ELECTRONIC JOURNAL OF POLISH AGRICULTURAL UNIVERSITIES

2004
Volume 7
Issue 2
Series AGRICULTURAL ENGINEERING

BIEDA W., RADOŃ J., HERBUT E. TUBULAR RECUPERATOR WITH A SOLAR COLLECTOR FOR RECOVERY OF HEAT FROM POULTRY HOUSE EXHAUST AIR **Electronic Journal of Polish Agricultural Universities**, Agricultural Engineering, Volume 7, Issue 2.
Available Online http://www.ejpau.media.pl

TUBULAR RECUPERATOR WITH A SOLAR COLLECTOR FOR RECOVERY OF HEAT FROM POULTRY HOUSE EXHAUST AIR

Wacław Bieda[1], Jan Radoń[1], Eugeniusz Herbut[2]
[1]Department of Rural Building, Agricultural University of Cracow, Poland
[2]Department of Technology, Ecology and Economics of Animal Production, National Research Institute of Animal Production, Cracow, Poland

ABSTRACT

Results of long-term operating tests on a prototype tube-within-tube recuperator designed for recovery of heat from broiler house exhaust air are presented. The construction and operation of the recuperator accounts for specific conditions of the poultry house, such as very high dustiness and humidity of air. Two-year tests of the recuperator in real operating conditions of a typical broiler house for 16,000-18,000 chickens showed that its energy efficiency is 30-37% and it can be used over the entire production cycle of 42-45 days without the need to remove the dust deposited on the exhaust channel walls. The results of microbiological tests give no indication that the recuperator might pose a threat to biosafety of the broiler house after the 2-year operation. The results of comparative studies on basic parameters of microclimate and production efficiency in the experimental and control part of the broiler house showed that the recuperator's operation was beneficial for the energy management and production results.

Key words: recuperator, recovery of ventilation heat, acquisition of solar radiation, broiler house, microclimate.

INTRODUCTION

The use of exhaust heat from ventilation systems is finding increasing application in Poland, not only in industrial facilities and retail outlets, but also in livestock buildings [1, 8]. Reuse of (sensible and latent heat) energy contained in air for heating incoming air, involves a process of heat exchange between flows of (warm) exhaust air and (cold) incoming air in air-conditioners, which are low-temperature recuperators of the air-to-air type.

Recuperative exchangers proved the most effective means of limiting the use of heat and the most profitable form of saving energy in heated rooms requiring ventilation, on condition that the exchangers are produced serially [3, 9]. The known types of air-to-air recuperators have a relatively high operating efficiency (60-95%), are environment-friendly, and improve microclimatic conditions by making them more hygienic [1, 3, 9, 11].

However, hitherto attempts to use recuperative exchangers in heated livestock buildings were generally unsuccessful. The principal limitation to this type of heat recovery were high dustiness and humidity of air typical of livestock buildings, especially poultry houses [6, 9], which cause obvious problems in the operation of conventional recuperative exchangers that are not adjusted for working in such conditions. Due to contamination and icing on the recuperators, which appears at below-zero external temperatures, their operating efficiency was noted to drop practically to zero. Together with high labour inputs needed to keep them operational, they proved so uncomfortable and expensive to operate that their use has been generally abandoned. Breeders turned their attention to earth-tube heat exchangers that are less energy efficient and more expensive [1] and to direct-contact heat exchangers [2].

Careful analysis of many factors involved in the use of low-temperature recuperative exchangers in ventilation systems of poultry houses, our own experiments and those of other authors indicate that the lack of success is due not to the very idea of recovering waste heat from exhaust air of poultry houses, but results from the use of unsuitable equipment for conditions of very high dustiness and high content of water vapour in the production rooms.

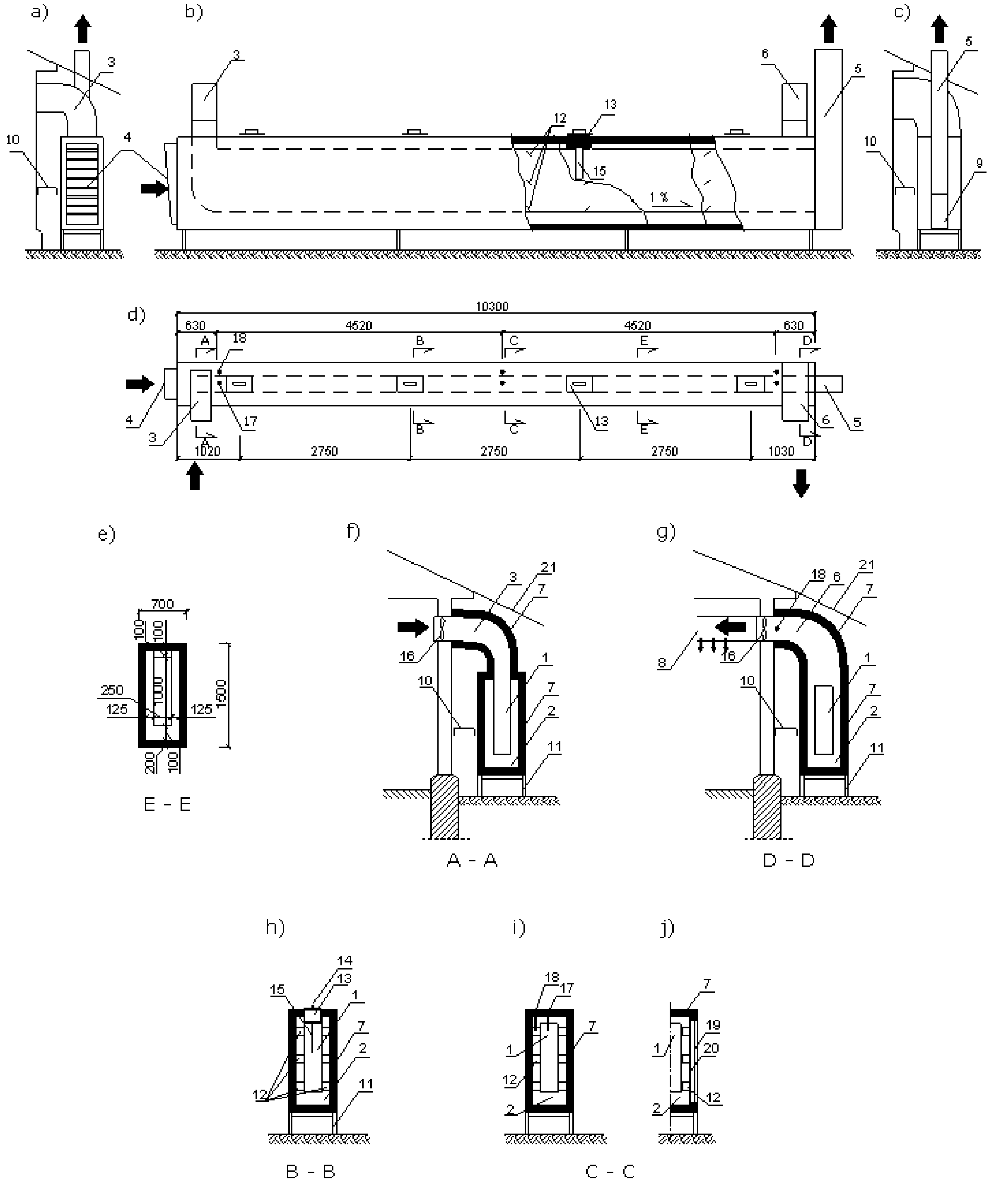
In the years 2001-2004, the Department of Rural Building of the Agricultural University of Cracow, in collaboration with the National Research Institute of Animal Production in Cracow, carried out a KBN research project no. 6 P06E 038 20 "A new type of recuperator for recovery of heat and optimization of microclimate in poultry houses". The principal goal of this project was an attempt to solve a complex problem of recovering (sensible and latent) waste heat contained in ventilation air blown away from poultry houses, especially broiler houses, using a new, low-temperature recuperative heat exchanger of the tube-within-tube type, coupled with a ventilation system of the broiler house, and adjusted to operation under conditions of high dustiness and high water vapour content in the production room. It was assumed that the recuperator would decrease energy consumption, improve the efficiency of production and optimize the poultry house microclimate.

MATERIAL AND METHODS

Construction and operation of the recuperator

To determine the relationship between the path and velocity of (incoming and exhaust) air flowing in adjacent channels of the exchangers, and to determine the effect of air flow turbulence on heat exchange, preliminary laboratory tests were made on the recuperator model. The results of the experiment were used to develop the design proper and to construct a prototype recuperator. Construction of the recuperator is shown in Figure 1. The principal part of the recuperator is formed by a thermally insulated channel of supply ventilation, which contained a second, uninsulated channel designed for exhaust ventilation. Both channels had their own air intakes and ejectors and ventilators equipped with speed governors. Streams of (cold) incoming air and (warm) exhaust air ran parallel. The collector supplying waste air to the exhaust channel (2) was constructed of rustproof metal sheet 0.5 mm in thickness. Individual segments of the incoming air channel and elbows supplying the air to the broiler house (6) were constructed of zinc coated sheet 0.65 mm in thickness, and the external cover of the recuperator (7) was made of a 0.65 mm coated steel sheet. In the vertical parts of the inlet channel were used air flow disturbers (12) in the form of plates from zinc-coated steel sheet positioned at a 45° angle, linking the walls of the internal (exhaust) and external (inlet) channels, placed pairwise 1.0 m apart. These plates, aside from disturbing the flow of air, made the recuperator more rigid. No such disturbers were designed for the exhaust channel, because they would greatly increase the thickness of dust deposited on the walls of the exhaust channel.

Figure 1. Recuperator for recovery of heat from poultry houses, designed at the Department of Rural Building of the Agricultural University in Kraków: a – view from the side of supply air intake, b – south view, c – view from the side of exhaust air ejector, d – top view, e – E-E section, f – section through exhaust air intake, g – section through supply air intake, h – B-B section, i – C-C section, j – variant with solar radiation absorber and transparent 3-paned set; 1 – exhaust air channel, 2 – supply air channel, 3 – exhaust channel elbow, 4 – supply air intake, 5 – exhaust air ejector, 6 – supply channel elbow, 7 – thermal insulation, 8 – perforated supply channel, 9 – exhaust cleanout hole, 10 – platform, 11 – base, 12 – supply air disturbers, 13 – cleanout exhaust channel plug, 14 – holders, 15 – dustiness control plate, 16 – fan, 17 – exhaust channel temperature sensors, 18 – supply channel temperature sensors, 19 – 3-paned thermoinsulation set, 20 – solar radiation absorber



The flaps closing the cleanout holes of the exhaust channel were fitted with indicator plates to measure deposit (15), 100×500 mm and 0.1 m^2 in area each.

The channel segments were joined by soldering and additionally insulated with silicone. The incoming air channel was insulated with 5 cm plates of Styrofoam, $\lambda = 0.045$ W/(m·K), laid next to each other in a 10 cm layer. The structure was made stronger and more rigid using steel sections.

The longitudinal wall of the inlet channel, facing south, was painted matt black and covered with a 3-pane thermoinsulation set of U = 0.70 W/(m^2·K). In this way an aerial solar collector, about 10 m^2 in area, was created. Its task was to use solar radiation as an additional source of heat for heating the incoming air (Fig. 2).

Figure 2. View of recuperator mounted in the broiler house in Ujazd. On the left, solarimeter and weather house for measurement of external air temperature and humidity

The construction of the recuperator solves an important operational problem of removing the deposit and draining steam condensate from the exhaust air channel in the following way:

– large cross-section area and rectinilearity of the exhaust channel is ensured to allow a relatively free flow of air,
– the exhaust channel is sloping longitudinally towards the exhaust air ejector, thanks to which the steam condensate drains continuously towards the exhaust air ejector, where it is captured and released into the drainage system,
– the interior of the exhaust channel can be rinsed with a jet of water, which flows towards the ejector, where it is captured and drained,
– the external walls of the exhaust channel and the interior of the inlet channel can be cleaned after the exhaust channel has been disassembled.

Long-term operating tests

Long-term operating tests of the prototype recuperator for recovery of heat were performed from the summer of 2002 to the spring of 2004 in one of ten broiler farms in the town of Ujazd (Małopolska province). The longitudinal axes of the broiler houses with a productive area of about 1001 m^2 are facing east-west. The broiler house is constructed of steel, with one span of 12.0 m and frames spaced 3.0 m apart. Flat roof is covered with trapezoid sheet metal and with suspended flat ceiling of sheet metal. Broiler house is heated mainly by air using water heaters, and supported by central heating with wall radiators. Ventilation of the broiler house is mechanical and transverse with exhaust fans in the north wall and with gravitational ventilation and an adjustable gap in the south wall. Feeding and drinking lines run parallel to the longitudinal axis of the building. Broilers are kept in the floor system on litter.

The prototype recuperator was positioned along the south elevation of the broiler house (Fig. 2). Ends of the exhaust and inlet channels were led inside the production facility. Incoming air was distributed inside using a plastic sleeve with holes placed in its lower part.

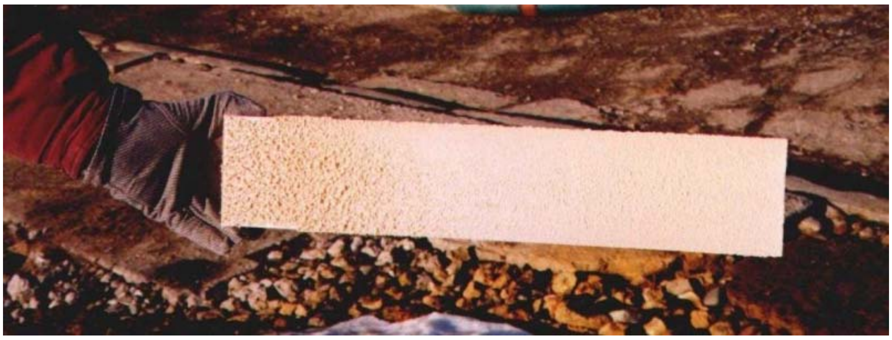
The two channels of the recuperator were each equipped with 4 class A sensors PT100 having an accuracy of ±0.12°C. Air temperature and humidity inside and outside the broiler house were measured with 12 PT100 sensors and 3 relative humidity sensors PWW100 having an accuracy of ±3%. Solar radiation per vertical area was measured with a German-made electronic solarimeter. Frequency of automatic measurements of air temperature and humidity and litter temperature and moisture was 15 min., and frequency of ground temperature measurements was 1 h. Measurement data were recorded with a 30-channel logger Agilent 34970A Data Acquisition/Switch Unit equipped with 3 HP 34901A 20-Channel Multiplexer cards having a memory storage of 50 000 readings with a time marker.

Air temperature in the recuperator channels was measured automatically by 8 PT100 sensors, 4 per channel, placed as shown in Figure 1. Air temperature in the cross-section within the reach of the recuperator was measured by 6 PT100 sensors placed 0.5 m above the floor and 0.5 m under the ceiling. The same number of sensors was used to measure temperature in the cross-section of the broiler house beyond the reach of the recuperator. Frequency of air temperature measurements was 15 min. Relative air humidity was measured in both cross-sections of the broiler house using 2 PWW100 sensors, one per each cross-section, which were placed 0.5 m above litter.

Air stream velocity in the recuperator channels, in order to calibrate speed governors of the fans and velocity of air motion in the broiler house were measured with a thermoanemometer type TA-5. Measurements of air motion in the living area of the birds were taken after each week of rearing in the afternoon, when the exchange of air was at its peak.

Weekly observations and measurements of dust deposited on the walls of the exhaust channel, using the weighing method, were made with 4 indicator plates (15) from rustproof sheet, each 0.1 m^2 in area, spaced 2 m apart. The plates were fastened to the flaps closing the cleanout holes. View of the plate with deposit after taking out of the recuperator is shown in Figure 3.

Figure 3. Deposit control plate after taking out from the recuperator



Samples for microbiological tests were taken at three sites: from the inlet and exhaust channel of the recuperator, from the reflux of the exhaust channel, and from the production facility. Microbiological tests were performed in conformation with generally accepted standards and needs, using standard analytical methods for quantitative and qualitative determinations.

The effects of the recuperator on the microclimate of the production facility and production results were evaluated from the measurements of the following parameters: temperature, humidity and velocity of air, body weight gain, feed conversion per 1 kg weight gain, water consumption and mortality, as determined after each week of rearing.

Calculations

The amount of heat recovered from the recuperator can be calculated as a change in the enthalpy of humid air blown into the building. The enthalpy of humid air (except the heat of vaporization), depending on its temperature ϑ, can be determined from the formula [5]:

$$h(\vartheta) = m_p \cdot (c_p + c_v \cdot w) \cdot \vartheta \cdot 1000 \tag{1}$$

where: m_p – mass of dry air [kg],
c_p – specific heat of dry air (1.01 kJ/(kg·K)),
c_v – specific heat of vapour (average value 1.86 kJ/(kg·K)),
w – absolute humidity of air [kg/kg].

Hence the increment of enthalpy (heat gain) [W] is:

$$\dot{Q}_w = \dot{m}_{pe} \cdot (1{,}01 + 1{,}86 \cdot w_e) \cdot (\vartheta_p - \vartheta_e) \cdot 1000 \tag{2}$$

in which: $\dot{m}_{pe}$ – mass of external air carried into the building through the recuperator [kg/s],
ϑ_e – temperature of external air [°C],
ϑp – temperature of air heated in the recuperator [°C],
w_e – absolute humidity of external air [kg/kg].

Mass of incoming air $\dot{m}_{pe}$, with regard to changes in density depending on temperature (with atmospheric pressure of 101325 Pa), can be determined from the formula [10]:

$$\dot{m}_{pe} = \dot{V}_{we} \cdot \frac{353{,}4}{273 + \vartheta} \tag{3}$$

where: $\dot{V}_{we}$ – volume of external air carried into the building through the recuperator [m³/s].

Product of $m_{pe} \cdot w_e$ yields total mass of moisture carried into then building through the recuperator [kg/s]:

$$\dot{W}_e = m_{pe} \cdot w_e \tag{4}$$

Inserting into the equation (2) gave:

$$\dot{Q}_W = (\frac{356{,}934}{273 + \vartheta_e} \cdot \dot{V}_{we} + 1{,}86 \cdot \dot{W}_e) \cdot (\vartheta_p - \vartheta_e) \cdot 1000 \tag{5}$$

Knowing the area of the channel and air flow velocity, the volume of incoming air can be calculated from the formula:

$$\dot{V}_{we} = A_k \cdot v \tag{6}$$

in which: A_k – cross-section of the channel, m^2,
v – air flow velocity, m/s.

Equation 5 contains total humidity mass, but the parameter measured during the operational tests was relative humidity of air φ. Both values are connected through the law of gases [10]:

$$\dot{W}_e = 0{,}622 \frac{\varphi \cdot p_s(\vartheta_e)}{101325 - \varphi \cdot p_s(\vartheta_e)} \cdot \rho_p(\vartheta_e) \cdot \dot{V}_{we} \tag{7}$$

where: ρ_p (air density), which can be determined from the formula:

$$\rho_p(\vartheta_e) = \frac{353.4}{273 + \vartheta_e} \tag{8}$$

Inserting (8) into (7) gave:

$$\dot{W}_e = 219.81 \frac{\varphi \cdot p_s(\vartheta_e)}{[101325 - \varphi \cdot p_s(\vartheta_e)] \cdot (273 + \vartheta_e)} \cdot \dot{V}_{we} \tag{9}$$

Partial pressure of water vapour in the saturated condition $p_s(\vartheta)$ in formulas 7 and 9 was calculated from the approximation formula [4]:

$$p_s(\vartheta) = a \cdot (b + \frac{\vartheta}{100})^n \tag{10}$$

Values of parameters a, b, n, depending on the range of temperatures, are:

for $0°C \leq \vartheta \leq 30°C$: a = 288.8; b = 1.98 and n = 8.2
and $-20°C \leq \vartheta < 0°C$: a = 4.89; b = 1.86 and n = 12.0

Moisture content of external air, in the winter periods at low temperatures, is small and could be neglected when calculating heat gains. However, because moisture content can be of some significance when determining changes in the enthalpy of internal air, the moisture content of air, calculated according to formula 5 and using relationships 6-10, has been accounted for.

Heat is recovered through the heating of cold (incoming) air by hot (exhaust) air. Heating is only possible when the temperature of exhaust air is higher than the temperature of incoming air. Full recovery of heat (100% efficiency) takes place when the entire surplus heat in the exhaust air is used to heat the incoming air. The reference heat, when calculating the recuperator's efficiency, is the decrease of enthalpy, during cooling of humid exhaust air from the internal temperature in the building to the external air temperature.

Hence the momentary efficiency of the recuperator is:

$$\eta = \frac{\dot{Q}_w}{\dot{Q}_i} \tag{11}$$

where: $\dot{Q}_w$ – increment in enthalpy of the incoming air [W],

$\dot{Q}_i$ – total possible decrease in enthalpy of internal air [W].

The decrease in enthalpy of internal air was calculated similarly to $\dot{Q}_w$ from the formula 5 and also from formulas 6-10, replacing ϑ_p with ϑ_i (temperature of internal air, formula 5) and humidity mass of internal air (formula 9).

Averaged efficiency was calculated by dividing total heat gains of incoming air by total possible heat losses of exhaust air according to the formula:

$$\eta_s = \frac{\sum_j \dot{Q}_{w,j} \cdot \Delta\tau_j}{\sum_j \dot{Q}_{i,j} \cdot \Delta\tau_j} \tag{12}$$

A constant value of heat gain in the measured time interval ($\Delta\tau$, cf. formula 12) of usually 15 min. was assumed. Heat of vaporization in the exhaust air was neglected in the calculations.

Fans were set to make the speed of incoming and exhaust air flow identical. Sections of the inlet and exhaust channels, however, are different, hence the volume of incoming air stream is suitably greater than the volume of the exhaust air stream.

RESULTS AND DISCUSSION

Heat gains and efficiency

Figure 4 shows sample patterns of solar radiation, relative humidity and temperature of internal and external air, temperature of air in the recuperator, actual and theoretically possible heat gains, and momentary efficiency in the period 11 December 2002 to 2 January 2003. Air flow velocity was 2 m/s during the first 17 days and 3 m/s later on. In the winter period, relative humidity of external air was not measured, and in the calculations an average value for the winter period (85%) was used. Averaged results of actual heat gains and efficiency of the recuperator in selected measurement periods were brought together in Table 1. Averaged efficiency of the exchanger for all periods was 30% without regard to radiation, and 37% when taking into account heat gains from solar radiation.

Table 1. Calculation results for heat gains and recuperator efficiency in different measurement periods

Period	Duration (days)	Air velocity (m/s)	Heat gains (kWh)	Efficiency without solar radiation (-)	Efficiency with solar radiation (-)
9.10-25.10.2002	16	2	1710.2	0.341	0.396
25.10-14.11.2002	20.1	2	1841.7	0.303	0.352
11.12.2002-2.01.2003	22.4	2/3	4330.9	0.353	0.381
2.01-15.01.2003	12.8	3	2226.5	0.28	0.307
18.02-10.03.2003	19.9	3	4577.3	0.303	0.37
10.03-24.03.2003	14	3	2192.3	0.304	0.36
27.04-20.05.2003	23	3	2458.8	0.276	0.379
10.09-18.09.2003	8	2	795	0.325	0.402
5.10-16.10.2003	10.7	2	754.9	0.276	0.314

The results from the entire measurement period were used to develop a relationship between heat gains in the recuperator and the difference between internal and external temperature of air for a velocity of 2 and 3 m/s. Separately, the effect of solar radiation on the recuperator's efficiency was taken into account. Figure 5 shows the magnitude of heat gains depending on the difference of temperatures during the entire measurement period and the approximation (solid line) at an air velocity of 2 m/s. Due to the predicted nonlinearity of the pattern, a second-degree polynomial was assumed. Ultimately, characteristics of recuperator work, thanks to which averaged gains of heat with and without solar radiation can be determined, were obtained (Fig. 6 and 7). These graphs can be used to predict gains in climatic conditions other than those that occurred during the operating tests, but radiation can be accounted for only when the insolation is similar.

Figure 4. Course of solar radiation (top graph), external and internal relative air humidity (2nd graph from top), internal temperature (ti), external temperature (te) and air temperature in exhaust channel (3rd graph from top), actual and theoretically possible heat gains and efficiency (bottom graph), from 11 Dec. 2002 to 2 Jan. 2003

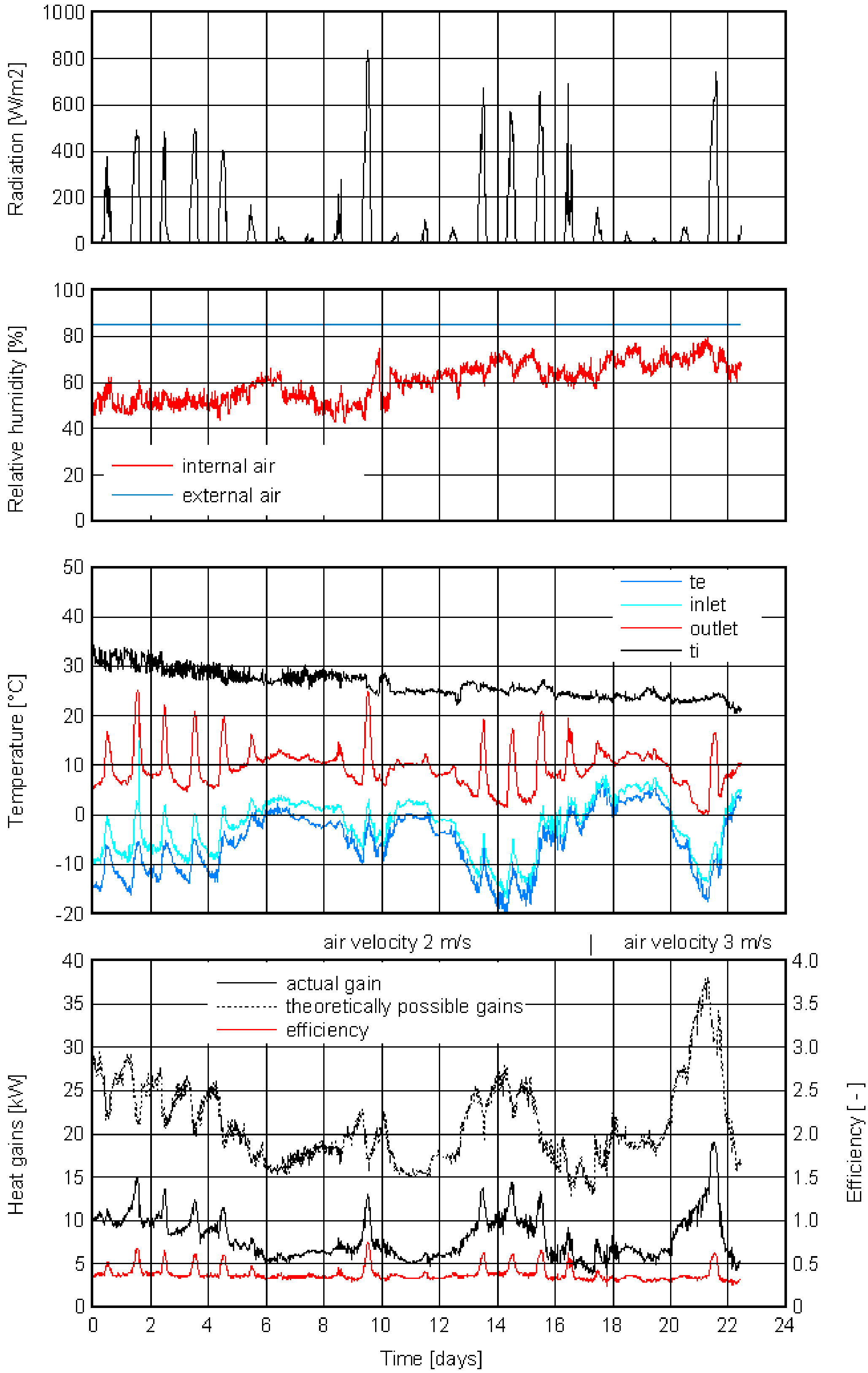


Figure 5. Heat gains in recuperator at an air velocity of 2 m/s, during the whole study period: a – without solar radiation, b – with solar radiation

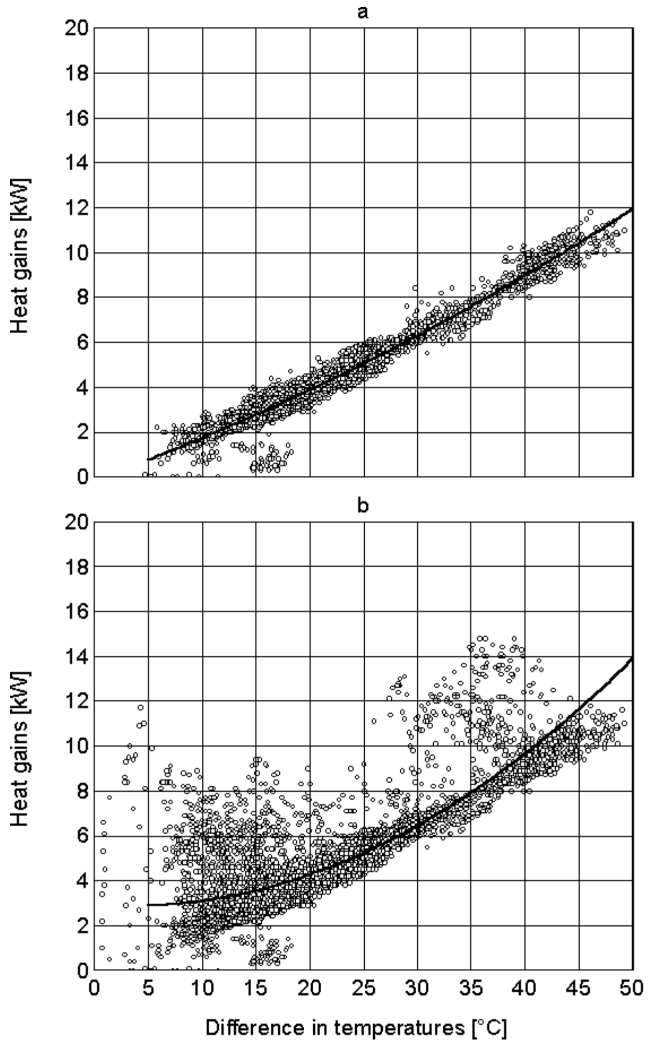


Figure 6. Averaged recuperator gain at air velocity of 2 m/s, during the whole study period

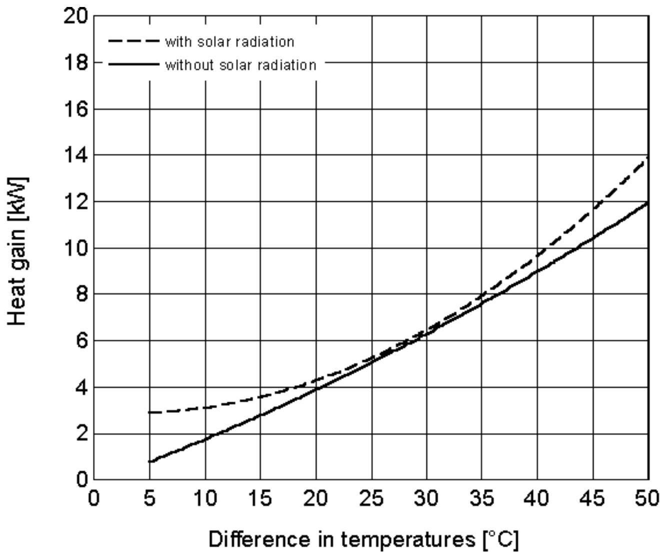
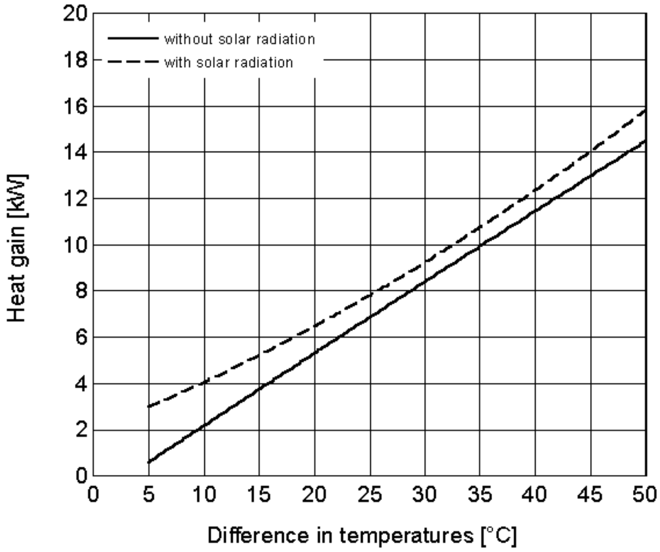


Figure 7. Averaged recuperator gain at air velocity of 3 m/s, during the whole study period



Results and tests of dust deposited on the walls of the exhaust channel

Examples of dust deposit masses during the autumn production cycle at an air velocity of 2 m/s are shown in Table 2.

Table 2. Course of exhaust channel contamination during the summer production cycle, at an air velocity of 2 m·s^{-1}

Measurement point	Deposit weight on the surface of indicator plate (g) at days of rearing			Deposit weight on the walls of exhaust channel (g · m^{-2}) at days of rearing		
	16	23	39	16	23	39
Inlet	0.3	0.6	1.5	3	6	15
II	0.2	0.5	1.7	2	5	17
III	0.2	0.4	1.4	2	4	14
Outlet	0.1	0.3	1.4	1	3	14

The present results indicate the occurrence of an unexpectedly small dust deposit on the walls of the exhaust channel. The greatest increment of deposit occurred from the 4th week of rearing. This shows the possibility of increasing the energy efficiency of the recuperator thanks to the use of disturbers in the exhaust channel. However, this requires measuring the dust deposit during normal operation of the broiler house.

To determine the contamination of the exhaust channel when the volume of exhaust air stream is greater, an experiment was conducted during the summer production cycle. The equipment worked in such a way that the air flowed with a maximum efficiency of the fan (about 4500 m^3/h) only in the exhaust channel. The experiment was 27 days long, from the 14th day of rearing to the end of the production cycle. The ultimate result of deposit mass on indicator plates ranged from 290 g/m^2 at the inlet to 270 g/m^2 at the outlet. About 20-fold increase in the weight of deposit on the exhaust channel walls, compared to the deposit that occurred at a rate of 2 m/s, resulted from the greater volume of air stream and more turbulent flow of air.

During detailed quantitative microbiological tests after the incubation period, colony forming units were calculated and the presence of Salmonella pathogenic bacteria was determined (Tab. 3).

Table 3. Maximum microorganism count (‘000) in individual samples (data for measurements taken in October 2003)

Group of microorganisms	Number of sample		
	1	2	3
Bacteria	350.5	250.5	850.3
Fungi	37.3	39.5	47.5
Salmonella, Shigella	0	0	0
Coli bacteria	50.2	30.2	180.3

In the tested samples of dust, the number of microorganisms varied. The greatest number was found in the production facility of the broiler house, and the lowest number in refluxes from the recuperator and in the recuperator itself, which can be attributed to changeable conditions outside and inside the exhaust channel of the equipment. Only the number of fungus spores in each place was similar. The results of the tests indicate that after a 2-year period of recuperator operation, which after each production cycle was routinely cleaned and disinfected, there was no biosafety threat for the broiler house.

The results of measurements of selected parameters of bioclimate obtained during 5 successive production cycles, including the 2nd winter cycle and the 1st summer cycle showed that air temperature in the experimental part, in the living area of broilers, was at a level of temperature required for individual stages of broiler rearing. Frequent but short-term fluctuations of internal temperature of up to 4 K were previously found in the summer period, which can be attributed to greater intensity of ventilation. Short-term fluctuations in temperature within the area of recuperator operation did not exceed 1.5 K, while air temperature at a height of 0.5 m was about 1 K lower than outside the reach of the recuperator. Air velocity within the reach of the recuperator was greater than outside its reach, but it was within the upper limit of the standard, which had a positive effect on chickens in the summer period.

The effects of the recuperator on the productive results are best reflected in weight gains, which in the experimental part of the broiler house were slightly more favourable than in the control part outside the reach of the recuperator. The results of feed conversion per 1 kg weight gain showed that feed consumption was 10-40 g lower within the reach of the recuperator than in the control part. This attests to the favourable effect of the recuperator on the productive results.

CONCLUSIONS

Based on the present experiment the following conclusions can be made:

1. Recuperator efficiency, averaged for the period of measurement, without regard to solar radiation, was estimated to be approximately 30%. Solar radiation increased this efficiency up to 37% on average, while momentary efficiency reached several hundred percent.
2. The dust deposited on the exhaust channel walls, at an air velocity of up to 3 $m \cdot s^{-1}$, proved surprisingly small (not more than 17 g/m^2 after 39 days of rearing). This was influenced by the construction of the recuperator, which allowed almost undisturbed flow of the air stream.
3. After 2-year operation the recuperator was routinely cleaned and disinfected after each production cycle and posed no microbiological threat to the broiler house.
4. Within its reach, the recuperator was found to have no adverse effect on air temperature, humidity and flow velocity in the living area of broilers. A positive effect was found for the constant inflow of fresh ventilation air, which was often lacking in those sections of the broiler house outside the reach of the recuperator, where fresh air arrived only when the ventilation system was on.
5. Analysis of production results showed that the recuperator tested had a favourable influence on them.

ACKNOWLEDGEMENTS

The authors would like to thank the KAWI-Eksport Company Ltd. of Łódź for providing polyurethane foam panels as well as equipment and accessories needed to construct the recuperator model for laboratory tests.

REFERENCES

1. Bieda W., Herbut E., 1999. Koncepcja rurowego, gruntowo-powietrznego wymiennika ciepła działającego w systemie wentylacyjnym brojlerni (A concept for an earth-tube heat exchanger operated in the ventilation system of a broiler house). Zesz. Naukowe AR w Krakowie nr 355. ser. Inż. Środowiska z. 19. 153-163 (In Polish).
2. Besler G. J., Gryglewicz W., 1983. Wzrost produkcji zwierzęcej poprzez optymalizację mikroklimatu przy wykorzystaniu ciepła i chłodu zmagazynowanego w gruncie (An increase in animal production by optimization of microclimate using heat and cool air stored in the ground). Przegląd Hodowlany 11, 24-26 (In Polish).
3. Cielejewski H., Isensee E., Krueger J., 1984. Berechnungs- und Planungsgrundlagen für den Einsatz von Wärmetauschern. ETA, Edition A, 42, A133-A138.
4. DIN 4108, Teil 4., 1981. Wärmeschutz im Hochbau. Wärme- und feuchteschutztechnische Kennwerte.
5. Glück B., 1991. Zustands- und Stoffwerte. Wasser – Dampf – Luft. Verlag für Bauwesen, Berlin.
6. Górecki E., Mizerski A., 1998. Wykorzystanie ciepła z powietrza wentylacyjnego (Use of heat from ventilation air). Materiały Budowlane, nr 2. 64-66 (In Polish).

7. Krueger J., 1986. Untersuchungen an Wärmetauschern im praktischen Einsatz. Dysertacja doktorska. Universitätsbibliothek Kiel (Germany)
8. Kuczyński T., 1988a. Niekonwencjonalne metody ograniczenia strat ciepła w systemach wentylacji budynków inwentarskich (Unconventional methods for limiting heat losses in livestock building ventilation systems). Budownictwo Rolnicze 3, 18-20 (In Polish).
9. Kuczyński T., 1988b. Zastosowanie wymienników rekuperacyjnych do odzyskiwania ciepła w budynkach inwentarskich (Use of recuperative exchangers for recovery of heat in livestock buildings). Budownictwo Rolnicze 4, 11-14 (In Polish).
10. Recknagel H, Sprengel E., 1976. Ogrzewanie i klimatyzacja – poradnik [Heating and air conditioning guide]. Arkady, Warszawa. 112-127 (In Polish).
11. Wolski L., 1988. Mikroklimat w budynkach inwentarskich [Microclimate in livestock buildings]. PWN, Warszawa [in Polish].

Wacław Bieda, Jan Radoń
Department of Rural Building, Agricultural University of Cracow
Al. Mickiewicza 24-28, 30-059 Kraków, Poland
phone (+48 12) 662 40 09, fax (+48 12) 633 11 70
e-mail: rmbieda@cyf-kr.edu.pl

Herbut Eugeniusz
Department of Technology, Ecology and Economics of Animal Production,
National Research Institute of Animal Production
32-083 Balice n. Kraków, Poland
phone (+48 12) 285 67 20, fax (+48 12) 285 67 33
e-mail: eherbut@izoo.krakow.pl
