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PROBLEMS OF ENERGY SAVINGS IN DRYING OF FOOD AND AGRICULTURAL PRODUCTS

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An attempt was made to indicate the existing possibilities of reducing the amount of energy consumed in drying. A standard test procedure for evaluating the energy efficiency of dryers is presented.

INTRODUCTION

Drying, one of the most important stages of technological processes in many branches of industry and agriculture, is of great significance to the national economy.

In energy consumption the food processing industry ranks fourth behind metal, chemical and petroleum refining industries [1]. One of the conclusions reached by many investigations is that drying of solids is probably the most energy intensive of the unit operations. During the last decade, the rise of energy prices was accompanied by more stringent legislation on pollution, working conditions and safety. To meet these requirements and optimize energy consumption new ideas in drying methods and dryer design are required. Considering the problems encounteed in drying (Table 1) it is obvious that this is not an easy task.

The combined effect of increased fuel costs and the limited availability of fuels, particularly of the most versatile ones, was the appearance of a large number of studies aimed at energy conservation in the utilization of dryers. General principles of energy conservation have been outlined in some comprehensive monographs 2-4 but their application to the drying process was considered only briefly. Computerized literature survey revealed several hundred references to energy conservation. Perhaps 200 to 300 of these articles are related to industrial dryers [5, 6].

In food industry and agriculture drying plays a very important role as a method of food preservation. According to data publishe ed by FAO,

Table 1. Scope of problems encountered in drying

Mode of heating	— conduction, convection, dielectric, radiation
Energy sources	— coal, oil, natural gas, electric energy, waste materials, solar energy
Pressure	— high vacuum (freeze drying), vacuum, atmospheric pressure, high pressure
Scale	— from 10 kg/h to > 100 tonnes/h
Type of apparatus	— about 100 types of identified dryers are used in the world at present
What does the process control?	— boundary layer, boundary layer with inner diffusion, inner diffusion
Size and shape of material	— powder, granules, foil, film, plate
Material properties	— non-porous, capillary-porous, hygroscopic; solution, syrup, mud, gel, extruded material, crystalline, fabric, cardboard, fibre
Initial moisture content	— from almost dry (< 1% kg/kg dry material) to full saturation (> 100% kg/kg dry material)
Thermal resistance of the material	— from the material very sensitive to temperature (< 30°C) to thermally resistant materials (> 200°C)
Value of the product	— from bulk chemical products (< $ 70 per ton of dry material) to pharmaceutical products (> $ 150 000 per ton)

about 20% of foodstuffs are spoiled because no proper methods of storage are available [7]. Among physical methods of storage, drying is important as one of the methods of thermal treatment of foodstuffs [8].

GENERAL CONSIDERATION. ENERGY USAGE FOR DRYING IN VARIOUS INDUSTRIES

The energy used for drying in six British industrial sectors in 1978 was estimated to be $128 \cdot 10^9$ MJ or 4.85 million tonnes of coal equivalent ($26 \cdot 10^9$ MJ = 1 m.t.c.e.) which represents almost 12% of their total energy consumption. The overall pattern of energy usage for drying is presented in Table 2 [9]. We can see from the table that over 25% of

Table 2. Overall pattern of energy usage for drying

Subsector	10^9 MJ/yr		% due to drying
	drying	total	
Food and agriculture	35	286	12
Chemicals	23	390	6
Textiles	7	128	5
Paper	45	137	33
Ceramic and building materials	14	127	11
Timber	4	35	11
Total	128	1103	12

energy used in drying processes in the selected sectors of British Industry mentioned above goes to drying of food and agricultural products.

Table 3 summarizes the data for the food and agricultural subsectors. The major users of drying energy include the producers of animal feedstuffs, barley and other grains, baking and confectionery products, dairy products, breakfast cereals, grass and malt. It was assumed that 90% of the drying energy consumed in 1978 was accounted for by the listed products.

Table 3. Energy use data: food and agricultural products

Food/Agricultural Product	1978 Production		Drying		Total Energy	
	quantity	units	unit 10^3 MJ	annual 10^9 MJ/y	unit 10^3 MJ	annual 10^9 MJ/y
1	2	3	4	5	6	7
Alginate	7,600	t	11.30	0.09	16.14	0.13
Animal and marine oils/fats	432,000	t	0.12	0.05	5.02	2.17
Animal feedstuffs	10,964,000	t	0.20	2.19	0.69	7.57
Barley (drying)	10,700,000	t	0.57	6.13	0.57	6.13
Biscuits	645,000	t	3.62	2.34	7.43	4.79
Bread and flour confectionery	2,260,000	t	1.11	2.51	3.60	8.14
Breakfast cereals	229,000	t	5.02	1.15	8.80	2.02
Brewing	67.4×10^8	l	—	—		
Brewers spent grain	10,000	t	2.20	0.02	2.98×10^{-3}	20.09
Canned/bottled fruit	59,000	t	—	—		
Canned vegetables	847,00	t	—	—	5.30	4.80
Coffee (instant and soluble)	10,000	t	27.5	0.28	85.00	0.85
Confectionery (chocolate)	424,000	t	—	—	8.59	7.11
Confectionery (sugar)	404,000	t	—	—		
Crumb	26,000	t	2.00	0.05	2.00	0.05
Dehydrated fruit and vegetables	30,000	t	11.60	0.35	14.90	0.45
Distilled spirits	245×10^6	pg	—	—		
Distillers dark grains	160,000	t	2.25	0.36	0.146	35.77
Dairy industry						
liquid milk processing	8.2×10^9	l	—	—		
milk powder — skim	272,000	t	8.22	2.40		
— full cream	20,000	t				
— whey	28,000	t	14.00	0.39	1.65×10^{-3}	22.35
butter	162,000	t	—	—		
cheese	216,000	t	—	—		
condensed milk	159,000	t	—	—		
Fish meal	80,000	t	2.00	0.16	5.00	0.40
Frozen fruit and vegetables	435,000	t	—	—	2.10	0.91
Frozen fish, meat and poultry	640,000	t	—	—	2.90	1.86

ctd. Table 3.

1	2	3	4	5	6	7
Grain (drying) other than barley	6,100,000	t	0.57	3.48	0.57	3.48
Grass drying	170,000	t	12.65	2.15	12.65	2.15
Hops	10,300	t	26.40	0.27	26.40	0.27
Ice cream	292,000	t	—	—	3.70	1.08
Jam, marmalade and jelly	213,000	t	—	—	2.75	0.59
Malt	1,400,000	t	3.20	4.50	3.43	4.80
Margarine and compound fats	499,0	t	—	—	4.85	2.42
Pasta	23,000	t	2.28	0.05	3.48	0.08
Poultry manure	50,000	t	2.00	0.05	1.00	0.05
Rusk	56,000	t	2.00	0.11	2.00	0.11
Seed oils	408,000	t	2.02	0.82	4.30	1.75
Sugar — from raw cane sugar	1,400,000	t	—	—	4.80	6.72
— from beet	984,000	t	—	—	12.71	12.51
Sugar beet residue	700,000	t	0.74	0.52	0.74	0.52
Wet corn milling						
glucose	540,000	t				
maize starch	146,000	t	1.00}	0.94	3.88	3.63
maize gluten	250,000	t				
Wheat milling (for flour)	5,306,000	t	—	—	0.58	3.08
				31.36		168.83

denotes agricultural activity
AAbbreviations: t = tonne l = litre pg = proof gallon

The estimated total energy used for drying in the United States amounts to about $1600 \cdot 10^9$ MJ/yr [6]. A comprehensive study of fuel utilization and energy conservation for the six biggest US energy-consuming industrial groups: chemicals, primary metals, petroleum, paper, stone/clay/concrete/glass and food with an account of energy use in particular unit operations (including drying) is given by Reding et al. [10]. The authors claim that in the short term, use of a variety of conservation measures should reduce the annual fuel use in the six industrial sectors by about 17% of total energy consumption.

Baker and Reay [9] summarize the potential energy savings in the UK in Table 4. The figures quoted are estimates of savings which would accrue if the technical problems associated with development were overcome and the development implemented today wherever it is expected to be technically feasible. As we can see in Table 4, the most promising technological options for energy conservation in drying are:

1) heat recovery from dryer exhaust (other than heat pump),
2) optimization of dryer design and operation.

In both these cases, a relatively large energy-saving potential is combined with a "high" penetration rating.

The results of a comprehensive survey of industrial dryers for solids [6] show that the thermal efficiency (defined as a relation of energy re-

Table 4. Potential energy savings

Development	Potential energy savings		Penetration rating*)
	10^9 MJ/yr	% total	
Heat recovery from dryer exhaust (other than heat pump)	18.9	15	high
Heat pumps (closed cycle)	8.9	6	medium
Vapour compression	26.2	20	low
Better instrumentation and control	4.3	3	medium/high
Optimization of dryer design and operation	11.0	9	high
Improved dewatering of feedstock	5.3	4	high

*) Penetration rating — a guess of the degree of penetration of the potential market for that development which will eventually be achieved.

quired for moisture evaporation to total energy supplied to dryer) of the 17 types of dryers considered ranges from 20% for the tower continuous direct (convective) dryer to about 90% for some types of indirect (contact) dryers (cylinder, rotary, agitated pan dryers). The weighed average annual energy requirement for industrial solid dryers is presented in Table 5.

The analysis of the above table shows that five types of dryers: flash, cylinder (indirect), tower, rotary (continuous direct and indirect and batch indirect vacuum) and fluidized bed account for about 99% of the total energy consumption of the 17 dryer types considered. This conclusion, although based on approximate data and only from the USA's industry, can be considered to be a very good pointer as to which type of dryers must be tackled in order to achieve large overall energy savings from drying processes.

Several methods of energy savings in drying process can be applied. Nevertheless, a general problem arises: how to standardize the assessments of performance for drying equipment, based on rates of moisture removal and energy requirements, since first cost and throughput information alone is inadequate for the selection and proper utilization of a drying system. In performing a drying test, it is necessary to specify certain test conditions in order to adequately assess the dryer performance.

At the present state-of-the-art of drying theory and practice, and bearing in mind the very wide variety of drying materials and types of equipment (cf. Tab. 1) it is not possible to propose a generalized method for a standardized determination of dryer efficiency. Nevertheless, this idea should be considered for further research in drying. It seems feasible to select the most important (by energy consumption) dryer types and by choosing appropriate material suitable for drying in these dryers some standard conditions at which a particular dryer should be tested can be specified. It is imperative that the conditions under which the efficiency is to be determined (or has been determined) be specified. Deyers are usually rated for throughput capacity only. In rare cases the energy efficiency is listed. A buyer frequently has difficulty interpreting the capacity and energy efficiency figures supplied by dryer manufacturers due to incompleteness of the data provided and the lack of standards for rating dryer capacity and energy performance.

Some proposals to standardize the procedure for rating dryer capacity and energy efficiency can be found in some publications concerned with grain drying. Bakker-Arkema et al. [11-13] have proposed a standard index — the Dryer Performance Evaluation Index (DPEI). The DPEI is defined as the total energy required by a dryer to remove 1 lb of moisture from the grain during drying under a set of specified conditions.

In order to make valid comparisons between dryers possible, experimental and simulated data on each dryer need to be available.

Table 5. Weighed average annual energy requirements and drying efficiency for industrial solid dryers

	Energy Requirement 10^9 MJ/yr	Efficiency %
Direct continuous		
Tower	137±32	20-40
Flash	528±211	50-75
Sheeting	2.8	50-90
Conveyor	1.9	40-60
Rotary	66	40-70
Spray	9.5	50
Tunnel	1	35-40
Fluidised ned	23	40-80
Batch		
Tray	1	85
Indirect continuous		
Drum	2.4	85
Rotary	53	75-90
Cylinder	127±53	90-92
Batch		
Agitated pan	1	90
Vacuum Rotary	11	up to 70
Vacuum Tray	1	—
Infra-red	1	30-60
Dielectric	1	60
Total	1261.10⁹ MJ/yr	

It is proposed that each dryer be tested experimentally under conditions approximating a set of standard conditions. For corn these standard conditions are tabulated and the data to be determined for a dryer performance evaluation is listed [12].

The effect of non-standardized operating conditions on the capacity and energy efficiency can be assessed with the use of tables generated by computer simulation.

Due to the fact that exhaustive experimental testing of every dryer model would be extremely expensive, a simulation technique based on a representation of a drying process (or a dryer) by a series of mathematical equations was developed [13-16]. A test procedure for rating the capacity and the energy efficiency of dryers has been proposed [12]. This procedure was intended for rating the performance of grain dryers but it can be applied with equal success to other dryer types or drying methods.

EXAMPLES OF ENERGY SAVINGS

Several drying variables can be manipulated to improve energy efficiency of a dryer. Some exemplary methods of energy savings in food processing and agriculture will be presented in this section.

Many cereal grains, nuts and some fruit crops are stabilized for long term storage through dehydration. Modern drying methods usually utilize heated, forced air to achieve rapid drying. The energy use of these systems is high. For some crops the amount of energy used for drying exceeds all other energy inputs [17]. In the future these drying techniques may prove to be too energy-intensive and will be abandoned in favour of methods which require less energy.

The energy use characteristic and energy conservation techniques were studied for prune and walnut dehydration by Thompson [17, 18]. The general areas where energy can be saved in all types of agricultural drying can be summarized as follows:

— improved maintenance including adjustment and cleaning of burners and sealing air leaks,
— insulation of dehydrator,
— recirculation of drying air,
— preventing overdrying (moisture content control),
— increasing product throughput,
— use of heat exchangers,
— reducing air flow rate.

Not all of these areas can be successfully modified in every operation. All dehydration facilities can utilize some of these techniques to reduce energy consumption. In some instances, different drying methods can also be utilized to reduce energy costs. Energy saving methods for walnut dehydration are presented in Table 6.

Flink [19] presents an analysis of energy requirements for air drying, drum drying and freeze drying of food. An analysis of energy streams out of the drying processes showed that significant energy content was lost in all three processes. In air drying, this was in the outlet air stream and convection heat loss from the dryer walls. In drum dryng, it was in the heating stream condensate outlet. In freeze drying it was in heat rejected to the environement from the vacuum pumps and refrigeration system condensers.

Table 6. Energy savings methods for walnut dehydration

	Savings, %
Improved burner design and operation	10
Insulation of dehydrator	3-4
Recirculation of drying air	25
Preventing overdrying	25-33
Reducing air flow rate	25

The effect of changes of the various process variables (initial concentration, initial air temperature, heating medium discharge temperature, two-stage operation, operation at sub-atmospheric pressure, insulation against thermal losses) on energy efficiency was also presented.

Energy requirement for liquid food concentration is discussed by Schwartzberg [20]. Liquid food is concentrated to reduce energy consumption during subsequent drying and to otherwise facilitate such drying; to induce crystallization; to reduce the weight and volume of products and thereby reduce packaging, transportation and storage costs; to reduce water activity so as to enhance storage stability; to recover by-products or remove pollutants from waste streams; and to induce desired texture and flavour changes. The estimated energy used in carrying out such concentration totals more than 4.8% of the energy used in processing of food in the USA ($62.2 \cdot 10^9$ MJ/yr). The author claims that the energy efficiency of most existing liquid food concentration systems could be advantageously upgraded. To maximize the economic advantages of such upgrading, techniques should be developed for retrofitting multieffect evaporator systems so as to increase their energy efficiency.

The use of combined reverse osmosis and multiple-effect evaporator systems should be actively investigated for diluted non-fouling, or preclassified liquid foodstuffs, intermediates and food processing wastes, such as clarified stillage, whey clarified corn-steep liquor, broths, clarified stick water, and potato-starch-plant discharge waters.

A regenerated desiccant (lithium chloride) crop drying concept is proposed by Ko and Merrifield [21] (Fig. 1). The concept is technically feasible and has the capability to achieve a drying efficiency of approximately twice that of a conventional crop drying system. When using a fossil fuel energy source, energy savings can be approximately 40 to 50%. With solar energy input, the total fossil fuel savings can be 70 to 90%.

Fuel savings of 20% in the drying of cereals using natural gas as a drying agent instead of hot air have been reported by Strehl [22]. According to Bakker Arkema [23] in the last decade, the minimizing of energy requirements has been one of the main criteria for dryer designers in grain drying. Among the techniques employed are

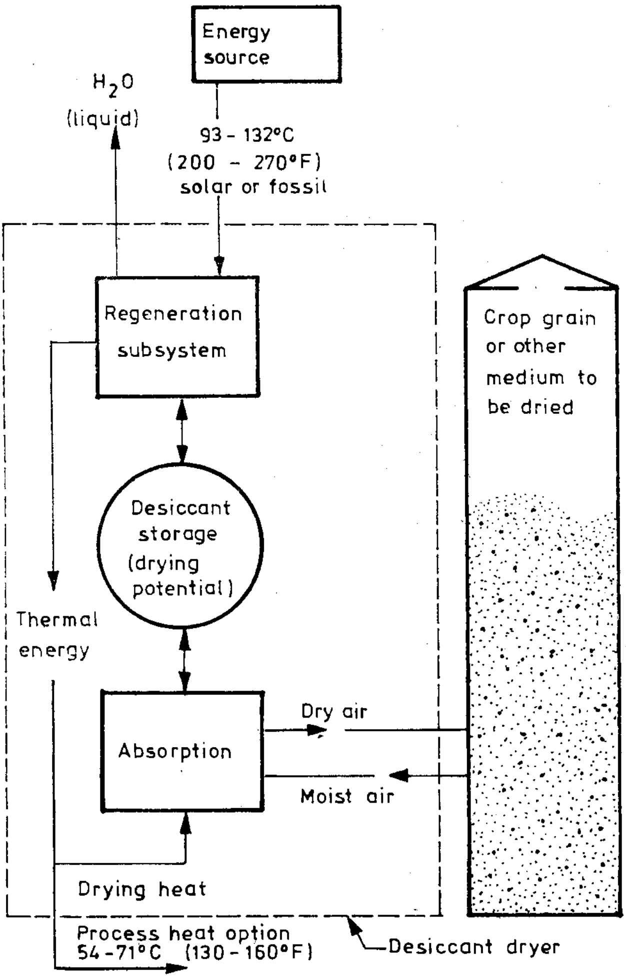

Fig. 1. Schematic of regenerated dessicant dryer concept

— air recirculation,
— grain pre-heating,
— dryer staging,
— grain tempering,
— dryer control.

The author presents various possibilities of energy savings by application of these techniques. For instance, a proper control strategy and microprocessor controller appear capable of saving 5-30% in energy use compared with a non-automatic control system.

The United States of America produced over 200 million tonnes of maize in 1982 of which about 75% was artificially dryed. The specific energy consumption of conventional high-temperature grain dryers is 4 to 7 MJ/kg of water evaporated. Installation of heat recovery equipment decreases this value to within the 3-5 MJ/kg range [24].

In France, the cost of drying is about 10% of the maize price. Lasseran [25] claims that specific energy consumption of already existing commercial dryers may be lowered from 5-6.5 MJ/kg to 2.7-3.35 MJ/kg of water evaporated thanks to a combination of various techniques. Apart from that the fossil fuel may be replaced by crop residues. Wheat or barley straw is now successfully burnt in air heaters of on-farm dryers. Also, in-bin solar drying is an alternative for maize harvested below a moisture content of 25% (wet basis).

Utilization of one three-stage concurrent flow dryer instead of two

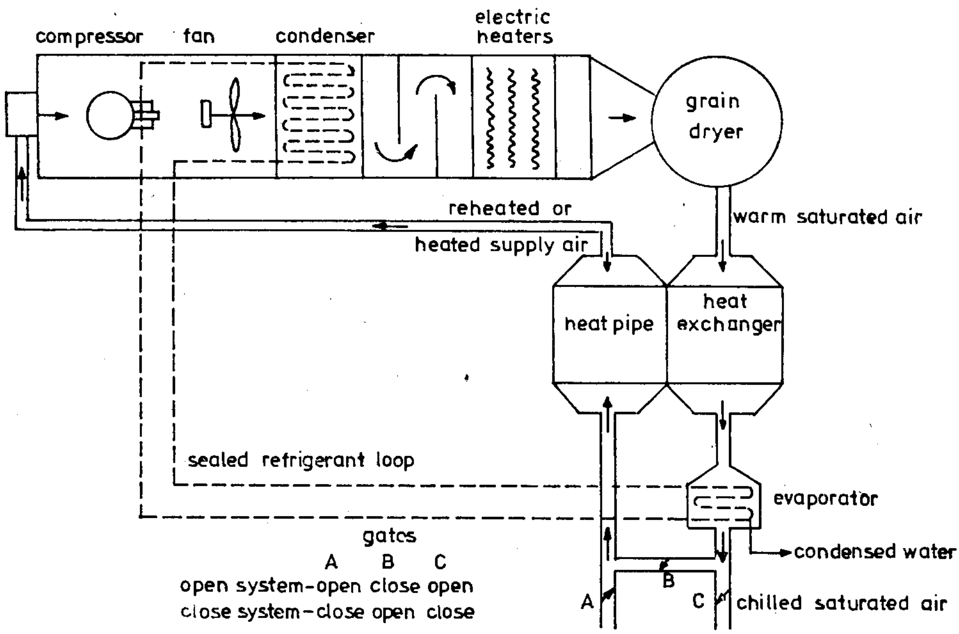

Fig. 2. Grain dryer with heat pump

rotary dryers in a commercial rice parboiling plant resulted in 34% savings in fuel energy and a significantly higher quality of the final product [26].

Lai and Foster [27] used a heat pipe heat exchanger and a heat pump in a variety of configurations to recover heat from and reduce the energy requirements of a grain dryer. Figure 2 shows the system layout. The authors reported that in comparison to normal dryer operation, a 42-56% decrease in the energy input required per unit mass of moisture removed was obtained when using both the heat pipe and heat pump.

Also a variety of optimization techniques may be used when studying grain drying. The objective function used in optimization varies depending on the specific interest of the program. It may include also energy costs. Thompson [28] presented a graphic comparison of energy use vs grain flow for a wide range of operation conditions. The performance characteristics are presented by the way of example in Fig. 3.

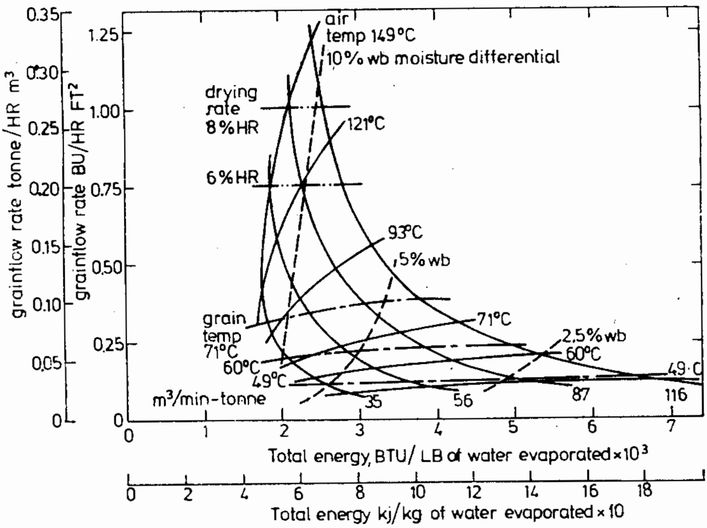

Fig. 3. Performance characteristics of a cross-flow dryer

Drying by means of radio frequency and microwave heating (dielectric heating) is under active development [29-31]. The use of these techniques in the falling drying rate period can save energy and improve efficiency of the overall drying process.

Wolf et al. [32] reports a new freeze-drying process under atmospheric pressure which appears two or three times less expensive than the classical freeze drying under vacuum.

A considerable proportion of the energy consumed in drying processes (often up to 50%) is associated with overdesign, poor capacity, turn-down characteristics and non-steady state operation. Better control techniques and understanding of process dynamics are needed.

Until recently the control of industrial dryers was generally regarded as being of secondary importance. Consequently, many of the dryers in operation today have still only rudimentary controls. Among the many benefits that can result from the efficient control of dryers may be increased fuel economy and improved efficiency of associated processes.

Although humidity control certainly saves energy, it only partially compensates for one of the most important criteria of dryed product quality, namely moisture content. There is usually a stiff price to pay for exceeding the upper moisture limit, such as spilage in the case of food products or possible rejection of batches in the case of chemicals [33] Fig. 4. The average moisture content is therefore kept low enough to prevent the occasional peaks from exceeding the upper limit. If the variation could be reduced, the average moisture content could be raised. In addition by clear profit, energy is saved by eliminating unnecessary evaporation.

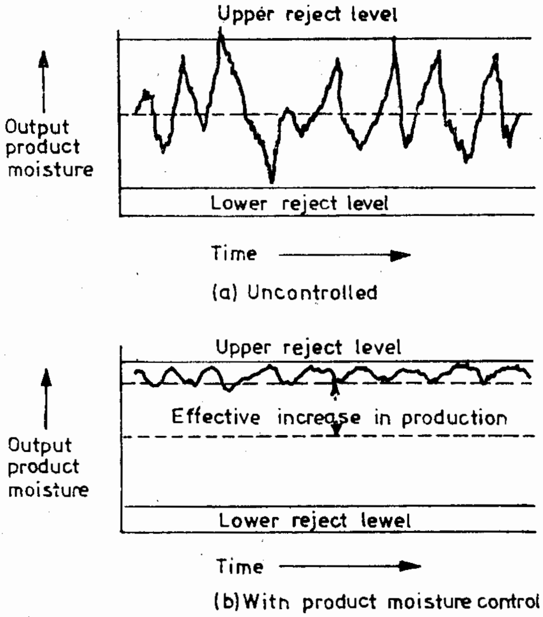

Fig. 4. The effective increase of production attainable by automatic product moisture control

A precise control of moisture content and heat recovery in milk powder production enabled the specific energy consumption of a spray dryer for whole milk powder to be reduced [34].

Generally we can state that improved energy efficiency can be obtained by most continuous flow dryers with improved dryer control. Recent developments of microprocessors should lead to the design of better dryer control systems.

In a comprehensive study of food materials drying Bruin and Luyben [35] stressed that energy analysis of drying processes has been getting more and more attention and considered suggestion for ways of energy savings.

CONCLUSIONS

Some general conclusions can be drawn from the reviewed and analysed literature:

— Significant potential energy savings in drying offered by different technological options were presented.

— Large energy savings can be achieved by improving the efficiency of some dryer types which consume most of the energy used in drying.

— Dryer costs and throughput information is inadequate for the selection of drying systems.

— Standard test procedures for evaluating the energy efficiency of dryers should be agreed upon. Proposition for standardization of energy efficiency based on simulation techniques can be taken from the literature.

— Various options have been presented for reducing the amount of energy consumed in drying processes.

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PROBLEMY OSZCZĘDNOŚCI ENERGII
W SUSZENIU PRODUKTÓW SPOŻYWCZYCH I ROLNICZYCH

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S t r e s z c z e n i e

Artykuł przedstawia zagadnienie oszczędności energii w suszarnictwie. Spośród operacji jednostkowych, stosowanych w przemyśle przetwórczym, suszenie jest praw-

dopodobnie najważniejsze, ponieważ jest ono wspólne dla wszystkich działów przetwórstwa. Suszenie jest często uznawane za etap końcowy w procesach przemysłowych, chociaż nierzadko stosuje się je bezpośrednio w przetwórstwie surowców lub materiałów pośrednich.

Wielu autorów dochodzi do wniosku, że suszenie jest prawdopodobnie najbardziej energochłonną operacją jednostkową. Wzrost cen energii i potrzeba optymalizacji zużycia energii wymagają nowego spojrzenia na metody suszenia i konstrukcje suszarek.

W artykule starano się naświetlić możliwości obniżenia zużycia energii w szerokim zakresie operacji suszarniczych. Tam, gdzie to było możliwe podano przybliżone wskaźniki oszczędności energii uzyskiwane dla danej metody.

Przedstawiono także standardowe procedury testowe do oceny sprawności energetycznej suszarek, oparte na technikach symulacyjnych. Na podstawie analizy cytowanej literatury sformułowano kilka wniosków uogólniających.