidity behaviour. For the multi-layer wall made of ferroconcrete with PUR foam core, however, there is a risk of condensation of water vapour on the interface between the board and insulation, but the humidity entirely evaporates in the spring. Thus, the multi-layer ferroconcrete walls can be taken into consideration with respect of performance of wall prefabricated elements.

Conclusions and resumée

The above analysis shows that both the multi-layer ferroconcrete walls with PUR foam core with thickness 8 cm and two-layer traditional walls satisfy heat and humidity criteria in the pig breeding in the climate zones II, III and IV in Poland, like two-layer traditional walls with heat insulation made of Styrofoam boards with the thickness of 10 cm. The specific usable energy demand needed to ensure proper microclimate conditions and heat comfort shows small diversity for the same ranges of internal temperature, both for prefabricated walls and for masonry two-layer walls, as well as for various variants of roof construction.

If compared to traditional constructive solutions of external walls, the walls made in the industrialized technology generate lower usable energy demand, guarantee repeatability of dimensions, fast assembly with minimum share of so-called wet works, hence contribute to earlier beginning of production of slaughter animals.

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Summary

Material and design analysis of external baffles in inventory buildings with consideration of optimization of usable energy consumption. The main objective of the performed investigations was an analysis of baffles of various construction and production technology with respect of usable energy demand. The investigations encompassed calculations of the energetic performance of fatteners' piggery building as well as heat and humidity calculations of baffles. The energetic calculations were performed for two variants of execution and heat insulation of external baffles as well as two variants of roofs. The analysis contained the baffles made in two technologies: industrialized and traditional modernized, for three climate zones. For the individual variants, the usable energy demand in heating season as well as specific usable energy demand per one fattener were calculated.

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