Using meteorological data to determine the risk of heat stress

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Abstract: This paper first proposes a technique of computing air temperature and humidity in stables based on outdoor air parameters and biological production of animals. The computation technique is outlined. The calculated values are then used to assess the potential of evaporation cooling in mild climatic conditions. Graphs illustrate the assumed effect of evaporation cooling equipment inside a stable housing of egg laying hens. Used in the computation were hourly meteorological readings obtained during the period May to August in years 2000 to 2002, in the locality with a potential installation of a cooling system. Other Graphs illustrate the time the animals spent in an environment with a particular air temperature. For instance in June 2002, the time animals in the stable were exposed to temperatures 27°C or higher was reduced by using an air cooling system from 39 h to 22 h, and in July 2002 from 33 h to 4 h. The envisaged model can be modified for other kinds of gallinaceous poultry and pigs.

Keywords: laying hens; air temperature; air humidity; evaporation cooling; temperature-humidity index

One of the problems of current farming is heat stress of the kept animals. This problem is being dealt with not only by countries with intensive agriculture in subtropical and tropical areas, but also by countries with mild climate such as the Czech Republic.

All over the world this problem represents a significant research potential. In most cases the research focuses on livestock, poultry and pigs.

When assessing the suitability of different cooling systems for mild climatic conditions, important is mathematical modelling of air temperature and humidity inside the stables. In the past, works on this problem were published for example by Gates and Timmons (1988), Lucas *et al.* (2000), Silva *et al.* (2005).

The hereby presented mathematical model can be used for various categories of gallinaceous poultry. It determines in particular the air temperature and humidity inside the stable in conditions where evaporation cooling is and is not used, respectively.

In order to express the risk of heat stress of animals, the temperature-humidity index, THI, is used instead of the temperature itself (Ingram 1965). In addition to THI, the following terms are used in connection with heat stress of animals: effective temperature (Beckett 1965), lower critical temperature LCT (Bruce & Clark 1979), upper critical temperature UCT (Black *et al.* 1986). In the presented model, running of the cooling equipment is controlled by the values of THI inside the stable.

Building a model allows the locality to be assessed from the evaporation cooling system suitability point of view, aimed at reducing the risk of heat stress of animals.

MATERIAL AND METODS

A mathematical model of thermodynamic changes in the moist air inside a stable was designed using a computer program called MathCAD. A schematic diagram of the computations is illustrated in Figure 1. For the model to function correctly, it is necessary to specify items identified as IN, results of the computation are identified as OUT. The computation consists of seven parts which are identified by the rectangles 1 to 7. Individual parts of the computation are described in the following paragraphs. For selected cases are shown examples corresponding to particular parts of the model in the MathCAD program.

Before the computation it is necessary to input meteorological data in Excel files into MathCAD. In the period 2000 to 2002, air temperature and rela-

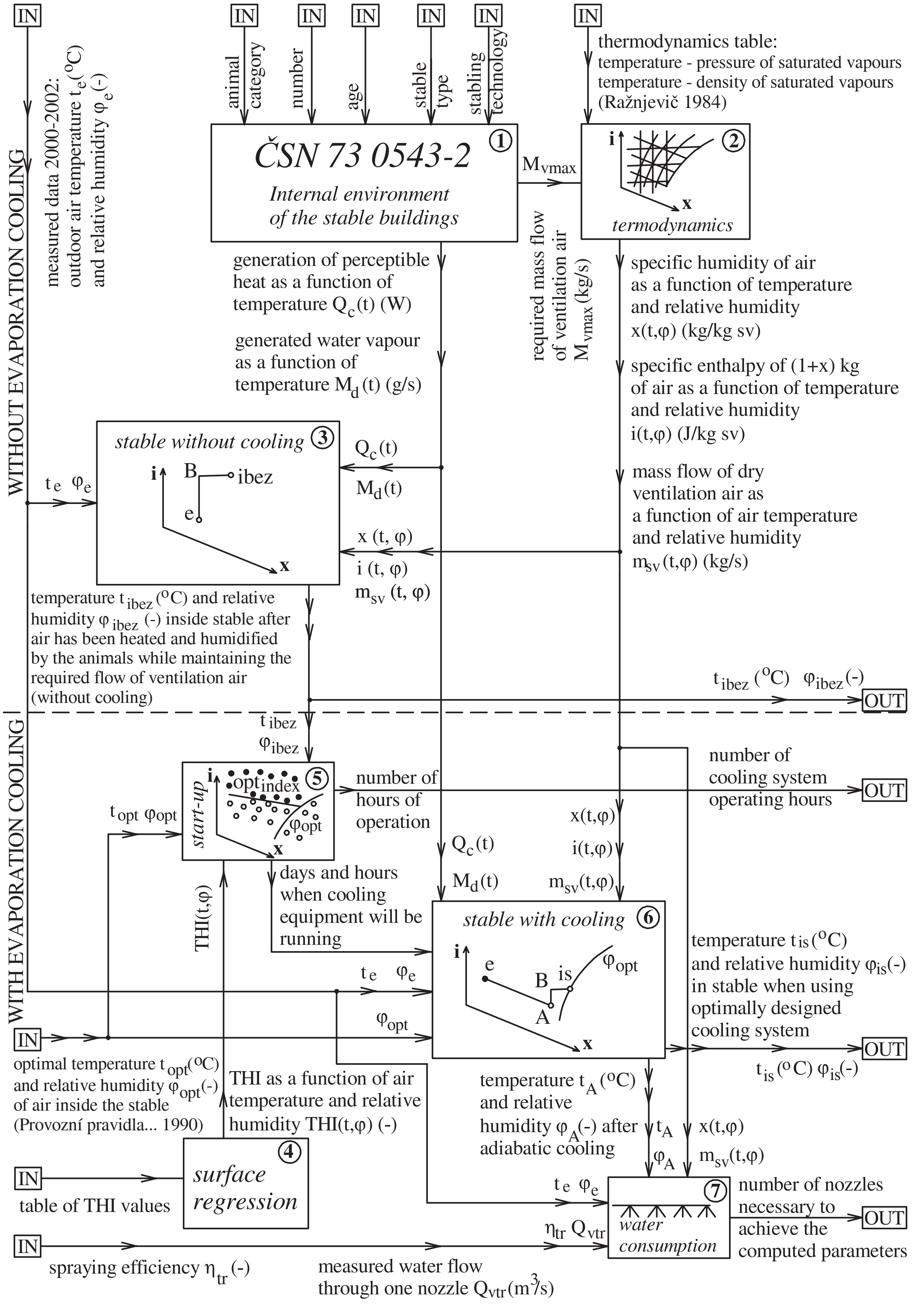

Figure 1. Schematic diagram of the computation

tive humidity readings were taken at hourly intervals at the České Budějovice station of the Czech Hydrometeorological Institute professional meteorological institute at Kněžský vrch, situated in the south-western part of the Central Bohemian Hillsides, at elevation 519 m above mean see level, at latitude 49°28'N and longitude 13°50'E. An average annual air temperature was 7.5°C, summary precipitations 295.1 mm, sunshine time 1676.6 hours, maximum temperature of 38.1°C was recorded on 27 July 1983.

Definition of the outdoor air temperature matrix and outdoor relative humidity matrix in MathCAD:

t_e = C: \.\temperature.xls φ_e = C: \.\humidity.xls

From the whole matrix of values was always selected data corresponding to the chosen days (d) and hours (h), for which the computation was carried out.

Computation parts 1, 2 and 3 constitute an independent entity (see Figure 1), in which were for the supplied outdoor air parameters t_e (°C) and φ_e (-) determined air temperature t_{ibez} (°C) and humidity φ_{ibez} (–) in the analysed stable without evaporation cooling.

Part 1. Using the stabling technology, stable type, specified category, number and age of the animals, computed was the generated heat Q_c (W) and water vapours M_d (g/s) and ventilation air flow M_{v}max (kg/s) in accordance with ČSN 73 0543-2. The computed generated heat and water vapour are a function of temperature inside the stable.

Part 2. Created was a regression function of the pressure of saturated vapours and density of the saturated vapours from table values within the range 0°C to 40°C (Ražnjević 1984). Specified were basic air parameters: specific gas constant of dry air 287 J/kg/K, specific heat capacity of dry air 1004 J/kg/K, median specific heat capacity of water vapours 1860 J/kg/K, for the temperature range 0°C to 40°C, specific water evaporation heat 2500 kJ/kg at 0°C and design moist air pressure 98 000 Pa. By means of regression functions and specified constants were in accordance with theoretical thermodynamic relations defined functions necessary to compute the processes taking place in the moist air: specific humidity $x(t,\varphi)$ (kg/kg$_{SV}$), specific enthalpy of (1+x) kg of air $i(t,\varphi)$ (J/kg$_{SV}$) and mass flow of dry ventilation air $m_{SV}(t,\varphi)$ (kg/s) (Chyský 1977).

Part 3. Parameters of air inside the stable t_{ibez} (°C) and φ_{ibez} (–) without evaporation cooling were computed from readings of outdoor air parameters t_e (°C) and φ_e (–), using the following system of equations:

heating e–B takes place at constant specific humidity

$$x(t_B, \varphi_B) = x(t_e, \varphi_e) \tag{1}$$

enthalpy increases with the heat generated by the animals

$$i(t_B, \varphi_B) = x(t_e, \varphi_e) + \frac{Q_c\,(t_i)}{m_{sv}\,(t_e, \varphi_e)} \tag{2}$$

humidification by vapour B-i takes place at a constant temperature

$$t_i = t_B \tag{3}$$

specific humidity increases by the animal generated humidity

$$\text{humidity } x(t_i, \varphi_i) = x(t_B, \varphi_B) + \frac{M_d\,(t_i)}{m_{sv}\,(t_e, \varphi_e)} \tag{4}$$

Individual thermodynamic processes are schematically illustrated in Figure 2.

Relations (1) through to (4) are system of four equations with unknowns t_B, φ_B, t_i (in this case t_i = t_{ibez}) and φ_i ($\varphi_i = \varphi_{ibez}$). Functions $Q_c(t)$ and $M_d(t)$ were defined in Part 1, functions $x(t,\varphi)$, $i(t,\varphi)$ and $m_{SV}(t,\varphi)$ in Part 2.

Model parts 4, 5, 6 and 7 solved the situation when a cooling equipment working on the evaporation principle was installed in the stable. Correctly designed equipment will start only at suitable outdoor air parameter values t_e, φ_e and humidify the air inside the stable to the correct value φ_{opt}. Result of the computation are air parameters inside the stable t_{is} (°C) and φ_{is} (-) at the time the equipment is running, the time the equipment is to run and the quantity of water necessary to achieve these parameters.

Part 4. By means of surface regression of the values of temperature-humidity index THI (see Table 1) (http://www.abe.iastate.edu/livestock/heat_stress.asp), determined was the function for computing the temperature-humidity index THI(t,φ) (–).

Part 5. Days (d) and hours (h) in which the cooling equipment was to be used were determined by comparing the temperature-humidity index corresponding to the values of air parameters inside the stable

$$\text{index}_{d,\,h} := \text{THI}\,(t_{ibez_{d,\,h}}, \varphi_{ibez_{d,\,h}})$$

with the limiting values of the index corresponding to optimal air parameter values. In order to save energy required to run the cooling equipment, it is desirable to select the maximum from within the range of recommended values, e.g. for egg-laying hens (Provozní pravidla 1990):

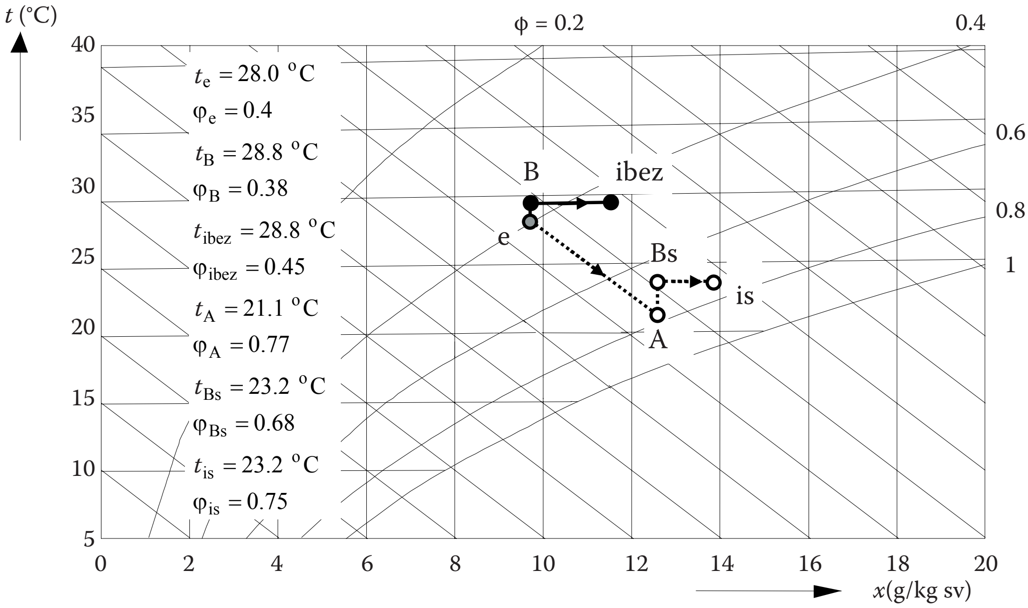

Figure 2. Assumed thermodynamic changes in moist air inside the stable
e → ibez – air parameter changes in a non-cooled stable
e → B – air heating by heat generated by the animals at t_{ibez}
B → ibez – air humidification by water vapours generated by the animals at t_{ibez}
e → is – air parameter changes in a non-cooled stable
e → A – evaporation air cooling
A → Bs – air heating by heat generated by the animals at t_{is}
Bs → is – air humidification by water vapours generated by the animals at t_{is}

$t_{opt} := 22°C \quad \phi_{opt} := 0.75$

$\text{opt}_{index} := \text{THI}(t_{opt}, \phi_{opt}) \ \text{opt}_{index} = 72.514$

The cooling equipment will be switched on if the value of the temperature-humidity index in the stable, $\text{index}_{d,h}$ (–) exceeds the value opt_{index} (–) and relative humidity in the stable is lower than ϕ_{opt} (otherwise the air would be undesirably humidified). From this condition can be determined the time the cooling equipment is to run.

Part 6. The values of air parameters t_{is} (°C) and ϕ_{is} (–) inside the stable with evaporation cooling are computed from the outdoor air readings t_e (°C), ϕ_e (–) and the defined optimal humidity ϕ_{opt} (-) using the following system of equations:

- air humidification e-A takes place at constant enthalpy

  $$i(t_A, \phi_A) = i(t_e, \phi_e) \tag{5}$$

- air temperature at the end of the humidification process is lower than at the beginning

Table 1. THI values depending on air temperature and relative humidity

Temperature		Relative humidity φ (%)									
t (°F)	t (°C)	10	20	30	40	50	60	70	80	90	100
70	21.1	65	66	67	68	69	70	70	71	71	72
75	23.9	70	72	73	74	75	76	77	78	79	80
80	26.7	75	77	78	79	81	82	85	86	88	91
85	29.4	80	82	84	86	88	90	93	97	102	108
90	32.2	85	87	90	93	96	100	106	113	122	
95	35	90	93	96	101	107	114	124	136		
100	37.8	95	99	104	110	120	132	144			
105	40.6	100	105	113	123	135	149				

$$t_A \leq t_e \qquad (6)$$

- maximum humidity to which the air can be humidified is 100%

$$\varphi_A \leq 1 \qquad (7)$$

- heating A–B takes place at constant specific humidity

$$x(t_B, \varphi_B) = x(t_A, \varphi_A) \qquad (8)$$

- enthalpy increases by animal generated heat

$$i(t_B, \varphi_B) = i(t_A, \varphi_A) + \frac{Q_c(t_i)}{m_{sv}(t_e, \varphi_e)} \qquad (9)$$

- humidification by vapour B – i takes place at constant temperature

$$t_i = t_B \qquad (10)$$

- specific humidity increases by animal generated humidity

$$x(t_i, \varphi_i) = x(t_B, \varphi_B) + \frac{M_d(t_i)}{m_{sv}(t_e, \varphi_e)} \qquad (11)$$

- required relative humidity inside the stable

$$\varphi_i = \varphi_{opt} \qquad (12)$$

In order to achieve a maximum cooling effect has been selected maximum possible humidity. Individual thermodynamic processes are again schematically illustrated in Figure 2.

Relationships (5) and (8) through to (12) constitute six equations of six unknowns t_A, φ_A, t_B, φ_B, t_i (in this case $t_i = t_{is}$) and φ_i ($\varphi_i = \varphi_{is}$). Functions $Q_c(t)$ and $M_d(t)$ were defined in Part 1, functions $x(t,\varphi)$, $i(t,\varphi)$ and $m_{sv}(t,\varphi)$ in Part 2.

Part 7. In order to be able to compute the required number of nozzles or units producing water mist, it is necessary to know the volume flow of water through one nozzle Q_{vtr} (m^3/s) or through one unit, and efficiency η_{tr} (–) of evaporation of the sprayed water in the equipment. If we assume that all sprayed water evaporates into the air, then we specify

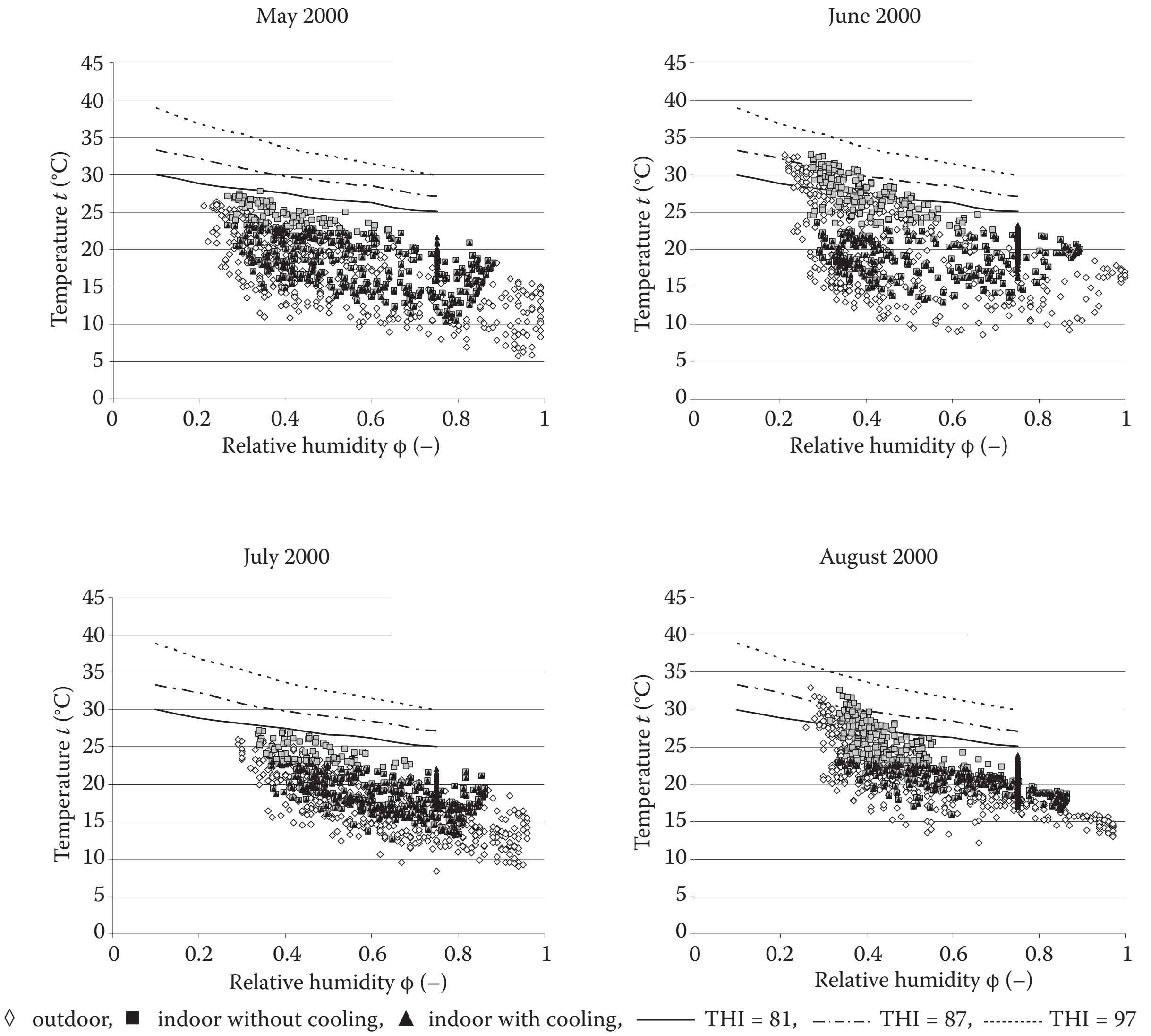

Figure 3a. Assumed effect of optimally designed evaporation cooling equipment with defined zone of heat stress for egg laying hens in 2000

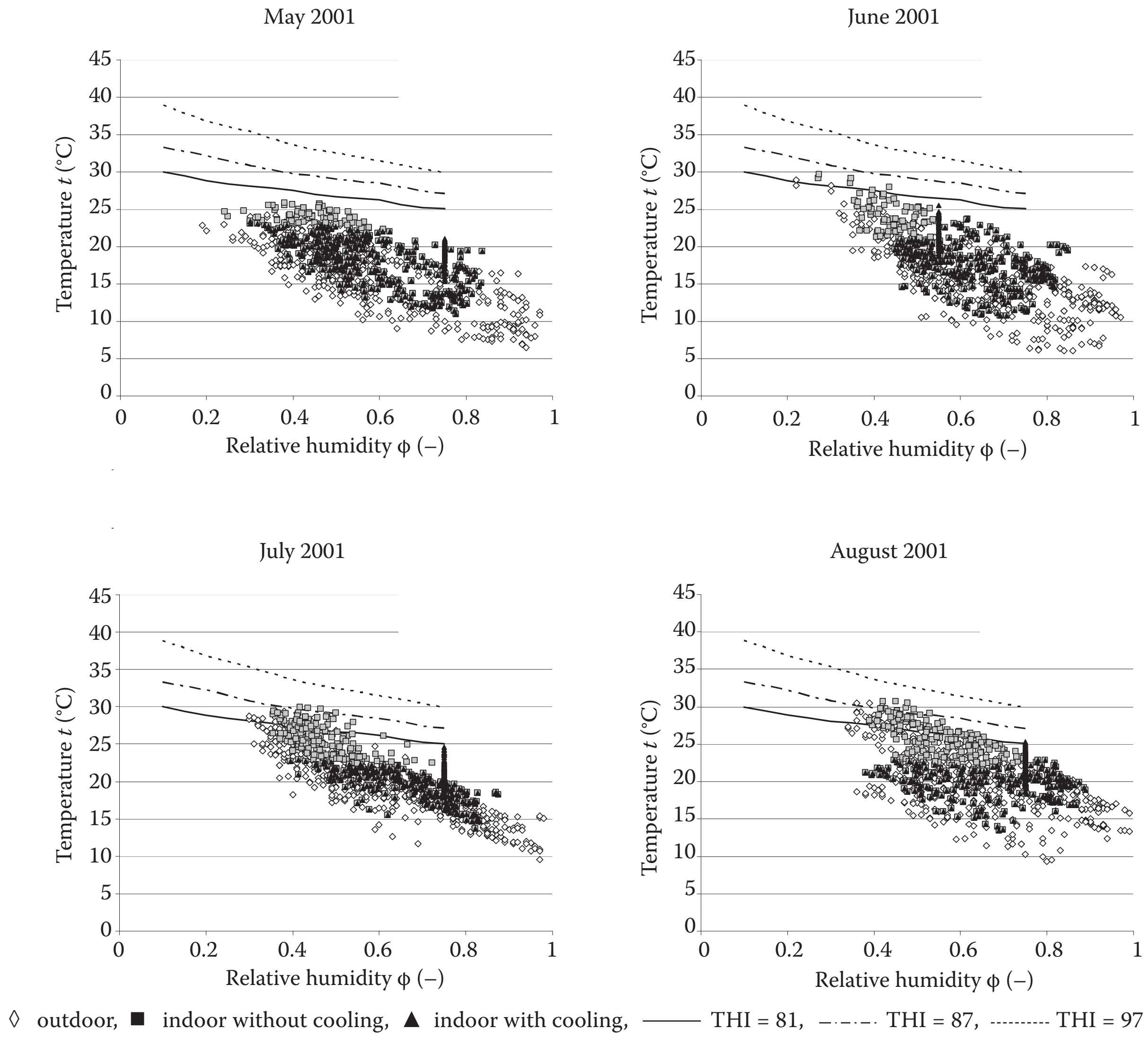

Figure 3b. Assumed effect of optimally designed evaporation cooling equipment with defined zone of heat stress for egg laying hens in 2001

$\eta_{tr} = 1$. The quantity of water flowing through the nozzle per unit of time can be determined in a graduated cylinder.

The mass of water flow M_w (kg/s) which must during the e–A process evaporate into the air is computed from equation

$$M_{w_{d,h}} := m_{sv}(t_{e_{d,h}}, \varphi_{e_{d,h}}) \times (x(t_{A_{d,h}}, \varphi_{A_{d,h}}) - x(t_{e_{d,h}}, \varphi_{e_{d,h}}))$$

where: t_e (°C), φ_e (–) – readings of outdoor air parameters,
t_A (°C), φ_A (–) – values of air parameters inside the stable after adiabatic cooling computed in Part 6,
$x(t,\varphi)$, $m_{sv}(t,\varphi)$ – functions defined in Part 2.

The number of nozzles, rounded off upwards to a whole number, is computed in the MathCAD embedded ceil function from relationship

$$\text{number}_{\,d,h} := \text{ceil}\left(\frac{M_{w_{d,h}}}{Q_{vtr} \times \rho_w \times \eta_{tr}}\right)$$

where: ρ_W (kg/m^3) – the density of water entering the spray equipment.

RESULTS

Computation using the above described methodology was conducted in a building with the ratio of the weight of above-ground structures to floor area not exceeding 200 kg/m^2, housing 20 000 egg laying hens aged up to 20 weeks, stabled on poultry bedding. The results of the computation of indoor air parameters in the non-cooled stable for a single outdoor air temperature and humidity are presented in Figure 2.

If hourly meteorological data obtained from readings taken between 10:00 a.m. and 10:00 p.m. in May to August 2000, 2001 and 2002, respectively, is used, we get Figures 3a, 3b and 3c, respectively.

THI = 81 represents a state of alert (http://www.abe.iastate.edu/livestock/heat_stress.asp). When

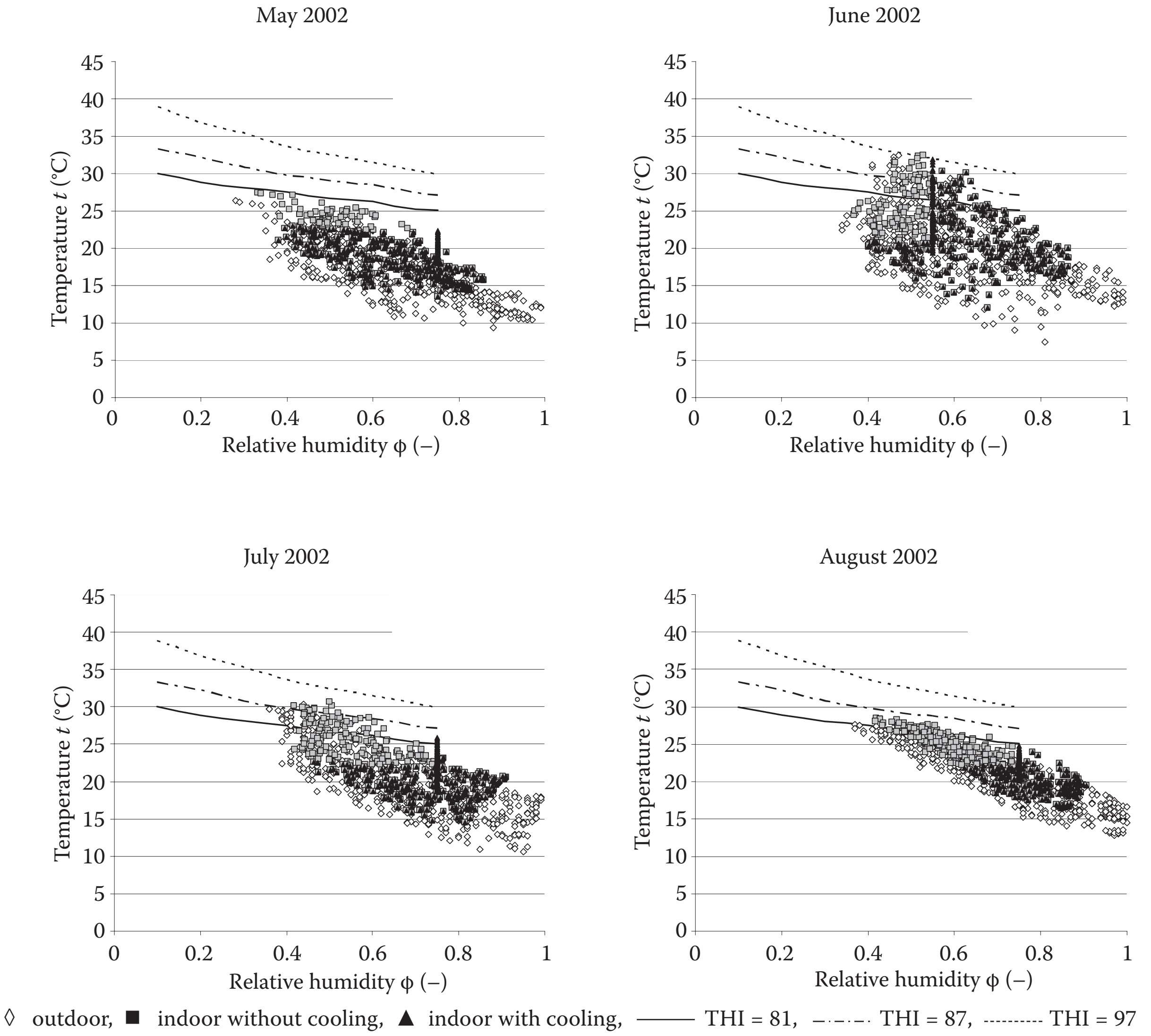

Figure 3c. Assumed effect of optimally designed evaporation cooling equipment with defined zone of heat stress for egg laying hens in 2002

this limit is reached, is recommended to increase ventilation.

THI = 87 represents a state of danger, above which it is necessary to use available evaporation cooling equipment.

THI = 97 represents a state emergency. Apart from cooling, it is recommended to limit the animals' activity by available means (transport, lighting, feeding).

An alternative way of presenting the model results is illustrated in Figure 4.

DISCUSSION

The graphs in Figure 3 present a qualitative view of the adjusted microclimate of the modelled stable by means of evaporation cooling. They compare the outdoor air parameter readings taken in individual months with indoor air parameters in the stable with and without cooling equipment installed. The graphs show a reduced risk of thermal stress when evaporation cooling is used. The reached temperature-humidity index (THI) in the stable is, when the cooling equipment is turned on, outside the critical zone. The recommended limit values of relative humidity inside the stable were exceeded only when the cooling equipment was due to high relative humidity of the outdoor air switched off.

A quantitative view of the adjusted microclimate in the model stable by means of evaporation cooling is presented by the graphs in Figure 4. The vertical axis represents time during which the animals in a stable with installed cooling equipment and in a stable without cooling equipment were, in the selected months in 2000, 2001 and 2002, exposed to the shown or higher temperature. Figures 3 and 4 show how air temperature and humidity differed in the same months in years 2000, 2001 and 2002.

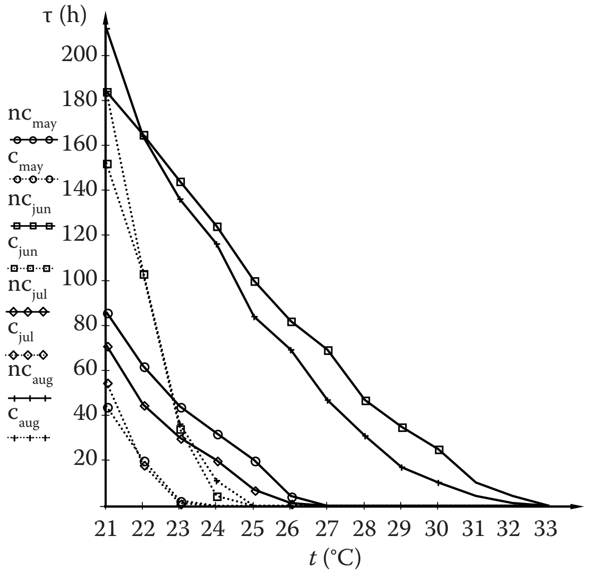

Figure 4a. Computed time during which the hens in different months in 2000 were exposed to the shown temperature or higher (c_{month} – cooling equipment installed, nc_{month} – no cooling)

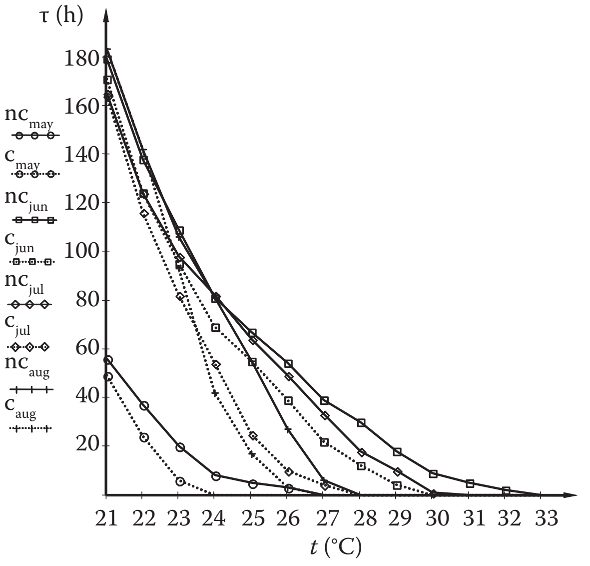

Figure 4c. Computed time during which the hens in different months in 2002 were exposed to the shown temperature or higher (c_{month} – cooling equipment installed, nc_{month} – no cooling)

When designing cooling equipment in a particular locality, it is necessary to take into consideration data from at least the period of thirty years (the so called normal line period).

From Figure 4, one can read out that for instance in June 2002, in the stable with no evaporation cooling equipment, the hens were exposed to temperatures 27°C and higher for 39 h. When cooling equipment was installed, the model shows that this time was reduced to 22 h. In July of the same year, this resulted in a reduction from 33 h to 4 h.

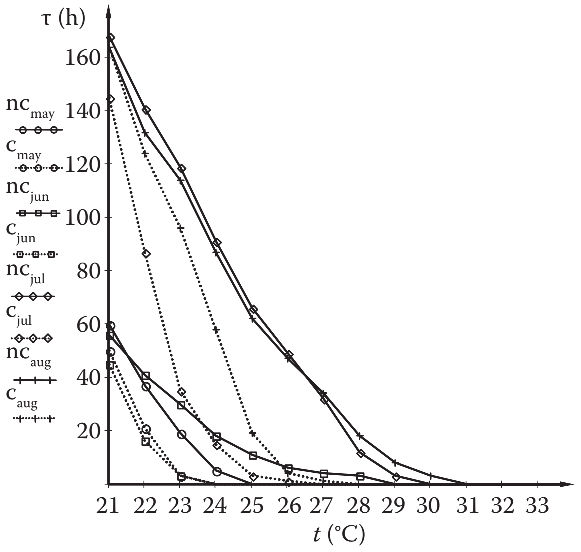

Figure 4b. Computed time during which the hens in different months in 2001 were exposed to the shown temperature or higher (c_{month} – cooling equipment installed, nc_{month} – no cooling)

The model presents basic information about the effects of a cooling system in the surveyed locality. The model can be modified for other kinds of gallinaceous poultry and for pigs.

Acknowledgement

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References

Beckett F.E. (1965): Effective temperature for evaluating or designing hog environments. Transactions of the ASAE, **8**: 163–166.

Black J.L., Campbell R.G., Williams I.H., James K.J., Davies G.T. (1986): Simulation of energy and amino acid utilization in the pig. Research and Development in Agriculture, **3**: 121–145.

Bruce J.M., Clark J.J. (1979): Model of heat production and critical temperature for growing pigs. Animal Production, **28**: 353–369.

Chyský J. (1977): Vlhký vzduch. SNTL, Praha.

ČSN 73 0543-2 (1998): Vnitřní prostředí stájových objektů. Část 2: Větrání a vytápění. Český normalizační institut, Praha.

Gates R.S., Timmons M.B. (1988): Stochastic and deterministic analysis of evaporative cooling benefits for Latiny hens. Transactions of the ASAE, **31**: 904–909.

Ingram D.L. (1965): Evaporative cooling in the pig. Nature, **207**: 415–416.

Lucas E.M., Randall J.M., Meneses J.F. (2000): Potential for evaporative cooling during heat stress periods in pig production in Portugal (Alentejo). Journal of Agricultural Engineering Research, **76**: 363–371.

Provozní pravidla pro větrání a vytápění stájových objektů (1990). MZe ČR, Praha.

Ražnjević K. (1984): Termodynamické tabuľky. ALFA, Bratislava.

Silva M.P., Baęta F.C., Tinôco I.F.F. *et al.* (2005): Evaluation of the evaporative cooling usage potential for the southeast region of Brazil with a simplified model for the estimation of the energy balance in sheds for broiler chickens. In: Proc. 7th Int. Symp., ASAE, Beijing.

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Abstrakt

Šleger V., Neuberger P. (2006): **Využití meteorologických údajů pro zjištění rizika vzniku tepelného stresu.** Res. Agr. Eng., **52**: 39–47.

V textu je nejprve navržen postup výpočtu teploty a vlhkosti vzduchu ve stájových prostorech na základě parametrů vnějšího vzduchu a biologických produkcí zvířat. Výpočty jsou zobrazeny pomocí blokového schématu. Vypočtené údaje následně slouží pro posouzení možností evaporačního chlazení v podmínkách mírného klimatu. Graficky je znázorněn předpokládaný účinek evaporačního chladicího zařízení ve stáji určené pro nosnice. K výpočtu byly použity hodinové meteorologické údaje naměřené v měsících květnu až srpnu v letech 2000 až 2002 v lokalitě s uvažovanou instalací chladicího systému. Dalším výsledkem je doba pobytu chovaných zvířat v prostředí o určité teplotě vzduchu – např. v červnu roku 2002 byla doba, kdy jsou zvířata ve stáji vystavena teplotě 27°C nebo vyšší, snížena díky chlazení vzduchu ze 39 hodin na 22 hodin, v červenci 2002 ze 33 hodin na 4 hodiny. Předkládaný model lze upravit pro další druhy hrabavé drůbeže a pro prasata.

Klíčová slova: nosnice; teplota vzduchu; vlhkost vzduchu; evaporační chlazení; teplotně-vlhkostní index

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