Published monthly at 24–28 Oval Road, London NW1 7DX by Academic Press Inc. (London) Limited on behalf of The British Society for Research in Agricultural Engineering.

1986: Volumes 33–35, 12 issues. Inland, £96.00 inclusive of postage and packing; abroad $196.50 inclusive of postage and packing. Subscription orders should be sent to Academic Press Inc. (London) Limited, High Street, Foots Cray, Sidcup, Kent DA14 5HP (Tel. 01-300 0155). Send notices of change of address to the office of the Publishers at least 6–8 weeks in advance. Please include both old and new addresses.

Second-class postage paid at Jamaica, New York 11431, U.S.A.

Air freight and mailing in the U.S.A. by Publications Expediting Inc., 200 Meacham Avenue, Elmont, N.Y. 11003, U.S.A.

ISSN 0021-8634

J. agric. Engng Res. (1986) **33**, 1–12

Development of New Control Techniques for the Ventilation and Heating of Livestock Buildings

D. Berckmans*; V. Goedseels*

From statistical analysis of field data, normal mechanical ventilating systems using exhaust fans were found to give no better mean production results than natural open-ridge systems. To explain this, components of the mechanical ventilating system, namely the fan and the controller, were analysed in a laboratory test installation. The equipment tested revealed important shortcomings that explain why normal mechanical ventilating systems do not perform adequately in the field. By use of a steady-state analysis, the effects of the air flow rate on indoor temperature and on energy losses in a livestock building were analysed. A new controller has been developed, in an attempt to achieve improved control of air flow and hence more effective environmental control in livestock buildings.

1. Introduction

The effects of environment (temperature, humidity, air velocity) on pig performance have been investigated for swine housed in test facilities. These studies represent an important step in achieving effective environmental control in livestock buildings.[1–6] Attempts have been made for some time to improve the environment in commercial livestock buildings by controlled ventilation and these studies have included the formulation of basic standards,[7,8] the application of different techniques[9,10] and the study and analysis of air flow patterns.[11,12] For the last 20 years there has been a trend towards more confinement housing. Mechanical ventilation systems are now more widely used and they have undergone intensive development. Although technical developments have taken place, such as the introduction of microprocessors, there has been little change from the control point of view. Neither time-proportional ventilation control,[13] nor linear ventilation rate temperature control[14] are widely used and so they have not succeeded in replacing the on/off control or the variable speed control using solid state devices.[15] Because of the costs of today's mechanical ventilation systems, there are doubts about the economics of their beneficial influence on production results.

It would be expected that automatically controlled ventilated buildings would give better production results compared to natural ventilated buildings in which the weather changes of wind velocity, wind direction and temperature have significant effects on the internal environment.[16] Little work seems to have been published concerning the influence of climatic control equipment on production results. Based on experience from measurements in the field, Goedseels *et al.*[17] put forward the hypothesis that the present generation of automatic controllers used in mechanically ventilated buildings, do not achieve an adequate control of the air flow through the building. In consequence, the pattern of the air distribution and the related climate in the pig house vary according to the outside conditions.[18] The objectives of this paper are to examine the effectiveness of existing mechanical ventilation systems, relative to that of natural ventilation systems, on pig production in the field, to check the hypothesis that automatic controllers do not give an adequate air flow rate control through the building in the field and to study the need for a proportional ventilation control by steady-state analysis.

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Received 3 November 1983; accepted in revised form 14 February 1985

Paper presented at AG ENG 84, Cambridge, UK, 1–5 April 1984

0021-8634/86/010001 + 12 $03.00/0

Notation

C_1	specific heat of air, Wh/kg°C
H_v	sensible heat production of the animals, W
H_l	latent heat production of the animals, W
j	specific weight of air, kg/m^3
K	global heat transfer coefficient, W/m^2°C
$\dot{m}$	ventilation rate, m^3/s
$\dot{m}_{min}$	desired minimal ventilation rate, a controller set-point m^3/s
$\dot{m}_{max}$	maximal ventilation rate: installed capacity of the fan, m^3/s
P	proportional band of the ventilation curve, °C
$P = T_2 - T_1$	
Q	artificial heat supply, W
Q_{inst}	maximum capacity of the heating system, W
T_i	inside temperature, °C
T_o	outside temperature, °C
T_{opt}	optimum temperature, a controller variable, °C
T_1	inside temperature from which the controller will increase the ventilation rate above the minimum ventilation rate to cool the building using fresh air, °C
T_2	inside temperature at which the maximum ventilation capacity of the fan is used, °C
T_3	inside temperature from which the controller will put on the heating system to heat the building, °C
V_{min}	voltage to the fan corresponding to the minimum air flow $\dot{m}_{min}$, V
Ω	surface, (m^2)
$\sum \Omega . K$	sum of products of heat transport coefficient and surface, of walls, floor and roof, $W/°C$

$$\sum \Omega K = \Omega_{wall} * K_{wall} + \Omega_{roof} * K_{roof} + \Omega_{floor} * K_{floor}$$

$$a = \frac{\dot{m}_{max} - \dot{m}_{min}}{T_2 - T_1}$$

$$\beta = \dot{m}_{min} - a . T_1$$

2. Methods and materials

2.1. *Statistical analysis*

In Belgium there is a unique structure of contractual farming under the Belgian Farmers' Association (Belgische Boerenbond) which has led to the installation of identical pig houses throughout the country. Buildings that were installed within the same period of time were identical as regards design, dimensions, materials, construction, air inlet and outlet arrangements and wind baffles. This makes it possible to select a large number of identical buildings for statistical analysis. During its life, a building may be changed from one type of pig house to another; for instance, a naturally ventilated system may be converted to a mechanically ventilated one. Over several years, profound changes may take place; some farmers abandon pig farming, while others start new pig enterprises, some farmers leave contractual farming, others introduce new techniques. For these reasons, the fattening period was considered to be the experimental unit, because no changes occurred within this period and the all-in/all-out system was used. Field data on pigs fattened under contract were put at our disposal by the Belgian Farmers' Association. These data included information on feed conversion ratio, growth rate, mortality, duration of

Table 1

Comparison of natural and mechanical ventilation systems

	Natural ventilation system open ridge	*Mechanical ventilation system with exhaust fan*
Data set 1		
Number of fattening periods	334	553
Mortality, %	3·8 (SD = 0·23)	3·65 (SD = 0·21)
Data set 2 (heated buildings)		
Number of fattening periods	162	254
Feed conversion kg/kg	3·49 (SD = 0·12)	3·48 (SD = 0·12)
Mortality, %	3·45 (SD = 1·6)	3·60 (SD = 1·9)
Data set 3		
Number of fattening periods	143	157
Feed conversion, kg/kg	3·47 (SD = 0·118)	3·50 (SD = 0·14)
Weight gain, kg	78·2 (SD = 3·58)	77·5 (SD = 3·46)

No significant differences were found ($P < 0·05$) between natural and mechanical ventilation systems

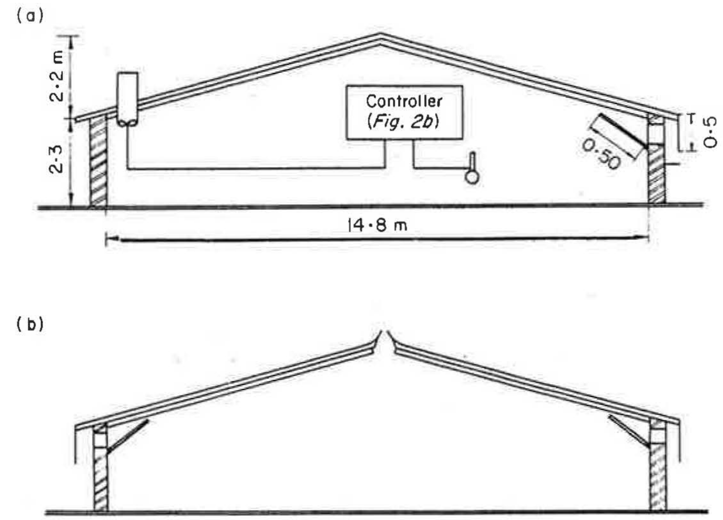

Fig. 1. (a) Mechanical ventilating system, exhaust fan and proportional controller. Length of house: 19 m. (b) Natural ventilating system, open ridge. Inlets on both side walls to permit ventilation from wall to wall when there is no buoyancy effect in summertime

fattening period, quality class of the meat produced and veterinary costs. Within the contractual farming organization, these data were used to calculate the margin awarded to the farmer and so accurate recording was required. The complete data set covered 6258 fattening periods collected on 450 houses throughout the Flemish region over the period 1969–1982. From these data, a first data set Data set 1, (Table 1) was made up of 137 comparable pig fattening units recorded between 1969 and 1980 and included 887 fattening periods. About 10% of the buildings were unheated.

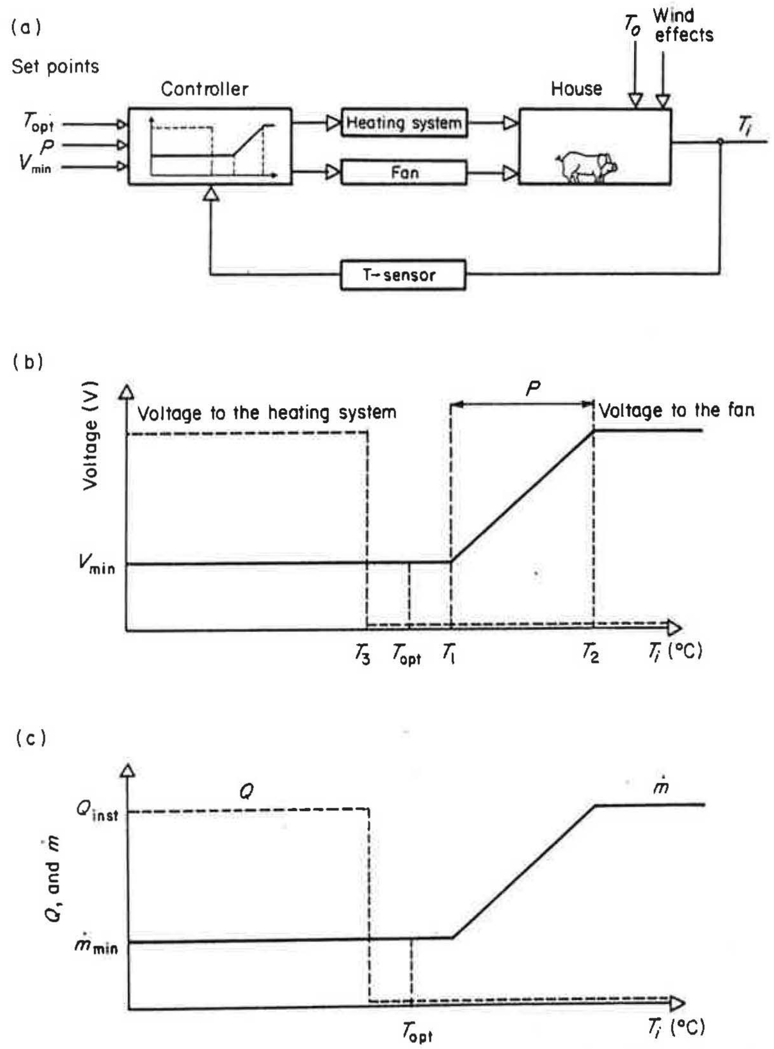

Fig. 2. (a) Controller and house relationships. (b) Controller characteristic with three different setpoints: T_{opt}, V_{min} and P. (c) Desired controller function for artificial heat supply (Q) and air flow rate ($\dot{m}$) in a livestock building

Because of possible improvements with respect to pig selection programmes, control equipment, management and feeding, only the data collected from 1980 onwards was considered for Data set 2 (Table 1). Data set 2 covers 416 fattening periods, all of them in heated buildings.

To obtain more information about the buildings in the analysis and to acquire more knowledge about the way the farmer operates the control equipment, we visited 300 pig houses from which we selected about 97 buildings of which 20% were unheated. They were visited four times during each fattening period over the years 1979–1982, which gave Data set 3 covering 300 fattening periods (Table 1). About 48% of the selected fattening periods had an open-ridge, natural ventilation system, while the rest had exhaust fans. The naturally ventilated buildings had air inlet vents and/or outlet vents that could be controlled by hand (*Fig. 1*). The propeller fan in the mechanically ventilated buildings was placed in a standard chimney in the roof and the speed was controlled by means of the control algorithm[19] shown in *Fig. 2*.

Table 2

Some general characteristics of the pig houses

	Mean	*SD*
Mean floor area enclosed by the walls (m^2)	284	131
Mean volume (m^3)	806	481
Number of animals	242	147
Pigs per m^2	1·27	0·236
Pen shape (length/width)	1·81	0·276
Slat area (proportion of the total pen floor)	0·40	0·177
Starting weight per animal (kg)	21·3	1·11
Final weight per animal (kg)	97·0	4·28
Feed conversion ratio	3·59	0·158
Growth rate *g/d*	571	34
Mortality (%)	3·66	0·163
Duration of fattening period (*d*)	133	7·79

Some general information about the pig houses is given in Table 2. Most pigs were Belgian Landrace and a sufficient number of animals was available to overcome possible genetic influence. All animals within the same period of time received the same commercial food. To eliminate as far as possible the influence of the individual farmer, only buildings of farmers with comparable good production results were chosen. All the buildings were visited four times during each fattening period, to assess the climatic conditions and the operation by the farmer. Statistical analysis was done by using skewness and kurtosis to test normality of distribution of each parameter and by using variance and covariance to test differences between means on a total of 639 fattening periods in naturally ventilated buildings and 964 fattening periods in mechanically ventilated buildings.[20,21]

2.2. *Laboratory tests*

To test the performance of the fan and controller, a laboratory installation was devised in which the important variables such as voltage, static pressure, air flow rate, could be varied and controlled. Voltage–temperature curves were measured for five of the most common types of controllers in Belgium. For this purpose, the controllers, connected to a fan under load, were tested with their temperature sensor in a temperature-controlled waterbath. The water temperature was changed very slowly relative to the time constant of the controller. Temperatures were increased and decreased to measure possible hysteresis effects. A series of 248 measurements was made for different values of the controller setpoints of optimum temperature, bandwidth and minimum voltage. In a second phase, the relationship was determined between voltage, static pressure and resultant air flow rate of the fan. This was measured in a standard installation used for testing fan performance.[22–24]

2.3. *Steady-state analysis*

The normal animal environmental control system attempts to regulate the inside temperature by varying the air flow rate (*Fig. 2*). A steady-state analysis can be used to analyse how the controller regulates the inside temperature by varying the air flow rate when the outside temperature is changing. The generally accepted energy balance equation to describe the heat balance of the building can be written[25] as

$$T_i = T_o + \frac{H_v + Q}{\dot{m}.j.c_1 + \sum \Omega.K}. \qquad \ldots (1)$$

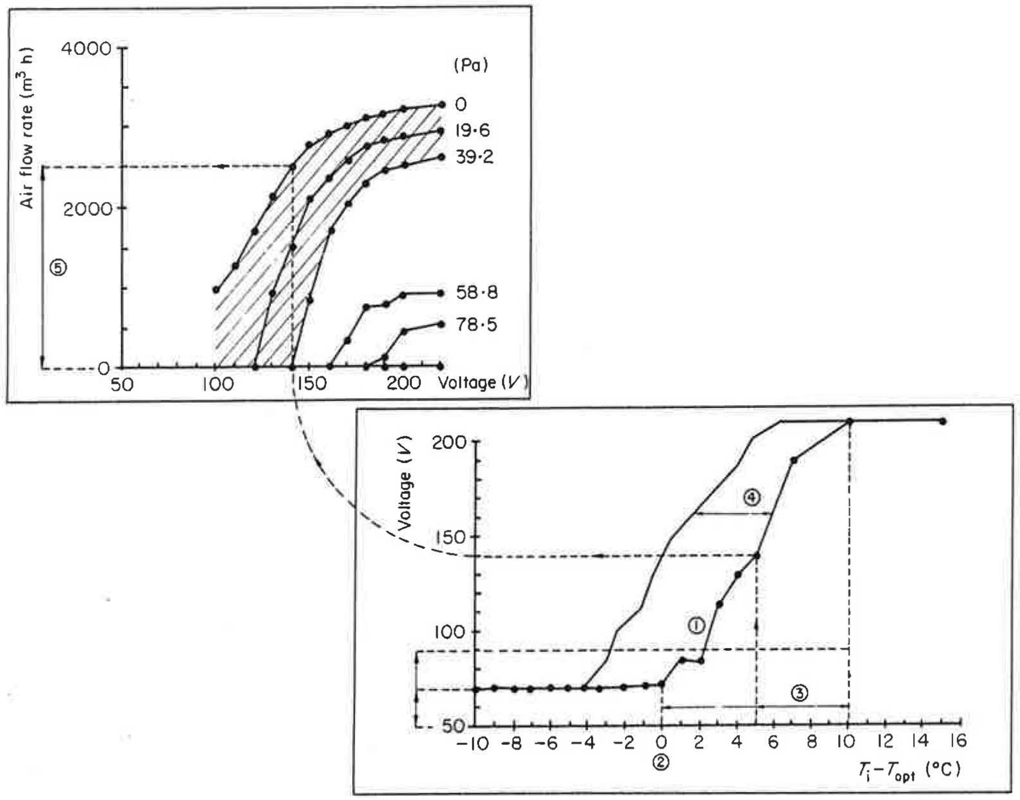

Fig. 3. Summary of the most important shortcomings of the usual combination of controller and fan. (Top) Fan characteristics; (Bottom) Controller performance. 1. Shape of the controller curve; 2. Position of the optimum temperature; 3. Stability of the proportional band; 4. Hysteresis; 5. Linkage of the controller line to the characteristic curve of the fan. ▨, *Working area with acceptable stability*

The controller (*Fig. 2*) can be represented as follows

$$\begin{array}{ll} T_i < T_1 & \dot{m} = \dot{m}_{min} \\ T_1 < T_i < T_2 & \dot{m} = a.T_i + \beta,\ Q = 0 \\ T_i > T_2 & \dot{m} = \dot{m}_{max},\ Q = 0 \end{array} \qquad \ldots(2)$$

A graphical solution can be found for this system with ventilating and heating curves in a similar manner to that presented by Cole *et al.*[14] for a controller without a heating curve. A mathematical solution can be found from Eqns (1) and (2), which gives the quadratic Eqn (3), of which only the positive solution is relevant.

$$H_v + Q = \frac{(\dot{m} - \beta)}{a} - T_o) \ . \ (\dot{m}.j.c_1 + \textstyle\sum \Omega.K) \qquad \ldots(3)$$

3. Results and discussion

The results of the statistical analysis are given in Table 1. It can be concluded that mechanical ventilation systems do not give significantly better mean production results from naturally ventilated buildings with an open ridge. Also, from the combined effects of heating, no heating, natural and mechanical ventilation on food conversion ratio, it can be concluded that there is no significance between natural and mechanical ventilation.[20,21] A fan can be considered to be a system in which the voltage to the fan is the input and the pressure to be overcome is the disturbing factor. These two variables will define the air flow rate which is the output of the system. Fan performance can be defined graphically in the form of fan characteristic curves;[26] they show the relationship between the voltage to the fan, the static pressure to be overcome and the resulting air flow rate. An axial propeller fan, as used in this application, has a rather small region (shown shaded) in which the stability is acceptable (*Fig. 3, top*). It will also be noticed that the air flow produced by the fan becomes very sensitive to pressure changes when the voltage to the fan is decreasing. *Fig. 3* (*bottom*) gives a summary, based on 248 empirical curves, of the most important shortcomings of the controller in relation to the theoretical curve (*Fig. 2b*). First, there is the shape of the ventilating controller curve, which is not linear and which can be very different from the ideal curve required. The second problem is that the setpoint of optimum temperature is not fixed relative to the voltage–temperature changes, its position in *Fig. 2b* can change in an unpredictable way; the optimum temperature can be near the maximum temperature of the bandwidth. The setpoint of bandwidth does not keep the set value when the setpoint of minimum voltage is changed. A mean hysteresis effect of 4 K was not exceptional, but this is unacceptable. The importance of the shape of the curve and the level of minimal voltage will be analysed in the steady-state analysis. The importance of the setpoint of bandwidth and of the hysteresis can be studied by using a non-linear dynamical analysis.[27]

The most important shortcoming appears when the voltage–temperature curve of the controller is linked to the characteristics of the fan. Because of the sensitivity of this system to pressure changes, a single measured inside temperature results in a variety of air flow rates (*Fig. 3*). For the most common type of fan, this spread of air flow rates can be 70% of the maximum range of air flow rate of the fan. In a building, air inlet baffles are used to reduce wind effects and to control air flow patterns, so the fan has to overcome a static pressure difference. Therefore, the extra pressure difference needed to counteract wind effects, will cause the fan to work outside its normal stable working region (*Fig. 3*).

It can be concluded that it is not possible for the farmer to use the setpoint of minimum voltage in a meaningful way. Because of the pressure factor he does not know the air flow rate corresponding to a setpoint of V_{min}. Even when there is a one-to-one relationship between the setpoint and air flow rate, a predetermined setpoint cannot cope with increasing wind pressure. This has long been considered an important reason for using an on-off controller rather than a proportional ventilation controller and may explain why most farmers in Belgium do not operate their control equipment efficiently. Similar reports have been published on farm experience in Britain and North America.[15]

The steady-state analysis permits us to calculate the inside temperature, the corresponding air flow rate and the heat supply as a result of the outside temperature, the controller action and the building heat losses. Applying this mathematical analysis to the practical problem, we may simplify it by assuming that the ventilation system operates at a constant differential pressure on compensates for changes of static pressure. For the two extreme limits of inside environmental conditions, piglets 20 kg, $T_{opt} = 23$°C and finishing pigs 100 kg, $T_{opt} = 16$°C, the inside temperature and corresponding heat supply and air flow rate have been calculated as a function of the outside temperature (*Fig. 4*). These curves are related to the frequency table of the mean outside temperature in Belgium. It can be concluded that, for most of the year, these environmental conditions can be achieved only when accurate control of the air flow rate is possible. There must be a minimum air flow rate for piglets and a proportional air flow rate is necessary for growing pigs to regulate the inside temperature.

The large influences of the air flow rate on the total (sensible and latent) energy losses is well known. In accordance with the calculation of *Fig. 4*, *Fig. 5* gives the energy losses resulting from the controller-building system as a function of outside temperature. *Fig. 5* shows that for most of the year, the proportional part of the control curve ($\dot{m} > \dot{m}_{min}$) is determining the energy losses.

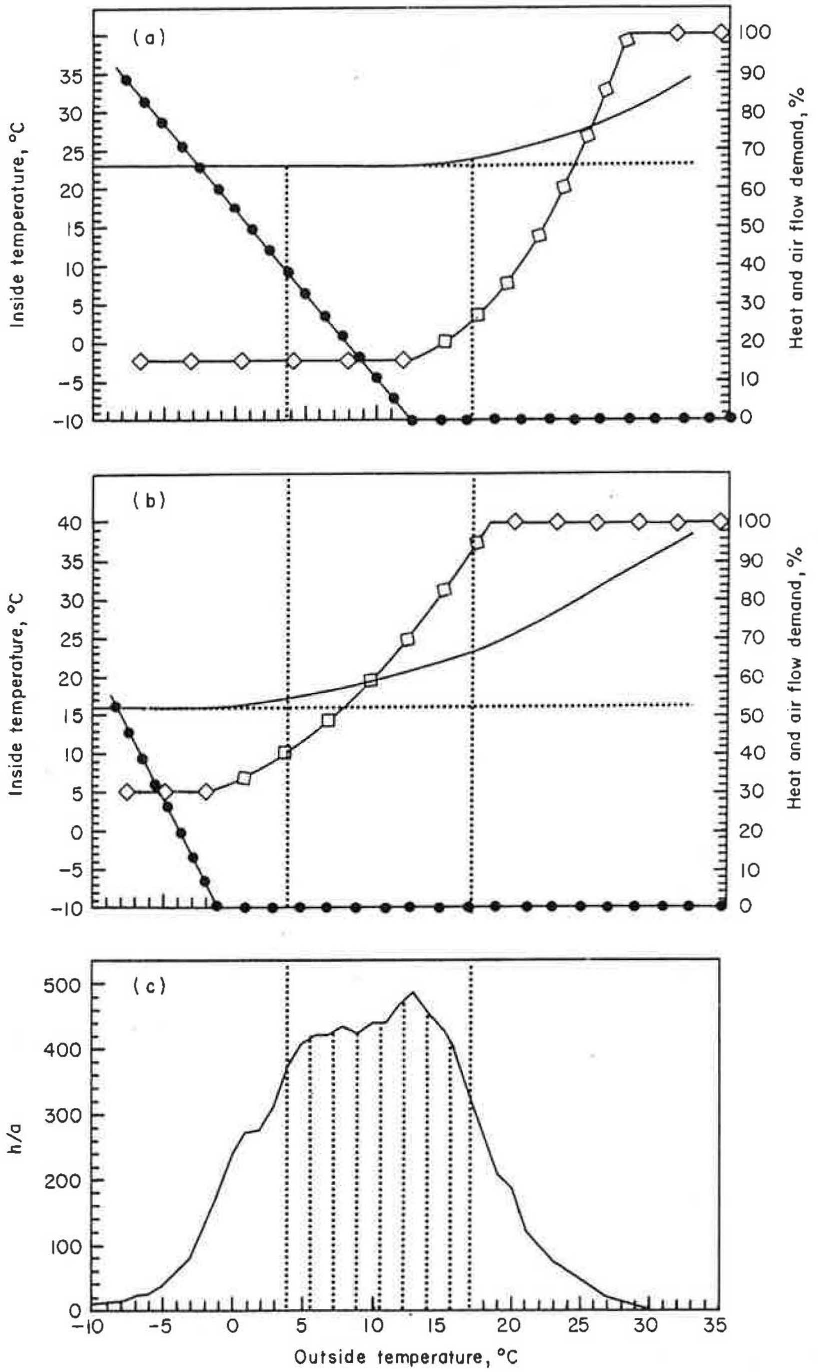

Fig. 4. Mathematical steady-state solution of a housing system showing inside temperature, corresponding heat required and air flow rate in relation to the outside temperature. (a) For beginning animals of 20 kg $T_1 = 23°C$, $T_2 = 30°C$, $T_3 = 23°C$ and $H_V = 55$ W; (b) for finishing pigs of 100 kg $T_1 = 16°C$, $T_2 = 24°C$, $T_3 = 16°C$ and $H_V = 150$ W; (c) frequency table of the mean outside temperature in Belgium. –●–, heat required; –◇–, air flow required

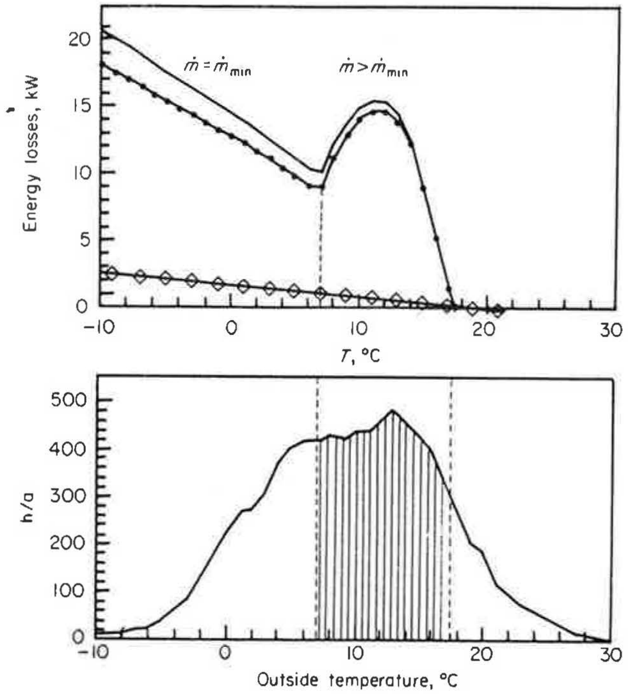

Fig. 5. Mathematical steady-state solution of a housing system (72 pigs, 60 kg/animal) showing the energy losses in relation to the outside temperature and the frequency of hours where the air flow rate $\dot{m} > \dot{m}_{min}$ and is determining energy losses and inside temperature. ——, total energy losses; –●–, ventilating losses; –◇–, wall and roof heat losses

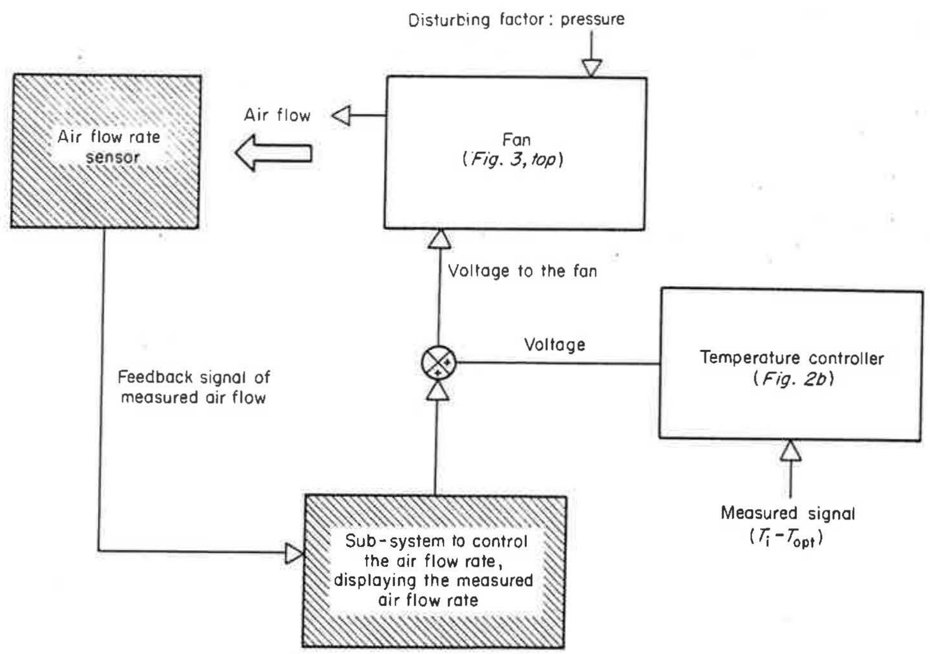

Fig. 6. Working principle of the new ventilation control system. □, usual controllers; ▧, extension of the new system

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Combine Speed Strategies in Cereal Harvesting. Part 2: Adjustment for Weather Variability

M. B. McGechan*; C. A. Glasbey†

Existing models of cereal harvesting have derived a common optimum combine speed for every harvesting day on a particular farm. This study is an assessment of the economic benefits of selecting a different speed for each day of the harvest, taking into account the history of previous weather. Both a simple simulation approach, and a dynamic–stochastic programming approach which incorporates a forecast of future work-days, have been developed.

Overall, the results showed small benefits from a strategy based on a selected daily speed compared with single constant speed operation, when averaged out over a number of years. However, substantial benefits were shown in the occasional very wet harvests, when combining could take place on only a small number of days, and in some other exceptional situations.

1. Introduction

Operational Research (OR) models of cereal harvesting, such as those developed by Audsley and Boyce[1] and by Philips and O'Callaghan,[2] determine the optimum values for combine size and speed for the crops and conditions on a particular farm. This two-part paper describes adaptations of the models to assess the value of adjusting the combine speed for changes in circumstances on the farm. Part 1[3] considered adjustments for the crop parameters (such as straw yield) in different harvest years, or for different crops, varieties or fields in the same year. Part 2 assesses the benefits of a daily adjustment of speed to allow for weather variations. The adjustment makes use of information about the weather history and the amount of crop remaining to be cut on each day throughout the harvest. This study indicates the potential value of a program which a farmer can run himself, on his own microcomputer, to recalculate the optimum combine speed daily as the harvest progresses.

Existing models include unvalidated equations for determining work-days from weather data. So far, in work with adaptations of these models,[3–9] the criterion suggested by Audsley and Boyce using daily rainfall data has been assumed. By comparing survey data on commercial combine working periods (McGechan[10]) with weather records, Glasbey and McGechan[11] developed a new criterion, which they considered to be an improvement on the arbitrary Audsley and Boyce criterion. In the current study, parallel assessments of benefits of a selected daily speed strategy were carried out using both Audsley and Boyce's and Glasbey and McGechan's criteria for determining work-days from weather. Since the effect of vatriations in other model parameters has already been examined thoroughly,[7,8] a single set of values was assumed here. Front end (i.e. shedding and cutter bar) losses were determined from the equations suggested by Audsley and Boyce; a farm with 200 ha of cereals with mean yield of both grain and straw 5 t/ha, and grain price £120/t, was assumed. As in Part 1, a range of alternative sizes of combine was assumed, each with a set of costs and values of the parameters of the exponential threshing loss equation suggested by Philips and O'Callaghan[2] (Part 1, Table 1).

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Received 20 February 1984; accepted in revised form 19 December 1984

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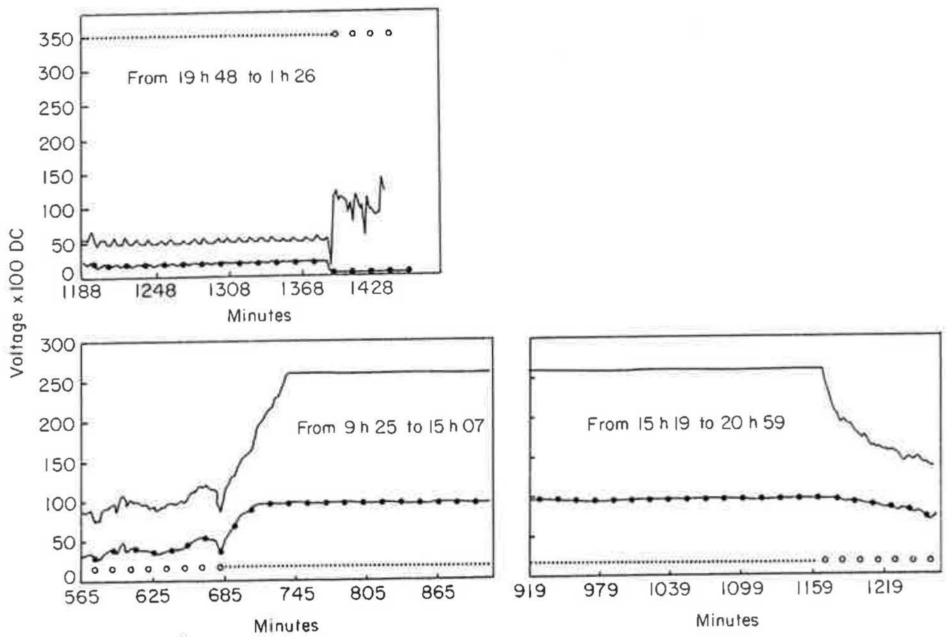

Fig. 7. Influence of the new air flow rate controller on air flow rate through a building. (a) When realizing a minimum air flow rate: measurement at Koksijde 14.6.82, inside temperature 23°C, outside temperature 13°C and windspeed 0·5–2·8 m/s; (b) when the fan has a given pressure to overcome: measurement at Koksijde 17.6.82, inside temperature 23°C, outside temperature 19°C and windspeed 1·5–4·8 m/s. ——, voltage to the fan; ●—●, air flow rate; . . . . , new controller is working; ○ ○ ○, usual controller is working

Calculation of the heat supply on yearly bases shows that the ventilation losses are 67% of the total sensible heat losses. As stated above, laboratory tests show that normal controllers have several technical shortcomings and do not permit adequate air flow control. On the other hand, it is important to have proportional control of air flow rate.

To solve the above problems, a new analogue system was developed. By use of improved electronic design, the new controller produces a voltage–temperature curve without the shortcomings illustrated in *Fig. 3 (bottom)* and this is shown in *Fig. 6*. Compared with earlier controllers, this unit not only provides a voltage to the fan as a function of the measured inside temperature but by using a feedback signal of measured air flow rate, the controller compensates for pressure changes by compensating the voltage to the fan. Thus, the spread of air flow rates corresponding to a measured inside temperature can be reduced to a more controlled air flow rate with higher stability. As a consequence of this compensating action of the controller, lower minimum air rates can be obtained. *Figure 7a* shows a field test of the new controller compared with the earlier controller. Because of the important influence of the ventilating losses on the yearly heating demand, the ability to achieve better control of minimum air flow rate saves energy. By using a steady-state calculation on a yearly basis, the annual energy saving is estimated as 8% of the total heating demand.

From the field test, it may also be noticed (*Fig. 7b*) that the new controller guarantees a high air flow rate when pressure changes cause the air flow rate to fall with earlier controllers. Measured air flow rate and temperatures are continuously displayed and this encourages significant use of the setpoints of minimum ventilation rate (as composed with minimum voltage), optimum temperature and bandwidth because of the automatic reactions of the controller when pressure changes through wind effects and changing air inlet vents. The controller has an ergonomic

layout explaining its working principle and displaying information to the operator, so that it may be readily understood and used by the farmer.

The expected effect on production results (mortality, feed conversion, growth rate) is difficult to estimate. However, if a reduction in feed conversion ratio of only 0·5% could be achieved, then the pay-back period for the controller would be better than the pay-back period for thermal insulation. The measurement of the air flow rate by the controller gives new possibilities for controlling the air inlet vents. At the present time, enough of these new controllers have been installed in commercial pig houses to set up a new experiment to monitor performance for subsequent statistical analysis.

4. Conclusions

1. Field data have shown that normal mechanical exhaust ventilating systems do not give better production results than natural ventilating systems.
2. Laboratory experiments with the two most important components of mechanical ventilating systems yielded the voltage–temperature curve of the controller and the air flow rate–voltage–pressure characteristics of the fan. These results show that the combination of these characteristics cannot give effective control of ventilation in practice.
3. The importance of having proportional air flow rate control on indoor temperature and on energy use has been shown by steady-state analysis.
4. Based on the measurements and on a theoretical analysis, a new analogue controller for air flow rate and temperature in livestock buildings has been developed. This is now undergoing field evaluation.

Acknowledgements

The authors thank the Instituut voor Wetenschappelijk Onderzoek in Nijverheid en Landbouw and the Belgische Boerenbond-A.V.V.

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