CONTROL OF FINAL STAGE OF HAY DRYING BY COLD AIR*

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The final stage of wilted forage by cold air has been widely spread in agricultural primary production recently. Advantages of this technology, e.g. decrease of weather effect on forage quality and reduction of losses due to rub off, are often denied in practice by human factor by unsuitable way of operation. The experiment described below verified ranking of the control system based on local microprocessor regulator into the technology of final stage of forage drying by cold air. The paper includes also knowledge obtained by practical verification.

final stage of wilted forage; local microprocessor regulator; program

INTRODUCTION

In evaluation of technical background of agricultural primary production, it may be concluded that energy-demanding agricultural systems in the majority of cases operate with insufficient control super-system. Efforts of some producers to automatize the whole process of final stage of drying using well-equipped electronic system regulators brings the complexity of the whole system, demandingness for the familiarity with operation and particularly high buying costs (Haš, 1987; Gugenham, 1990). The proposed solution of selected problem using local microprocessor regulator, marked by relative constructional simplicity, undemanding connection, simple operation, high reliability as well as relatively low price may be that solution which will fulfil as technical, as investment demands of a user for providing solely selected functions and simultaneous fulfilment of requirements for the control quality.

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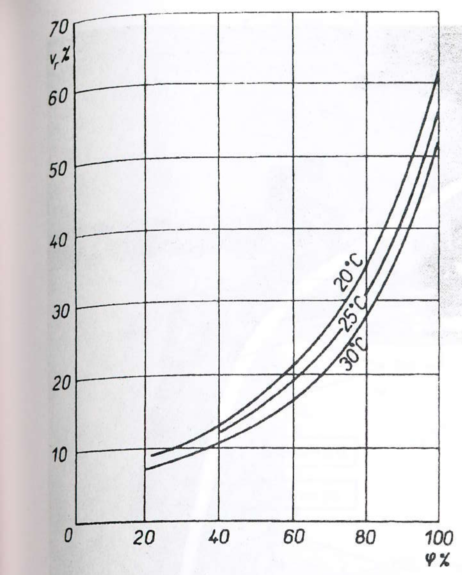
A typical technology in agriculture, marked by decision regime, these are also prerequisites for installation of regulator for final stage of forage drying. Free water comprised in forage is evaporating during drying similarly to water from free table into air. Evaporation of water bound in cell walls is already more difficult and chemically bound water cannot be released from dried material without its decomposition. Researches carried out in the past were concentrated on knowledge and analysis of drying process (Sladký et al., 1985; Sladký, Jirásek, 1990).

A prerequisite for application of large-scale production technology during hay drying is the use of complex mechanization which may work during harvest only with wilted forage. The subsequent final stage of drying by cold air on the slatted floor of hayloft is now most spread technology. A low drying capacity of external air continuously motivates searching for suitable technical means for its heating up. Suitable means are above all solar systems using solar energy (Sladký, Jirásek, 1989). In the 1980s the possibilities of the use of heat pumps (Sladký, Bradna, 1981; Sladký et al., 1984) were tested. Practical applications face too high investment costs. At the present possibilities of combustion of wood waste for heating of drying air (Sladký, Jirásek, 1990) are tested. Supplement of classic technology of the final stage of forage drying by cold air should be the step which follows after the full usage of drying capacities of external air. Practical materialization may have a form of the below described control system.

The proposed regulation of the drying process consists in the optimization of switching of drying fans. Their activity is derived from parameters of drying medium. From this viewpoint control algorithms for hayloft in traditional modification are in principle identical with those for haylofts with a device for heating up of air, that is the most often with a solar jacket. As in classic modification of hayloft the time suitable for drying by external air is limited to about 5 hours a day (Sladký, Bradna, 1984), optimization of the running of fans is in this case particularly very important.

Regulation systems of drying fans were developed in the past from simple analog models whose activity was derived from sensing of hay temperature and relative humidity of imbibed air. In principle, the function of these systems is based on the principle of switching of fans when a relative humidity of air incoming into forage is lower compared with the equilibrium humidity of air and forage (Fig. 1). This is given by known physical dependences (Sladký et al., 1985). More advanced systems are based on microprocessor regulators. The trials with sensing of air humidity outgoing from hay (Sladký et al., 1985) were carried out. One of the technical solutions of this problem is the device for measuring the temperature and air humidity in a building (Hutla et al., 1985) where air outgoing from forage was led by

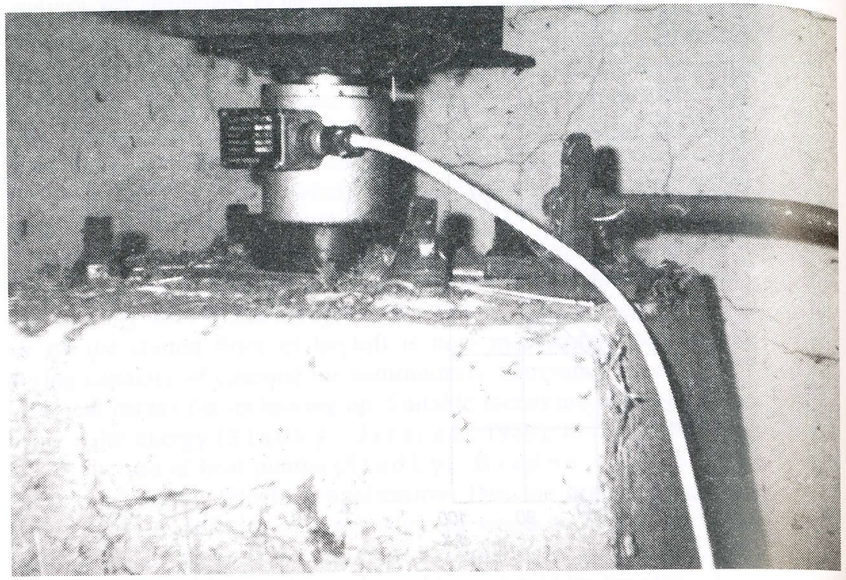


1. Diagram of equilibrium hay moisture content

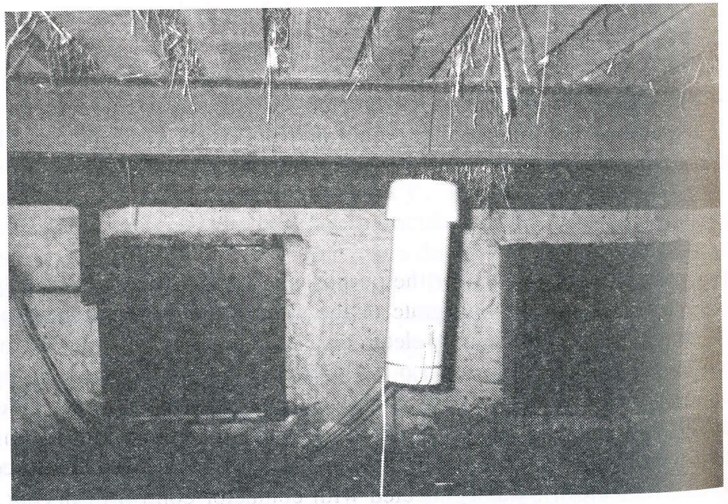
two air channels into double psychrometer. Drying was performed in time when absolute air humidity of outgoing air from dried material was higher than that of ingoing air.

MATERIAL AND METHOD

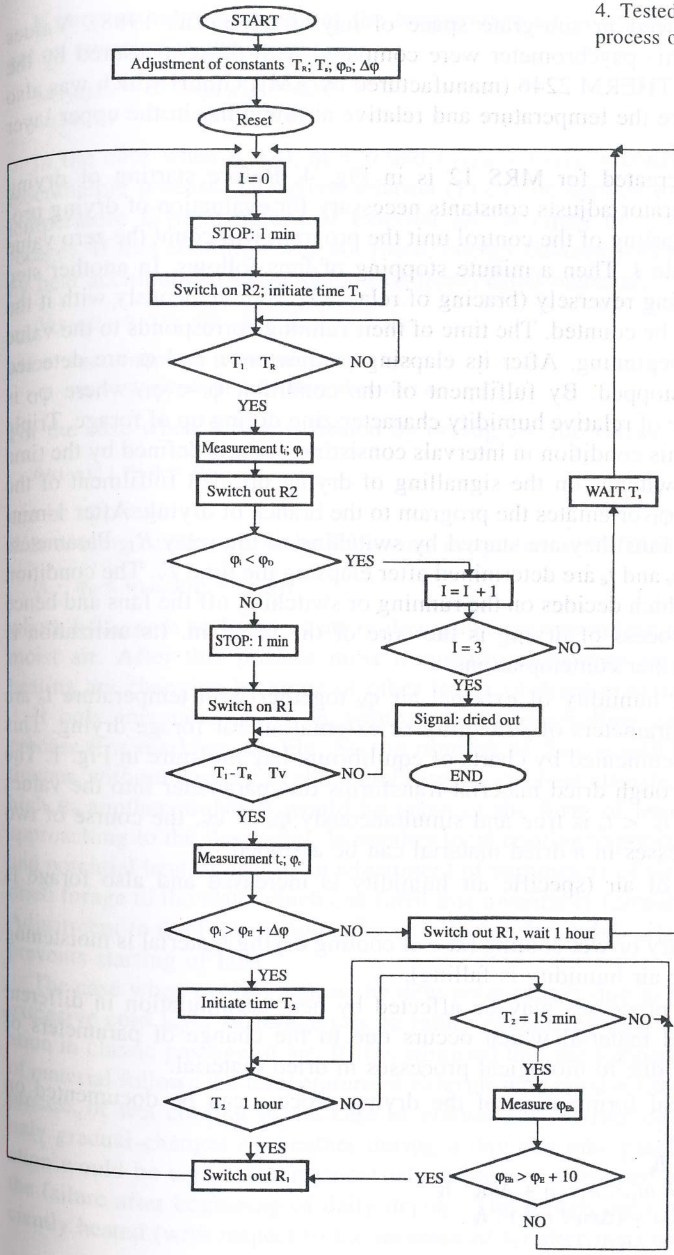
Experimental working site for the purposes of testing was modified by the following adjustments. Drying grate of the size 18 x 6 m was placed on 12 power sensors M 20 (Fig. 2) with electronic evaluating device JVA-01 (manufactured by RUKOV Rumburk s.r.o.). The recording obtained gave information on changes of weight, that is also on changes of moisture of dried material. Local microprocessor regulator, physically represented by microprocessor unit MRS 12 with supplementary relay module (manufactured by A.P.O. ELMOS v.o.s.), was connected with contactor control of drying fans and through the converter type 9206 (manufactured by interNET s.r.o.) with combined sensor to measure the temperature and relative air humidity (Fig. 3)



2. Position of grate in hayloft on pressure-weight element



3. Position of combined sensor for measuring of temperature and relative air humidity in the space under the grate



4. Tested algorithm of the process of forage drying

which was placed in sub-grate space of hayloft (Hutla, 1988). Values measured by this psychrometer were compared with those measured by the control device THERM 2246 (manufactured by AMR GmbH which was also used to measure the temperature and relative air humidity in the upper layer of dried matter.

Algorithm created for MRS 12 is in Fig. 4. Before starting of drying regime the operator adjusts constants necessary for evaluation of drying process. After restarting of the control unit the program will count the zero value into the variable I. Then a minute stopping of fans follows. In another step fans start running reversely (bracing of relay R2). Simultaneously with it the time T_l start to be counted. The time of their running corresponds to the value T_R set at the beginning. After its elapsing parameters t_i and φ_i are detected and fans are stopped. By fulfilment of the condition $\varphi_i < \varphi_D$ where φ_D is definable value of relative humidity characterizing drying up of forage. Triple fulfilment of this condition in intervals consisting of parts defined by the time of testing T_S switches on the signalling of drying up. Not fulfilment of the condition $\varphi_i < \varphi_D$ orientates the program to the branch of drying. After 1-minute run-out of fans they are started by switching of the relay R_1. Parameters of drying air φ_e and t_e are determined after elapsing the time T_v. The condition $\varphi_i > \varphi_e + \Delta\varphi$ which decides on the running or switching off the fans and hence also on the process of drying is the core of the program. Its utilization is allowed by further contemplations.

Relative air humidity of external air φ_e together with temperature t_e are determining parameters of suitability of external air for forage drying. This assertion is documented by charts of equilibrium hay moisture in Fig. 1. The air passage through dried material transforms this parameter into the values φ_e^* and t_e^*. If $t_e^* < t_e$ is true and simultaneously $\varphi_e^* > \varphi_e$, the course of two different processes in a dried material can be assumed:

1. moistening of air (specific air humidity is increased and also forage is drying up).
2. Process of dry or wet cooling (at wet cooling drying material is moistening and specific air humidity is falling).

Both these processes may be affected by heat accumulation in different layers of dried material which occurs due to the change of parameters of external air or due to biological processes in dried material.

Mathematical formulation of the drying process can be documented on energy balance:

$$I_{vv2} = I_{vv1} + I_k$$
$$m_{sv} \,.\, i_{(1+x)2} = m_{sv} \,.\, i_{(1+x)1} + \Delta m_k \,.\, i_k$$
$$i_{(1+x)2} = i_{(1+x)1} + (\Delta m_k / m_{sv}) \,.\, i_k$$
$$\Delta i_{(1+x)2,1} = \Delta x \,.\, i_k$$

If zero enthalpy of liquid at the temperature $t_0 = 0$ °C is considered, we get an equation in the form:

$$\Delta i_{(1+x)2,1} = \Delta x \,.\, c_{pk} \,.\, (t_k - t_0)$$
$$\Delta i_{(1+x)2,1} = \Delta x \,.\, c_{pk} \,.\, t_k = q_k \qquad (1)$$

In the case when $t_k = 0$, $q_k = 0$ and $i_{(1+x)1} = i_{(1+x)2} =$ constant. This is an isoenthalpic process. The given relation (1) can be applied to the case when temperature t_e (temperature of external air) is equal to t_p (temperature of forage). If this condition was not filled, energy balance will be also affected by heat accumulated into (withdrawn from) dried material.

$$\Delta i_{(1+x)2,1} = \Delta x \,.\, c_{pk} \,.\, t_k \pm q_p = q_k \pm q_p \qquad (2)$$

where: $+q_p$ corresponds to the action when $t_p > t_e$
$-q_p$ corresponds to the action when $t_p < t_e$

For the case when forage is heated by drying air, the variant

$$\Delta i_{(1+x)2,1} = q_k - q_p$$

can be applied.

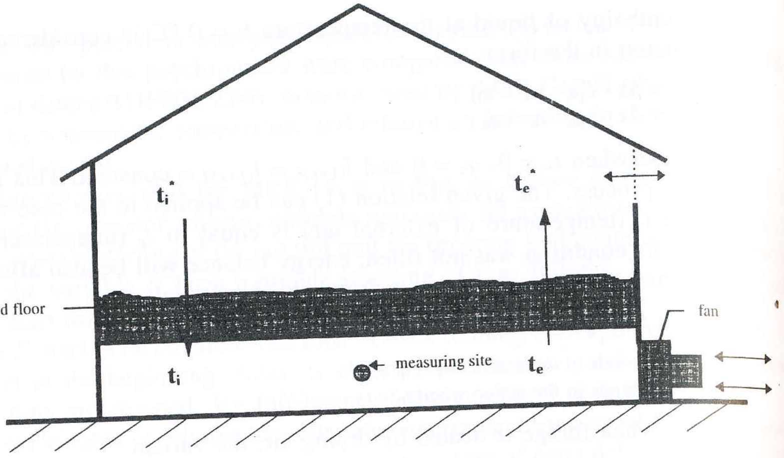
Wet cooling occurs when the following inequality is fulfilled:

$$q_k - q_p < i_{(1+x)RB1} - i_{(1+x)1}$$

where $i_{(1+x)RB1}$ is enthalpy of air in dew point corresponding to the state 1 of moist air. After this process most frequently measuring air parameters by heating are changing by some of other layers of dried material.

If only inequality $\varphi_e^* > \varphi_e$ was used as a controlling condition of the process (for marking see Fig. 5), the running of fans would be almost continuous without respect to the suitability of external climate for drying. At high φ_e another moisture would be taken in the form of liquid, that is also approaching to the dew point. In another local cooling vapours are condensed and potential heating results in adjustment of parameters of air outgoing from dried forage to the state which can fulfil this unsuitably formulated condition. Adjustment to the formulation $\varphi_e^* > \varphi_e + \Delta\varphi$' and suitably selected value $\Delta\varphi$' prevents starting of fans.

The case when cooling below the dew point occurs due to its contact with extensive cold layer of forage can be rather considered as a breakdown situation in classic passage of air. If it is admitted that the temperature of a layer of material follows the temperature of exterior with certain time delay, classic process of wet cooling in the case of continuous running cannot occur and only gradual changes of weather during a day can take place. Critical situation would be e.g. in the moment when fans were stopped working due to the failure after beginning of daily drying. The forage layer may be insufficiently heated (with respect to the increase of t_e) after their repeated starting



5. Diagram of measuring in the hayloft

and in relation to drying air it can behave like cooler with a surface temperature lower than is the temperature of dew point. The problem of finding the value φ_e^* forces to search for similar condition. As mentioned above, the value φ_i can be detected sufficiently simply, that is relative air humidity outgoing from dried forage after starting the reverse motion of fans. Simple substitution of φ_e^* for the value φ_i is not possible because φ_i is finding during the process only similar to the finding of φ_e^*. Both these processes differ particularly by parameters of entering air. In reverse run of fans air enters the layer of forage whose temperature is usually higher than t_e and relative humidity, on the contrary, is lower than the value φ_e. This is caused by warm air inside the building. In a sunny day its jacket has a function of solar collector of low efficiency. In enumeration of differences reverse arrangement of layers of drying forage with respect to the direction of drying air flow cannot be omitted. It follows from the mentioned facts that in relation $\varphi_e^* > \varphi_e + \Delta\varphi'$ in substitution of measured variable φ_e for φ_i, $\Delta\varphi'$ has to be modified to $\Delta\varphi$. This substitution leads to the relation $\varphi_i > \varphi_e + \Delta\varphi$ which is a part of the flow chart.

Measurements carried out (for example see Tab. I) verified the value $\varphi_i < \varphi_e^*$ in all cases. Decrease in $\Delta\varphi'$ to the lower value $\Delta\varphi$ follows from this inequality.

When the condition $\varphi_i > \varphi_e + \Delta\varphi$ was not fulfilled, drying is stopped and after an hour of putting out of operation, the whole decision process is put into operation again. In the opposite case the forage is aerated an hour. During

I. Measured values of relative humidity of hay

Date	Relative humidity of material v_{ri}						
	v_{r01} (%)	v_{r02} (%)	v_{r03} (%)	v_{r04} (%)	v_{r05} (%)	v_{r06} (%)	$\overline{v}_{ri}$ (%)
27. 9. 1995	30.89	33.66	27.62	29.88	28.94	–	30.20
28. 9. 1995	32.06	35.87	31.33	35.48	32.06	–	33.36
2. 10. 1995	25.01	25.45	26.73	24.06	24.08	–	25.08
9. 10. 1995	15.75	11.85	18.41	17.12	11.62	17.21	15.33

II. Parameters of air in hayloft during drying on 9 October 1995

Measurement No.	Time (h)	Drying							
		t_e (°C)	φ_e (%)	t_e^* (°C)	φ_e^* (%)	t_1^* (°C)	φ_i^* (%)	t_i (°C)	φ_i (%)
1	11:00	19.3	68.9	17.8	82.0	23.0	56.0	16.8	79.4
2	13:00	20.4	58.3	18.3	74.0	24.0	51.5	19.2	71.2
3	15:00	19.8	67.0	19.4	71.4	20.7	61.4	20.5	65.9

this time interval parameters of drying air are tested in 15-minute intervals. In the case of their abrupt significant change, drying is broken up and the whole decision process is started again.

It has to be emphasized that the process which was denoted in direct running of fans as a breakdown, can be in reverse run of fans recorded very frequently, particularly at the beginning of a day of drying. This situation occurs as a result of the function of hayloft jacket in principle identical with that of the above-mentioned solar collector. The given results can be documented by examples from Tab. II.

RESULTS

In the proper course of testing of the automatic control process, in accordance with the technological requirement the forage moisture should be reduced using the air flow from the value of average initial relative humidity $v_{ri} = 30.2\%$ to the value for storage (below 20%). The data on average relative humidity of forage v_{ri} was obtained by averaging of the values of relative humidity found in the laboratory of n samples taken at random during storage.

The moisture content of material during drying was identified by three control samplings. Samples for laboratory evaluation were taken from different layers of stored material. The values found, including average values, are in Tab. I.

Recorded increase of average relative humidity from 27 September 1995 to 28 September 1995 was caused by forced aeration under unfavourable weather conditions. In the time of running time constants of the program were verified. Subsequent decrease in v_{ri} was obtained during automatic control of the process.

Based on parameters φ_i, φ_i^*, φ_e, φ_e^*, t_e, t_e^*, t_i, t_i^* obtained from testing of the process of drying controlled after the given algorithm, thermal processes inside the dried material can be considered. The results of measurements on 9 October 1995 can serve as an example. The diagram of measuring sites is in Fig. 5.

DISCUSSION

The possibility of the control of drying process by local microprocessor regulator on the basis of detecting the parameters of incoming and outgoing air was tested in one section of large-capacity hayloft. Realized technical solution allows the application for four hayloft sections. The regulator, including the used sensor for sensing of relative air humidity during testing, showed trouble-free running.

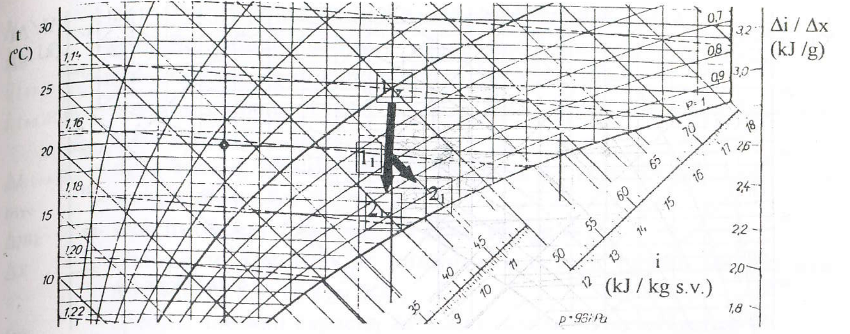
The system of control applied in operating experiment in minimization of interventions of attendance provided the reduction in relative humidity of approximately 500 mm layer of forage from the value corresponding to the wilted state to parameters suitable for storage. Its testing was not performed with greater layer of dried material with respect to the advanced season. This will require corresponding change of set constants (prolongation of time of aeration).

Data from Tab. II can be used for the following reflections:

Measurement No. 1: (Fig. 6)

$1_{1z} - 2_{1z}$: process characterizing reverse passage of air before the first cycle of drying.

Resultant recording is corresponding to wet cooling of air. It cannot be omitted that aeration by reverse motion of fans occurred after their stopping working. Cooling of surface and lower layer of forage and heating of wet layer by passing biological processes can be assumed. Under these prerequisites the combination of dry and wet cooling with heating and drying cannot be eliminated.



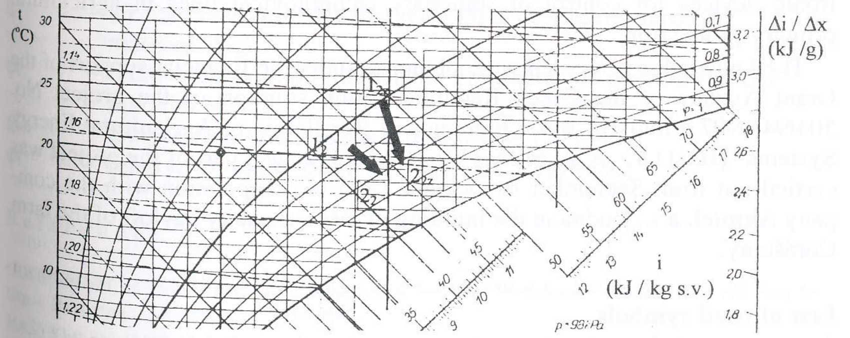
6. Measurement No. 1 in *i-x* diagram of moist air

$1_1 - 2_1$: process characteristic for moistening of air by water.

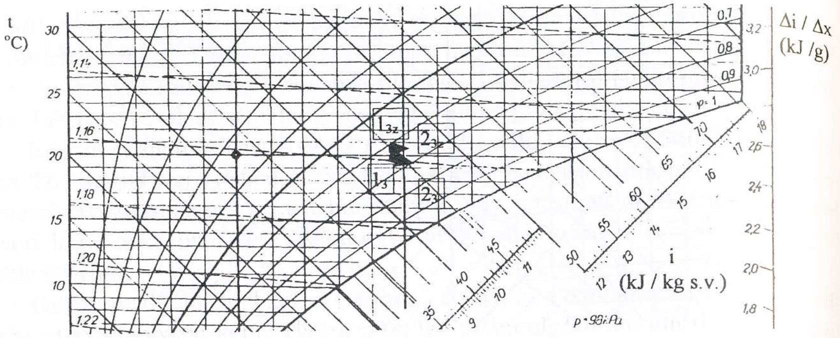
Measurement No. 2: (Fig. 7)

$1_{2z} - 2_{2z}$: the process in which the heat withdrawn from ingoing air used, except evaporation of liquid from forage, also for heating of dried material. The condition $q_k - q_p < i_{(1+x)RB1} - i_{(1+x)1}$ was not fulfilled, therefore forage was not moistened.

$1_2 - 2_2$: the process identical with $1_1 - 2_1$.



7. Measurement No. 2 in *i-x* diagram of moist air



8. Measurement No. 3 in *i-x* diagram of most air

Measurement No. 3: (Fig. 8)

$1_{3z} - 2_{3z}$: the process whose resulting form cannot be described only as moistening of air by water. It consists of simultaneous heating of drying air from previously heated forage and its moistening by water. The variant $i_{(1+x)2,1} = \Delta x \cdot c_{pk} \cdot t_k + q_p = q_k + q_p$ of the relation (2) is applied.

$1_3 - 2_3$: the process identical with $1_{3z} - 2_{3z}$.

An example of recordings of processing which took place within a single measuring day confirm the justification to use decision conditions in algorithm of the drying process. The proposed algorithm can hardly be materialized without using microelectronics. Application of local microprocessor regulator in the given experiment proved the usability of these simple electronic devices for control of stationary technological lines in agricultural primary production.

The knowledge presented were obtained under the financial support of the Grant Agency of the Czech Republic within solution of the project No. 504/94/0907 „Study of Basic Elements of Regulation of Agricultural Energy Systems“ (Hutla, Adamovský, 1996). Practical part of the project was carried out from September to October 1995 in co-operation with the company Agrotel, a.s., Rudná in the building of large-capacity hayloft of the farm Chrášťany.

List of used symbols

I_{vv1} – enthalpy of moist air before passing through dried forage (J)
I_{vv2} – enthalpy of moist air after passing through dried forage (J)

I_k – enthalpy of liquid (water) evaporated from forage (J)
i_k – specific enthalpy of liquid evaporated from forage (J.kg^{-1} *s.v.*)
$i_{(1+x)n}$ – specific enthalpy of moist air in the state *n* (J.kg^{-1} *s.v.*)
$i_{(1+x)RBn}$ – specific enthalpy of moist air in the dew point derived from the state *n* (J.kg^{-1} *s.v.*)
$\Delta i_{(1+x)2,1}$ – difference of specific enthalpies (1 + *x*)kg of moist air (J.kg^{-1} *s.v.*)
m_{sv} – weight of dry air (kg)
Δm_k – weight of liquid evaporated from forage (kg)
Δx – change in specific air humidity accepted during its passage through forage (g.kg^{-1} *s.v.*)
c_{pk} – specific thermal capacity of water (under constant pressure) (J.kg^{-1}.K^{-1})
t_0 – temperature (°C)
t_k – temperature of liquid = temperature of dried material (°C)
t_p – temperature of dried material (°C)
q_p – specific heat deposited into or withdrawn from dried forage in the case when $t_p \neq t_e$ (J.kg^{-1})
q_k – specific heat in liquid before evaporation (J.kg^{-1})
$\Delta\varphi$ – difference of relative air humidities (%)
v_r – relative humidity of dried forage

Drying:

t_e – external temperature (°C)
φ_e – relative humidity of external air
t_e^* – air temperature after its passing through dried material (°C)
φ_e^* – relative air humidity after its passing through dried material (%)

Testing (reverse motion of fans):

t_i – air temperature under the grate after its passing through material (°C)
φ_i – relative air humidity under the grate after its passing through material (%)
t_i^* – temperature of air ingoing into forage (°C)
φ_i^* – relative humidity of air ingoing into forage (%)

References

GUGENHAM, E.: Modernste Gartenbautechnik bei Karl Wittmann Schechen. Zierpfl. Bau Int. Gtn – Bautechn., *30*, 1990 (9): 382–385.

HAŠ, S. et al.: Ověření možností využití jednočipových automatik (Verification of possibilities of the use of single-chip automatic machines). [Research Report.] Praha, VÚZT 1987. 59 p.

HUTLA, P.: Čidla pro systémy řízení prostředí (Chips for the systems of environment control). [Research Report.] Praha, VÚZT 1988. 33 p.

HUTLA, P. – ADAMOVSKÝ, R. et al.: Studium základních prvků regulace zemědělských energetických systémů (The study of basic elements of regulation of agricultural energy systems). [Research Report.] Praha, VÚZT 1996. 125 p.

HUTLA, P. – HAVEL, J. – LONSKÝ, J. – PAVLICA, I.: Zařízení pro zjišťování teploty a vlhkosti vzduchu v objektu (Device for measuring the temperature and air humidity in the building). AO 259 716. 9. 12. 1985.

SLADKÝ, V. – BRADNA, J.: Sluneční seník Zduchovice (Solar hayloft Zduchovice). [Research Report.] Praha, VÚZT 1981. 49 p.

SLADKÝ, V. – JIRÁSEK, P.: Dosoušení sena s využitím netradičních zdrojů energie (Drying out of hay using non-traditional sources of energy). [Research Report.] Praha, VÚZT 1990. 50 p.

SLADKÝ, V. – JIRÁSEK, P.: Intenzifikace a standardizace sušení sena (Intensification and standardization of hay drying). [Research Report.] Praha, VÚZT 1990. 55 p.

SLADKÝ, V. – BRADNA, J. – ANDERT, D.: Výzkum dosoušení zavadlé píce pomocí tepelného čerpadla (Research of drying out of wilted forage using the heat pump). [Research Report.] Praha, VÚZT 1984. 55 p.

SLADKÝ, V. et al.: Manipulační a automatizační zařízení pro halové seníky (Manipulation and automatic equipment for indoor haylofts). [Research Report.] Praha, VÚZT 1985. 72 p.

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Řízení dosoušení sena studeným vzduchem.

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V práci je prezentován experiment, jehož cílem bylo ověření možnosti řízení procesu sušení zavadlé píce studeným vzduchem lokálním mikroprocesorovým regulátorem.

Pro účely experimentu byla stavba seníku doplněna montáží tlakových váhových elementů napojených na vyhodnocovací zařízení pod rošt seníku (obr. 2). Tato úprava umožnila průběžné sledování úbytku hmotnosti sušeného materiálu.

Funkci použitého programu pro regulátor MRS 12 nastiňuje vývojový diagram 4. Teoretické odůvodnění rozhodovacích kroků uvádí vztahy (1) a (2), na které navazuje komentář k celému programu. Podkladem pro sestavení programu byl také diagram rovnovážné vlhkosti sena (obr. 1).

Samotný pokus používá jako vstupní informaci pro rozhodovací procesy relativní vlhkost venkovního vzduchu φ_e a netradičně i relativní vlhkost vzduchu vystupujícího ze sušené hmoty při reverzním chodu ventilátorů φ_i. Při zjišťování posledně jmenované veličiny se jedná o prostup sušicího proudu vzduchu v opačném smyslu než při klasickém provětrávání. Spouštění ventilátorů v tomto režimu, jak ukazují časové konstanty ve vývojovém diagramu, je časově omezené na dobu zjišťování potřebných vstupních signálů pro proces automatického řízení. Za výhodu tohoto uspořádání lze považovat možnost snímání různých vstupních signálů jedním senzorem, který je umístěn v podroštovém prostoru (obr. 3 a 5).

Pro úvahy o termodynamických procesech probíhajících ve vrstvě sušeného materiálu byly zjišťovány veličiny φ_i, φ_i^*, φ_e, φ_e^*, t_e, t_e^*, t_i, t_i^*. Místa jejich zjišťování jsou zobrazena na obr. 5. Ze vzorku takto získaných dat (tab. II) vychází úvahy uvedené v části Diskuse, včetně jejich grafické podoby na obr. 6, 7 a 8.

Funkčnost řídícího procesu dokládá snížení relativní vlhkosti sušeného materiálu z 30,2 % na hodnotu vhodnou pro skladování. Výsledky jejího laboratorního zjišťování jsou uvedeny v tab. I.

dosoušení zavadlé píce; lokální mikroprocesorový regulátor; program

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