SIMULATION OF VENTILATION AND INDOOR AIR CONDITIONS OF AGRICULTURAL BUILDINGS

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ABSTRACT

A simulation program VENTOLA was developed to study behaviour of the microclimatic situation inside buildings housing domestic animals. The model accounts for a large number of parameters including species, category and characteristics of animals, structure of building, local climatic data, ventilation rate, heating and heat recovery systems. The model has been programmed in Excel 5.0. Results are presented in tables and diagrams. The program running on PC can be used to design the ventilation systems, to predict the microclimate conditions in building, and to study the effect which various parameters have on the inside microclimatic conditions.

INTRODUCTION

The aim of this article is to present some information on the field of simulation of indoor air conditions in ventilated agricultural buildings used for breeding of domestic animals.

Ventilation of buildings for animal housing seems to be rather simple in comparison with ventilation and climatization of residential, administrative or industrial buildings. Nevertheless there are still many cowsheds, stables for pigs, poultry or other species of domestic animals, where the animals suffer during the breeding or fattening period under too low or too high temperatures, excessive humidity or a high concentration of noxious gases and dust. On the other hand farmers have to pay for energy consumption used for heating and ventilation which should not be in many cases necessary. What are the causes and how to improve this situation?

Imperfection of design, low quality of installation and construction work and lack of suitable maintenance can be mentioned as the principal causes of the insufficient performance of ventilation systems and unsuitable microclimate inside the animal houses. The right data for design including the prediction of microclimate expected during the different period of the year are the first steps on the way to better this situation.

A new program for exact calculation of all needed parameters for ventilation and heating of stables is a program VENTOLA. This program was created in collaboration of Department of Technological Equipment of Buildings, Technical Faculty, Czech University of Agriculture Prague and Department of Crop Production and Agricultural Technology at Agricultural Faculty of University of Udine in Italy.

The quality of microclimatic conditions inside this kind of buildings is the result of the complex influence of many factors. Housed animals are very important in the first place; building, technological equipment, external climatic conditions and technical equipment for environmental control are rather important as well.

Technical equipment for environmental control in animal houses covers mostly only ventilation and heating systems, but in some cases equipment for air cleaning, cooling and humidifying is used. In recent years there have been built also new ventilation systems equipped with heat recovery systems. The ventilation performance should be controlled by automatic regulators.

MODEL DEVELOPMENT

To choose the suitable ventilation system and its parts it is necessary to regard all advantages and disadvantages of different solutions and evaluate them from many points of view. The biological needs of housed animals must be respected in the first place. The minimal, optimal and maximal air temperatures and maximal allowable levels of carbon dioxide, determined according to the kind, category, age and other data of housed animals, are especially very important.

The basic structure of the program was created with the aim to prepare the principle data useful for design of ventilation system and to make available general idea about microclimatic parameters under different outside temperatures. These data would facilitate the choosing of a suitable ventilation system and its equipment.

The mutual relationship between the outside climatic conditions, construction and parameters of the inside air is most suitably studied by the use of physical and mathematical models which describe the steady or dynamic states and time behaviour of studied phenomenon.

As the commonly used modern animal houses in most countries with developed intensive agriculture are constructed from light and well insulating construction materials with a small heat capacity and the ventilation provided by big air flows, the steady-state methods of process modelling were used.

In a steady-state heat-transfer process, the temperatures of air and all heat sources and flows are constant with respect to time, and the thermal storage in the surrounding parts of construction and in the air are not taken into account.

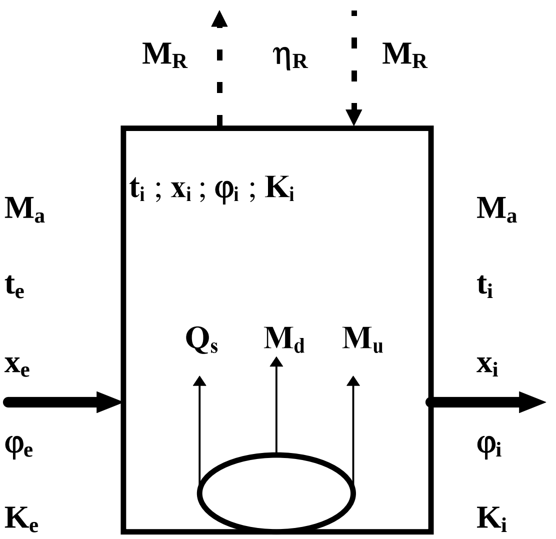

Figure 1 Scheme of model fluxes concept

In this part, a ventilation model is derived in detail from first principles. The main assumption on which the model is based are listed below. Other assumption are stated where appropriate in the model derivation :

1. The model is based on steady-state conditions.
2. The heat transfer by radiation is negligible
3. The temperature of air is uniform across the whole building
4. The flow of air through the building is uniform
5. The temperature gradients within the constructions are negligible
6. The building walls have negligible heat capacity
7. The density and heat capacity of air are constant
8. The heat capacities of air, water vapour and water are constant

The main parts of the model algorithm are:

- calculation of ventilation parameters for winter period
- calculation of ventilation parameters for summer period
- calculation of winter heat balance
- selection of suitable simulation method
- simulation of inside air conditions

A general flow chart of the model VENTOLA is shown in figure 2.

The minimum ventilation capacity for winter conditions is calculated according to the ventilation needed for the moisture balance and for the CO_2 balance. The first important calculations are based on the biological productions of heat, vapour, CO_2 of all species and categories of animals. The necessary values of biological productions used in this program are based on some practical values recommended in the reports of CIGR working group [1].
Total heat production per one animal, e.g. for cows:

$$q_s = 5{,}6 \,.\, m_z^{0{,}75} + 1{,}6 \,.\, 10^{-5} .\, p^3 + 22 \,.\, Y \qquad (1)$$

Production of the carbon dioxide per one animal:

$$m_u = 89{,}514 \,.\, 10^{-3} . q_s \qquad (2)$$

Production of the carbon dioxide in the animal house:

$$M_u = Z \,.\, m_u \qquad (3)$$

Ventilation rate needed for CO_2 balance:

$$M_{au} = \frac{M_u}{K_{uv} - K_{ue}} \rho_a \qquad (4)$$

Sensible heat production of one animal:

$$q_c = q_s \,.\, [0{,}8 - 1{,}85 \,.\, 10^{-7}(t_i + 10)^4] \qquad (5)$$

Latent heat of vaporization of water:

$$l_{wi} = 2500 - 2{,}36 \,.\, t_i \qquad (6)$$

Production of vapour per one animal:

$$m_d = \frac{10^3 (qs - q_c)}{l_{wi}} \qquad (7)$$

Production of vapour in the animal house:

$$M_d = Z \,.\, o \,.\, m_d \,.\, 10^{-3} \qquad (8)$$

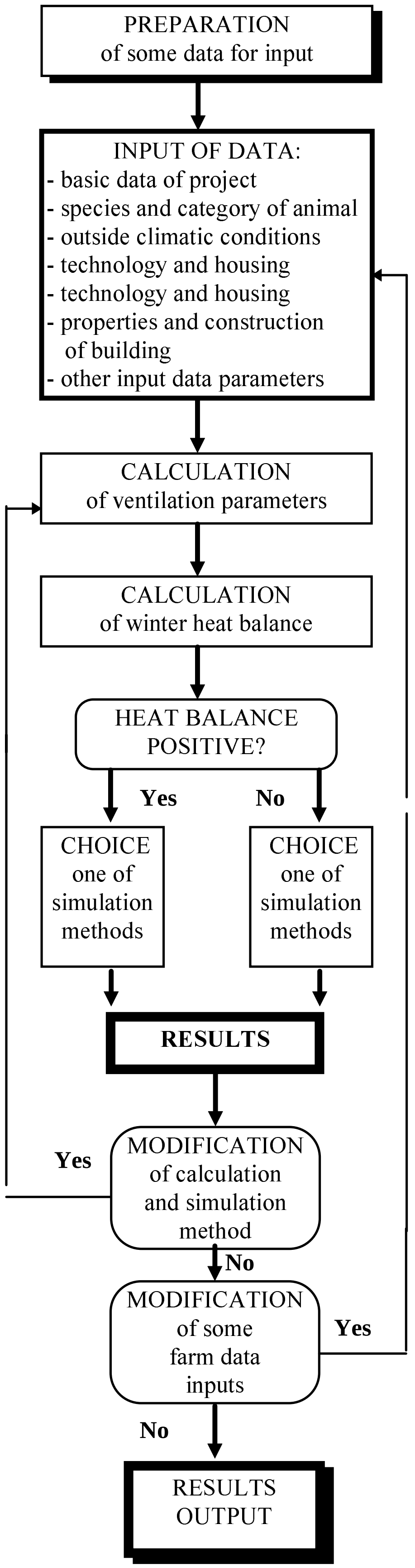

Figure 2 Overview of the model VENTOLA and its component layout

Net sensible heat production per one animal:

$$q_{cz} = q_s - m_{dv} \,.\, o \,.\, l_{wi} \,.\, 10^{-3} \qquad (9)$$

For the calculation of the supposed microclimatic conditions during the different periods of the year it is important to know the relation between the temperature and humidity of the outside air. The input values of outdoor climate are divided into eight climatic areas according to the winter temperatures and ten zones of humidity which indicate the moisture content and relative humidity of the air usual for those areas.

The relation between the temperature and moisture content of the air is expressed by the equations in two temperature ranges.

For the outside temperatures t_e (^oC):

$$-21 \le t_e < 15 \qquad (10)$$

and for the outside temperatures t_e (^oC):

$$15 \le t_e \le 45 \qquad (11)$$

$$x_e = K_1 + K_2 \,.\, t_e + K_3 \,.\, t_e^2 \qquad (12)$$

The coefficient recommended e.g. in the Czech Republic in the range (10) are:
$K_1 = 3,1$; $K_2 = 0,2015$; $K_3 = 0,0039$

and in the range (11): $K_1 = 0$; $K_2 = 0,56$;
$K_3 = -0,0062222$.

Moisture content of the air inside the building:

$$x_i = \frac{\varphi_i \,.\, p''_{di} \,.622}{p_b - \varphi_i \,.\, p''_{di}} \qquad (13)$$

Difference between the specific humidity of the inside and outside air:

$$\Delta x_{ie} = x_i - x_e \qquad (14)$$

Ventilation rate needed for vapour balance:

$$M_{ad} = \frac{M_d}{\Delta x_{ie}} \qquad (15)$$

Minimum ventilation capacity for winter conditions:

$$M_{av} = \max\,(M_{adv}; M_{auv}) \qquad (16)$$

The determination of the maximum ventilation capacity for summer conditions is based on practical experience and it is necessary to take the inside overproduction of the heat (of animals etc.) away from the animal house. This way of calculation was used in Czech standards [2].

Maximum summer ventilation rate for one animal:

$$m_{ax} = i \, . \, m_z^{\,r} \, . \, 10^{-3} \qquad (17)$$

Maximum ventilation capacity for the whole building in summer conditions:

$$M_{ax} = Z \, . \, y \, . \, z \, . \, m_{ax} \, . \, e_u \, . \, f_1 \, . \, f_2 \qquad (18)$$

Production of NH_3 by one animal:

$$m_N = m_{ns} \, . \, m_z \, . \, f_1 \qquad (19)$$

Production of NH_3 into the animal house:

$$M_N = Z \, . \, m_N \qquad (20)$$

To control the winter heat balance of the animal house the heat gains and heat losses are expressed in the form of following basic equations:

Sensible heat production by the animals into the animal house:

$$Q_{czv} = Z \, . \, q_{czv} \qquad (21)$$

Ventilation heat losses:

$$Q_{av} = M_{av} \, . \, c_a \, (t_{iv} - t_{ev}) \qquad (22)$$

Heat losses through the walls, ceiling, floor etc.:

$$Q_{kv} = Z \, . \, q_k \, (t_{iv} - t_{ev}) \qquad (23)$$

Heat balance of the building:

$$Q_{czv} - Q_{av} - Q_{kv} \geq 0 \qquad (24)$$

SIMULATION

The calculation course of microclimatic conditions in the animal house during the different periods of the year starts from the lowest winter temperature (design temperature) and continues to the highest one, which is chosen according to the properties of the construction and other factors influencing the inside conditions. The step of calculation (of outside temperatures) can be chosen according to the needs of the designer. Results of the simulation are presented both in the form of table and in the graphs.

Calculation of simulation I enables to calculate the inside air conditions (temperature, relative humidity, CO_2 and NH_3 concentrations) in the case of positive heat balance of the building. The calculation can be provided in two different ways.

Simulation I a) is based on the known relation between the inside and outside air temperature expressed by the equation:

$$t_i = t_{iv} + \text{tg}\, \beta (t_e - t_{ev}) \qquad (25)$$

The air flows are calculated in this case according to the predicted inside and outside conditions. The necessary precondition for this kind of calculation is to know the course of the relation outside-inside temperature from other similar buildings which were constructed and verified by the measurement in the past. Nevertheless the validation of this simulation method has only informative significance. As this kind of simulation was recommended in [2], it was also included in this calculation method.

Simulation I b) is based on the calculation of real heat losses and heat production in the building. The aim of this calculation is to determine exactly air flows M_a, which will ensure the optimum inside temperatures for a wide range of outside conditions.

$$M_{aj} = \frac{Z}{c_a} \left(\frac{q_{czj}}{\Delta t_{iej}} - q_k \right) \qquad (26)$$

As the biological production of sensible heat, vapour and gases depends on the inside temperature, the iteraction by calculation of inside parameters is used. An example of results of this simulation is shown in figure 3.

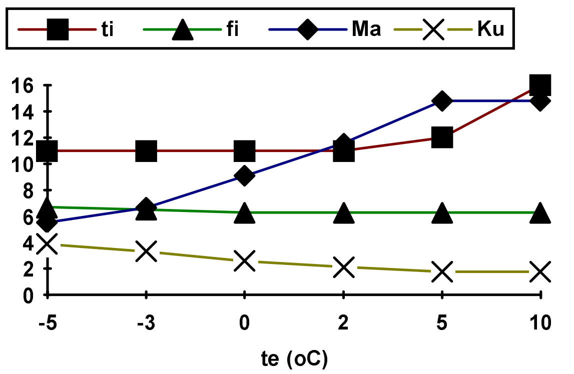

Figure 3 Results of simulation of inside air conditions for a cowshed in Italy

te = outside air temperature (^{o}C), ti = internal air temperature (^{o}C), fi = internal air humidity (10.%), Ma = air flow (kg.s^{-1}), Ku = CO_2 concentration (g.m^{-3})

Calculation of simulation II is used in the case of a negative heat balance. The calculation can be provided in more variants of simulation with different methods how to solve a negative heat balance of the building. The principle decision makes the program according to the results of the following equation:

$$\eta_{RP} = \frac{(M_{av}.c_a + Z.q_k)(t_{iv} - t_{ev}) - Q_{czv}}{M_{av}.c_a(t_{iv} - t_{ev})} \qquad (27)$$

If the following equation is valid:

$\eta_{RP} \leq \eta_{RS}$ (28)

then the negative heat balance can be solved without heating. The simulation can be provided by one of the three possibilities.

Calculation II a) simulates the ventilation without heating and without heat recovery systems. This solution is very useful in many cases for buildings used for cattle housing. These buildings have negative heat balance usually only for a short period when the outside temperatures are lowest. It would not be efficient to equip those buildings by heating systems or heat recovery system because cows or other cattle are thanks to their thermoregulation able to overcome this cold period without difficulties. The air flow M_a is offered by this kind of simulation to choose the suitable one (see figure 4). The final graph with results of inside conditions and ventilation rate in the course of different outside temperature periods according to VENTOLA results graph is shown in the figure 5.

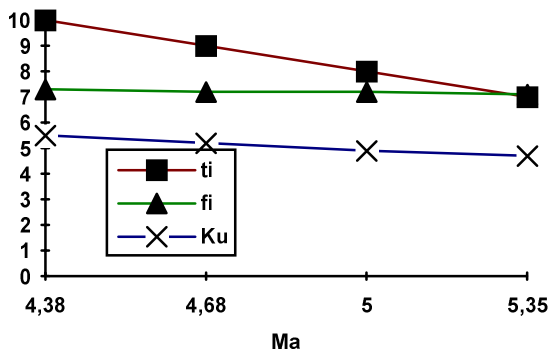

Figure 4 The program VENTOLA working screen (transformed from the VENTOLA) showing the influence of M_a on the inside air conditions (t_i, φ_i, K_{ui}) in a cowshed with negative heat balance for t_{ev} = -15°C
te = outside air temperature (°C), ti = internal air temperature (°C), fi = internal air humidity (10.%), Ma = air flow ($kg.s^{-1}$), Ku = CO_2 concentration ($g.m^{-3}$)

Simulation II b) for this kind of negative heat balance is based on the use of heat recovery systems. Animal houses are buildings with relatively high heat production inside the building and rather big ventilation rate during the whole year (in comparison with residential or administrative buildings). That is the reason why it is in many cases, from the view of energy efficiency, useful to use recuperative or regenerative heat exchangers. The equipment for heat recovery should be used by proper regulation. The purpose of the use of heat recovery is expressed by sequence of tasks in figure 6.

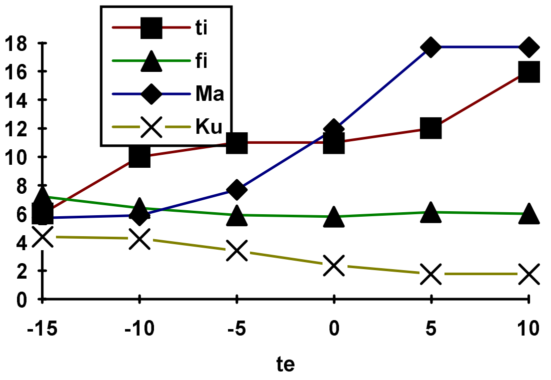

Figure 5 Results of simulation of inside air conditions in a cowshed with negative heat balance
te = outside air temperature (°C), ti = internal air temperature (°C), fi = internal air humidity (10.%), Ma = air flow ($kg.s^{-1}$), Ku = CO_2 concentration ($g.m^{-3}$)

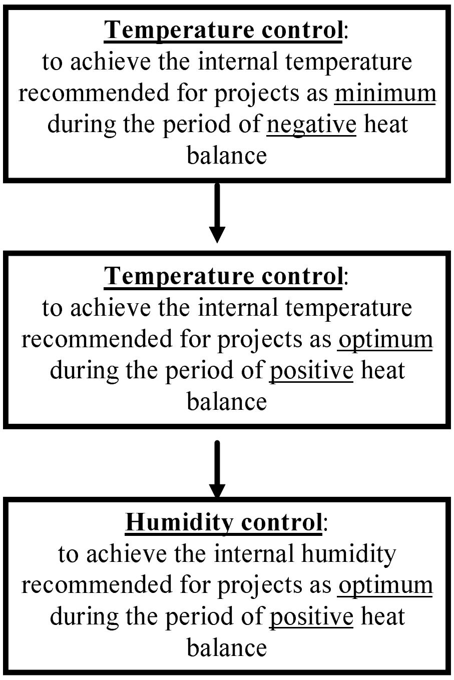

Figure 6 The purpose of use of heat recovery system in different levels of ventilation

The quantity of air flow used for heat recovery and some other parameters of ventilation and inside air conditions transformed from the VENTOLA results are in table 1.

By the simulation II c) is calculated heat consumption for the heating without heat recovery, to ensure at least the minimum internal temperature recommended for projects.

$Q_t = Q_{cz} - Q_a - Q_k$ (29)

The air flow must be sufficient for the vapour and noxious gases balance. An example of results of this kind of simulation transformed from the VENTOLA results is in the table 2.

Table 1 An example of VENTOLA results for ventilation of piggery with heat recovery

t_e (°C)	M_a ($kg.s^{-1}$)	M_R ($kg.s^{-1}$)	t_i (°C)	φ_i (-)	K_u ($g.m^{-3}$)
-15	1,59	1,55	22	0,62	5,5
-12	1,59	1,43	22	0,64	5,5
-9	1,59	1,28	22	0,66	5,5
-6	1,59	1,11	22	0,69	5,5
-3	1,99	1,46	22	0,60	4,51
0	2,16	1,43	22	0,60	4,19
3	2,37	1,37	22	0,60	3,87
5	1,63	0	22	0,80	5,37
8	2,08	0	22	0,72	4,34
10	2,5	0	22	0,68	3,70

Table 2 An example of VENTOLA results for ventilation without heat recovery

t_e (°C)	M_a ($kg.s^{-1}$)	Q_t (kW)	t_i (°C)	φ_i (-)	K_u ($g.m^{-3}$)
-15	1,59	24,6	18	0,65	5,5
-12	1,59	18,4	18	0,67	5,5
-9	1,59	12,2	18	0,70	5,5
-6	1,59	6,1	18	0,73	5,5
-3	1,59	0	18	0,77	5,5
0	1,72	0	19	0,75	5,11
4	1,76	0	21	0,76	5,02
6	1,76	0	22	0,77	5,02
8	2,08	0	22	0,72	4,34
10	2,5	0	22	0,68	3,70

If the equation (28) is not valid, the efficiency of the heat recovery system is not sufficient to cover the negative heat balance without heating. The following simulation can be used in these cases.

The first possibility is the simulation II a) without heating and without heat recovery. The second one is calculation of heat consumption by simulation II c). But in these cases the simulation II d) can also be used, based on calculation of heat consumption for heating when the heat recovery system is used as well. The scheme of use of both systems for heating and for heat recovery is on the figure 7.

The heat losses by ventilation are calculated in this case by following equation.

$$Q_{aR} = M_a \, . \, c_a \, . \, \Delta t_{ie} \, (1 - \eta_{RS}) \qquad (30)$$

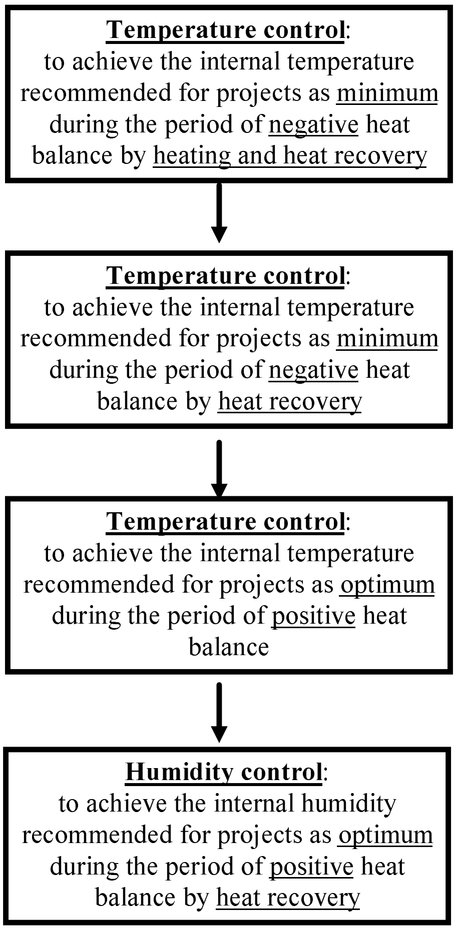

Figure 7 The purpose of use of heating and heat recovery system in different levels of ventilation

SOFTWARE DESCRIPTION

A simulation program based on the presented model and running on PC was developed in Excel 5.0 (Italian version). The performance of the program is based on interactive operation. The program graphical user interface with the data input window below are in figure 8. It consists of nine main entries. From this introductory screen exit is achieved by pressing any special key.

The main entrance menu for farm description „Insert the farm“ consists of 23 data inputs. Some of them are written into tables (name of farm, number of animals, body mass, milk production etc.), the other are achieved by pressing a special key (choice of animal species, category of animals etc.). E.g. the species and category of animals can be chosen from the following choices:

cattle

- cows
- fattening cattle
- calves
- heifers

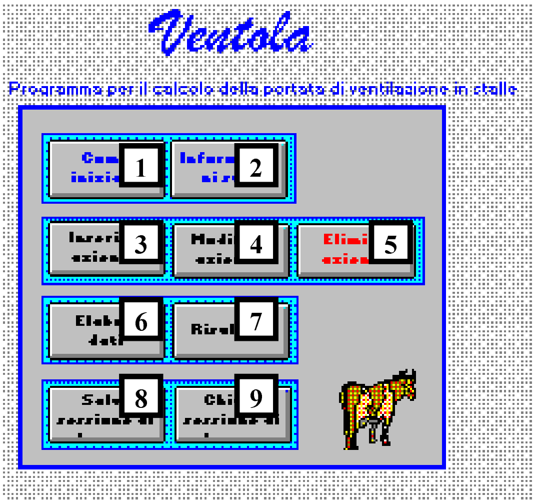

Figure 8 The program VENTOLA main working screen
1. How to begin, 2. Information about program, 3. Insert the farm, 4. Modification of the farm, 5. Elimination of the farm, 6. Elaboration of data, 7. Results, 8. Save, 9. Close

The housing system and technology used for breeding of the animals is chosen from the choice of the most typical stable equipment that is commonly used in countries with intensive and developed animal production. E.g. for cattle:

<u>housing</u>

- loose housing
- tying stalls
- calving stalls

<u>technology</u>

- with straw bedding
- without straw.

From this screen the user can enter also the building location (country, climatic zones) and basic building description (specific heat losses) and some factors and dimensions (e.g. specific weight of construction materials, floor surface, translucent areas) influencing the choice of several coefficients (e.g. coefficient for summer ventilation rate).

Information regarding the step of calculation and stopping outside air temperature of the winter period are entered from the menu offered by the program when the key „Calculation“ is pressed. The selection of the type of simulation is presented on the screen and can be specified by some subchoice or air flow choice if necessary.

Consequently, after the calculation, the results table with all mentioned data outputs is presented on the screen. The user can choose to present the data outputs in graph form.

CONCLUSIONS

The introduction of different simulation methods opened the possibilities of modifying and developing specific environmental strategies for practical purposes based on the individual situations and characteristics of the ventilated buildings. The program VENTOLA based on the presented mathematical model can be applied for calculation of ventilation in all types of animal houses. The potential benefits of using this heat and mass calculation system of ventilation rate and for simulation of predicted microclimatic parameters inside the building include:

- exact data of air flow rates required for ventilation system design
- appropriate performances of ventilation that will enable to achieve the suitable microclimatic conditions inside the animal house during different periods of year
- exact information needed for solving the negative heat balance of animal houses
- energy savings in environmental control of animal houses by:
    - improvement of thermal insulation properties of building construction
    - improvement of ventilation and heating performance
- assisting in testing and control of new or reconstructed existing buildings

The program was used several times for checking calculation of ventilation in different buildings for housing different categories of cows, pigs and poultry in the Czech Republic and Italy, constructed during recent years. The obtained results were compared with results of inside air conditions. The differences between those were mostly caused by unsuitable regulation and performance of ventilation.

The authors suppose the use of software for the design of new and reconstructed animal houses in both countries according to the construction possibilities. The different parameters will be defined with more precision in the future research work (measurement of biological production vapour, CO_2, NH_3 etc.).

REFERENCES

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2. ON 734502. Projektování vìtracích a vytápìcích zaøízení ve stájových objektech. (Designing of ventilation and heating in animal houses. Czech special standard.) Praha,1989.

NOMENCLATURE

c_a specific heat of air, $(J.kg^{-1}.K^{-1})$
e_u correction factor according production of milk, (-)
f_1 correction factor for calculation of biological production, (-)
f_2 correction factor for calculation of biological production, (-)
i coefficient for calculation of summer ventilation rate, (-)
K_e gases concentration of outside air, $(mg.m^{-3})$
K_i gases concentration of inside air $(mg.m^{-3})$
K_{uv} maximum CO_2 concentration of inside air (assumed calculation value), $(mg.m^{-3})$
K_{ue} CO_2 concentration of outside air, $(mg.m^{-3})$
K_1 coefficient for calculation of moisture content in outside air, (-)
K_2 coefficient for calculation of moisture content in outside air, (-)
K_3 coefficient for calculation of moisture content in outside air, (-)
l_{wi} latent heat of vaporization of water, $(kJ.kg^{-1})$
M_a mass air flow for ventilation, $(kg.s^{-1})$
M_{ad} ventilation rate needed for vapour balance, $(kg.s^{-1})$
M_{adv} ventilation rate needed for vapour balance by the internal temperature t_{iv}, $(kg.s^{-1})$
M_{aj} ventilation rate calculated by iteration, $(kg.s^{-1})$
M_{auv} ventilation rate needed for CO_2 balance by the internal temperature t_{iv}, $(kg.s^{-1})$
M_{av} minimum ventilation capacity for winter conditions, $(kg.s^{-1})$
M_{ax} maximum ventilation capacity for the whole building in summer conditions, $(kg.s^{-1})$
M_d production of vapour in the animal house, $(g.s^{-1})$
M_N production of NH_3 into the building, $(mg.s^{-1})$
M_R mass air flow for heat recovery system, $(kg.s^{-1})$
M_u production of the carbon dioxide in the animal house, $(mg . s^{-1})$
M_{uv} production of the carbon dioxide in the animal house by the internal temperature t_{iv}, $(mg . s^{-1})$
m_{ax} maximum summer ventilation rate per one animal, $(kg.s^{-1}.head^{-1})$
m_d production of vapour per one animal, $(mg.s^{-1}.head^{-1})$
m_N production of NH_3 into the building per one animal, $(mg.s^{-1}.head^{-1})$
m_{ns} production of NH_3 into the building per 1 kg of animal mass, $(mg.s^{-1}.head^{-1})$
m_u production of the carbon dioxide per one animal, $(mg.s^{-1}.head^{-1})$
m_z mass of one animal, $(kg.head^{-1})$
o correction factor for moisture evaporation from wet surfaces, (-)
p number of days pregnant, (day)
p''_{di} saturation vapour pressure of inside air,(Pa)
Q_a heat losses by ventilation air, (W)
Q_{aR} heat losses by ventilation air, (W)
Q_{av} air ventilation heat losses if the heat recovery is used, (W)
Q_{cz} net sensible heat production by the animals into the building, (W)
Q_{czv} sensible heat production by the animals into the building by the temperature t_{iv}, (W)
Q_k heat losses through the walls, windows, etc., (W)
Q_{kv} heat losses through the walls, ceiling, floor etc., (W)
Q_s total heat production into the building, (W)
Q_t energy consumption for heating, (W)
q_c sensible heat production per one animal, $(W.head^{-1})$
q_{cz} net sensible heat production per one animal, $(W.head^{-1})$
q_{czj} sensible heat production per one animal calculated by iteration, (W)
q_{czv} sensible heat production per one animal by the internal temperature t_{iv}, (W)
q_k specific heat losses through the walls, ceiling, floor etc., $(W.K^{-1}.head^{-1})$
q_s total heat production per one animal, $(W.head^{-1})$
r coefficient for calculation of summer ventilation rate, (-)
t_e temperature of outside air, (^oC)
t_{ev} winter design temperature, (^oC)
t_i temperature of inside air, (^oC)
t_{iv} the internal temperature recommended for projects as the minimum for animals, (^oC)
Δt_{ie} temperature difference between the inside and outside, $(g.kg^{-1})$
Δt_{iej} temperature difference between the inside and outside air calculated by iteration, $(g.kg^{-1})$
x_e moisture content of outside air, $(g.kg^{-1})$
x_i moisture content of inside air, $(g.kg^{-1})$
Δx_{ie} moisture content difference between the inside and outside air calculated by iteration, $(g.kg^{-1})$
Y production of milk, $(kg.head^{-1}.day^{-1})$
y correction factor according to the specific mass of the building construction, (-)
Z number of animals, (heads)
z correction factor according to the area of the translucent parts of the building, (-)
ρ_a density of air, $(kg.m^{-3})$
φ_e outside relative humidity, (-)
φ_i inside relative humidity, (-)
η_R efficiency of heat recovery system, (-)
η_{RP} desirable efficiency of heat recovery system, (-)
η_{RS} real efficiency of heat recovery system, (-)