International Meeting on Computer Science and Information Technology

microCAD'98

UM ITTC

Miskolc-Egyetemváros, February 24-26,1998

microCAD '98

International Computer Science Conference

February 25-26, 1998

MISKOLCI EGYETEM 1735

J: GÉP- ÉS SZERKEZETTERVEZÉS

Section J: Machine and Structure Design

OPTIMIZATION OF THE OPERATION OF SUGAR-DRYING EQUIPMENT

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The closing technological steps of the sugar-making process are the decreasement of the moisture and temperature of the outgoing sugar from spin-dryer. These steps are made in the Roto-Louvre type cylinder-dryer. The aims of drying and cooling are to decrease the moisture and temperature of the sugar to be stored for a middle length of time in silos. Drying-cooling is made using warm and cools air. The operation of dryer and the processes of the science of heat have been described in [1]. In this paper we would like to show a procedure, how to optimize the operation of the drying equipment due to minimize the energy used for it. The processes of the science of heat, which were described mathematically, are built into the optimization algorithm.

Lists of symbols and subscripts are as follows:

Symbols:

- $\dot{m}$ [kg/s] mass flow,
- q [m^3/s] volume flow,
- t [°C] temperature,
- T [K] absolute temperature,
- p [Pa] absolute pressure,
- P [W] performance,
- x [kg/kg] moisture relating to the mass of dry air,
- ξ [kg/kg] moisture relating to the mass of wet sugar,
- $\dot{Q}$ [J/s] heat flow,
- r [J/kg] hidden heat,
- c [J/(kgK)] specific heat,
- R [J/(kgK)] gas constant.

Subscripts:

- c: sugar,
- m: warm air,
- h: cold air,
- b: incoming,
- k: outgoing,
- 1,2: cross-sections,
- t: axis,
- f: heating,
- o: environment,
- a: relating to 20°C,
- s: drying,
- z: cooling,
- p: constant pressure,
- g: steam,
- v: water,
- tel.: saturated.

The working scheme of sugar-drying cylinder is visible in Fig.1.

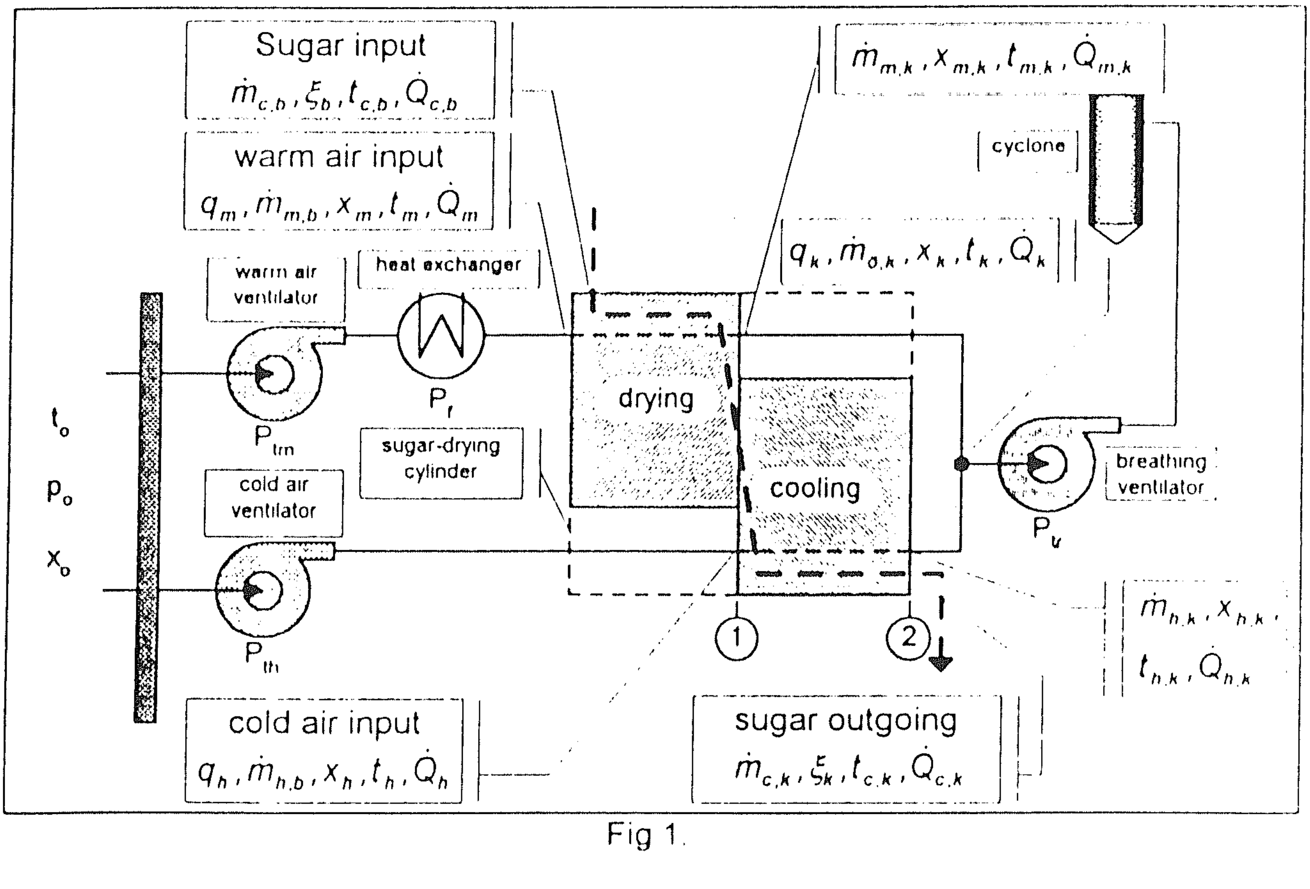

Fig 1.

The wet sugar input is at the left side of the sugar-drying cylinder. First it contacts with the warm air. Most part of the sugar's moisture is given to this air, while its temperature is decreasing. At the right side of the sugar-drying cylinder the incoming cold air under the sugar decreases its temperature. The heat-power engineering model is described in [1]. Here we would like to emphasize, that at the first part, at the end of the drying process in the sugar-drying cylinder (1st cross-section) the temperatures of the sugar and drying air are equal:

$$t_1 = t_{c,1} = t_{m,1} \; (= t_{m,k}) \,. \tag{1}$$

The moisture of the air and sugar is as follows:

$$x_1 = x_{m,1} \; (= x_{m,k}) \,, \tag{2}$$

$$\xi_{c,1} = \xi_k \,. \tag{3}$$

At the second part, at the end of the cooling process in the sugar-drying cylinder (2nd cross-section) the temperatures of the sugar and cooling air are also equal:

$$t_2 = t_{c,2} \; (= t_{c,k}) = t_{h,2} \; (= t_{h,k}) \,. \tag{4}$$

In this sector neither the sugar's, nor the air's moistures are not changing greatly:

$$x_{h,k} = x_h \,. \tag{5}$$

Using these heat considerations our aim is to do the drying and cooling of the sugar using the smallest energy. We should do this using the environmental air, what is available.

The total performance to be minimized is as follows:

$$P = P_t + P_{tm} + P_{th} + P_{t\ell} \,. \tag{6}$$

In Eq. 6 the performances are the following:

- The thermal performance of the warm air in the heat exchanger:

$$P_t = (c_p + c_{pg} \cdot x_m) \cdot \dot{m}_m \cdot (t_m - t_o) \;, \tag{7}$$

  where $\dot{m}_m = \dot{m}_{m,h} / (1 + x_m)$ the mass of the incoming dry air.

- The axial output of the „warm air" ventilator:

$$P_{tm} = q_m \cdot \frac{T_a}{T_o} \cdot \frac{\Delta p_{\delta,m}(q_m)}{\eta_m(q_m)} \;, \tag{8}$$

  where $\Delta p_{\delta,m}(q_m)$ and $\eta_m(q_m)$ the total pressure and efficiency curves of the ventilator at temperature T_a.

- The axial output of the „cold air" ventilator is similar:

$$P_{th} = q_h \cdot \frac{T_a}{T_o} \cdot \frac{\Delta p_{\delta,h}(q_h)}{\eta_h(q_h)} \,. \tag{9}$$

- The performance of the breathing ventilator, outgoing from the drying cylinder and incoming to the dust-collecting cyclone:

$$P_{t\ell} = q_k \cdot \frac{T_a}{T_k} \cdot \frac{\Delta p_{\delta,\ell}(q_k)}{\eta_\ell(q_k)} \,. \tag{10}$$

We are looking for the minimum of Eq.6 due to the following circumstances:

■ Given constants:	t_o, p_o, x_o,	i.e. the environmental properties, where the drying-cooling air comes from;
	$\dot{m}_{c,b}, t_{c,b}, \xi_o$,	i.e. the condition of the incoming sugar.
■ Prescribed data:	$t_{c,k}$,	i.e. the temperature of the outgoing sugar, which is necessary for the long-term storage.

■ Variables: $t_m, q_m,$ i.e. the volume and temperature of the warm air, with upper and lower limits:

$t_o \le t_m \le t_{c.b}$,

$q_{m,min} \le q_m \le q_{m,max}$ (high efficiency working-region of the ventilator).

■ Constraints: $q_h,\ q_\ell,\ \xi_h,$ i.e. those quantities, which have upper and lower bounds:

$q_{h,min} \le q_h \le q_{h,max}$ (high efficiency working-region of the ventilator),

$q_{\ell,min} \le q_\ell \le q_{\ell,max}$ (high efficiency working-region of the ventilator),

$q_{k,min} \le q_k \le q_{k,max}$ (necessary moisture for the storage).

The available formulae from the heat technique model are as follows:

Drying phase:

★ Degree of heat-change

$$\Delta\dot{Q}_s = k \cdot \dot{m}_{c.b} \cdot (t_{c.b} - t_m) \quad , \tag{11}$$

where k is a reduced heat-change coefficient, characteristic to the drying equipment, can be determined by measurements.

★ Sugar heat-loss:

$$\Delta\dot{Q}_s = \dot{m}_{c.b} \cdot \left\{ \left[c_c \cdot (1 - \xi_0) + c_v \cdot \xi_0 \right] \cdot t_{c.b} - \left[c_c \cdot (1 - \xi_k) + c_v \cdot \xi_k \right] \cdot \frac{1 - \xi_0}{1 - \xi_k} t_1 \right\} \tag{12}$$

★ Absorbed heat by the warm air:

$$\Delta\dot{Q}_s = \dot{m}_m \cdot \left\{ \left[c_p \cdot t_1 + x_1 \cdot \left(c_{pg} \cdot t_1 + r_o \right) \right] - \left[c_p \cdot t_m + x_m \cdot \left(c_{pg} \cdot t_m + r_o \right) \right] \right\} \tag{13}$$

★ Moisture changing:

$$\left(\xi_0 - \xi_k \cdot \frac{1 - \xi_0}{1 - \xi_k} \right) \cdot \dot{m}_{c.b} = \left(x_1 - x_m \right) \cdot \dot{m}_m \ . \tag{14}$$

Cooling phase:

★ Sugar heat-loss:

$$\Delta\dot{Q}_t = \dot{m}_{c.b} \cdot \left[c_c \cdot (1 - \xi_k) + c_v \cdot \xi_k \right] \cdot \frac{1 - \xi_0}{1 - \xi_k} \left(t_1 - t_2 \right) \ . \tag{15}$$

★ Absorbed heat by the cold air:

$$\Delta\dot{Q}_t = \dot{m}_h \cdot \left\{ \left[c_p \cdot t_2 + x_h \cdot \left(c_{pg} \cdot t_2 + r_o \right) \right] - \left[c_p \cdot t_h + x_h \cdot \left(c_{pg} \cdot t_h + r_o \right) \right] \right\} \ . \tag{16}$$

Mixing of air after the drying cylinder:

★ Degree of moistures:

$$\left(\dot{m}_m + \dot{m}_h \right) \cdot x_k = \dot{m}_m \cdot x_1 + \dot{m}_h \cdot x_h \ . \tag{17}$$

★ Degree of heat energy:

$$\begin{aligned} &\left(\dot{m}_m + \dot{m}_h \right) \cdot \left[c_p \cdot t_k + x_k \cdot \left(c_{pg} \cdot t_k + r_o \right) \right] = \\ &\quad = \dot{m}_m \cdot \left[c_p \cdot t_1 + x_1 \cdot \left(c_{pg} \cdot t_1 + r_o \right) \right] + \dot{m}_h \cdot \left[c_p \cdot t_2 + x_h \cdot \left(c_{pg} \cdot t_2 + r_o \right) \right] \end{aligned} \tag{18}$$

Using the previous equations we can establish the calculation, with the following main steps:

❶
$$\Delta\dot{Q}_s = k\cdot\dot{m}_{c,b}\cdot(t_{c,b}-t_m)\ ; \tag{19}$$

❷
$$\xi_k = \xi_b - \left[\frac{1}{r_o}\cdot\left[\frac{\Delta\dot{Q}_s}{\dot{m}_m} + c_p\cdot t_m + x_m\cdot\left(c_{pg}\cdot t_m + r_o\right) - D\left(\xi_k\right)\right] - x_m\right]\cdot\frac{\dot{m}_m}{\dot{m}_{c,b}}\cdot\left(1-\xi_k\right) \tag{20}$$

convergent iterative calculation to determine ξ_k, where:

$$D\left(\xi_k\right) = \left[c_p + c_{pg}\cdot\left(x_m + \frac{\dot{m}_{c,b}}{\dot{m}_m}\cdot\frac{\xi_b-\xi_k}{1-\xi_k}\right)\right]\cdot t_1\left(\xi_k\right)\ , \tag{21}$$

$$t_1\left(\xi_k\right) = \frac{\left[c_c\cdot\left(1-\xi_b\right)+c_v\cdot\xi_b\right]\cdot t_{c,b} - \dfrac{\Delta\dot{Q}_s}{\dot{m}_{c,b}}}{\left[c_c\cdot\left(1-\xi_k\right)+c_v\cdot\xi_k\right]\cdot\dfrac{1-\xi_b}{1-\xi_k}}\ ; \tag{22}$$

❸ t_1 can be calculated using the previous iterative calculation, from Eq.22 we can get;

❹
$$x_1 = \frac{\dfrac{\Delta\dot{Q}_s}{\dot{m}_{c,b}} + c_p\cdot t_m + x_m\cdot\left(c_{pg}\cdot t_m + r_o\right) - c_p\cdot t_1}{c_{pg}\cdot t_1 + r_o}\ ; \tag{23}$$

❺
$$\dot{m}_h = \dot{m}_{c,b}\cdot\frac{\left[c_c\cdot\left(1-\xi_k\right)+c_v\cdot\xi_k\right]\cdot\dfrac{1-\xi_b}{1-\xi_k}\cdot\left(t_1-t_2\right)}{\left[c_p\cdot t_2 + x_h\cdot\left(c_{pg}\cdot t_2 + r_o\right)\right] - \left[c_p\cdot t_h + x_h\cdot\left(c_{pg}\cdot t_h + r_o\right)\right]}\ ; \tag{24}$$

❻
$$\dot{m}_k = \dot{m}_m + \dot{m}_h\ ; \tag{25}$$

❼
$$x_k = \frac{\dot{m}_m\cdot x_1 + \dot{m}_h\cdot x_h}{\dot{m}_k}\ ; \tag{26}$$

❽
$$t_k = \frac{\dot{m}_h\cdot\left[c_p\cdot t_2 + x_h\cdot\left(c_{pg}\cdot t_2 + r_o\right)\right] + \dot{m}_m\cdot\left[c_p\cdot t_1 + x_1\cdot\left(c_{pg}\cdot t_1 + r_o\right)\right] - \left(\dot{m}_m + \dot{m}_h\right)\cdot x_k\cdot r_o}{\dot{m}_k\cdot\left(c_p + x_k\cdot c_{pg}\right)}\ ; \tag{27}$$

❾
$$\dot{m}_{a,k} = \dot{m}_k\cdot\left(1 + x_k\right)\ ; \tag{28}$$

$$q_m = \frac{\dot{m}_{m,b}}{\rho(t_m, p_m)}, \quad q_h = \frac{\dot{m}_{h,b}}{\rho(t_h, p_h)}, \quad q_k = \frac{\dot{m}_{o,k}}{\rho(t_k, p_k)}, \tag{29a.b.c}$$

where

$$\rho(t,p) = \left[\frac{p}{R} - \left(\frac{1}{R} - \frac{1}{R_g}\right) \cdot p_{g\,tel}(t)\right] \cdot \frac{1}{(t + 273.15)} \tag{30}$$

The equations above have built into the optimization system, Hillclimb [4,5]. Using this technique we can calculate the minimum energy consumption, the volume and temperature of warm and cold airs due to given environmental conditions, in- and outgoing sugar temperatures.

In our example the incoming sugar moisture is varies, the followings are constants

- environmental conditions: t_o=17.8°C, p_o=1,038bar, φ_o=61.3%;
- volume and temperature of incoming sugar: $\dot{m}_{c,b}$ = 11,4 kg/s, $t_{c,b}$=55°C;
- temperature of outgoing sugar: $t_{c,k}$=34°C.

Upper and lower limits are as follows:

$0{,}00018 \le \xi_k \le 0{,}002 \qquad 4\,m^3/s \le q_m,\ q_h \le 9\,m^3/s \qquad 8\,m^3/s \le q_k \le 17\,m^3/s$

The results of the calculations can be seen on Fig. 2.,3.,4. and 5.

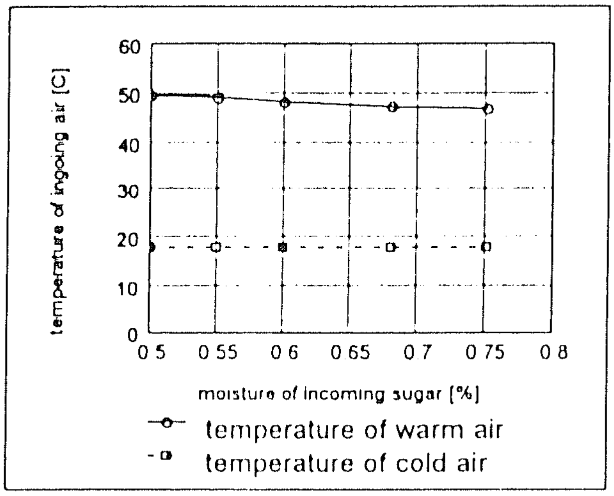

Fig.2.

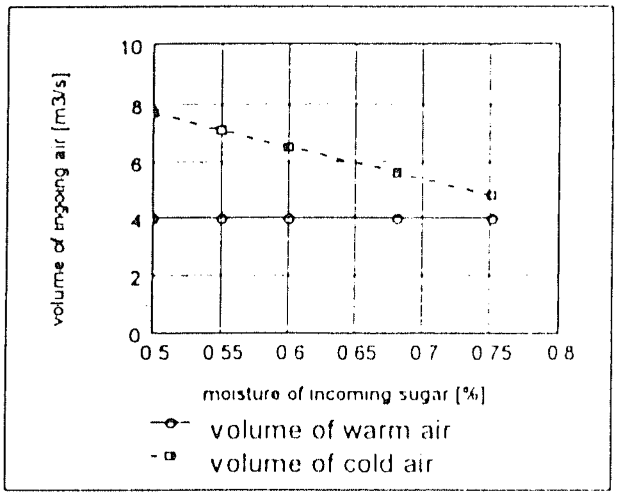

Fig.3.

According to the figures it is visible, that increasing the moisture every parts of the performance are decreasing, but the ratio of these parts are nearly the same. 60% part of the performance comes from the heating of warm air, 20% comes from the breathing ventilator, and 10-10% comes from the warm and cold air ventilators. Increasing moisture of sugar causes a small decreasement in the temperature of the drying air, while the volume of air is at the lower bound given by the ventilator. This minimal volume of air is also necessary to keep the sugar in this fluidization stage. The necessary volume of cold air can be decrease by increasing the moisture content.

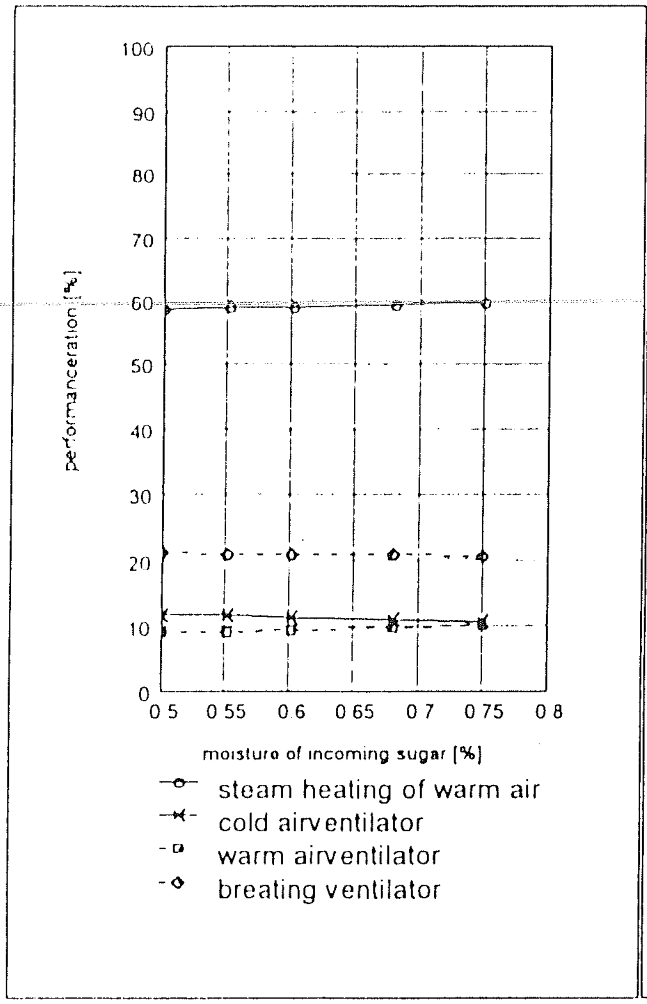

Fig.4

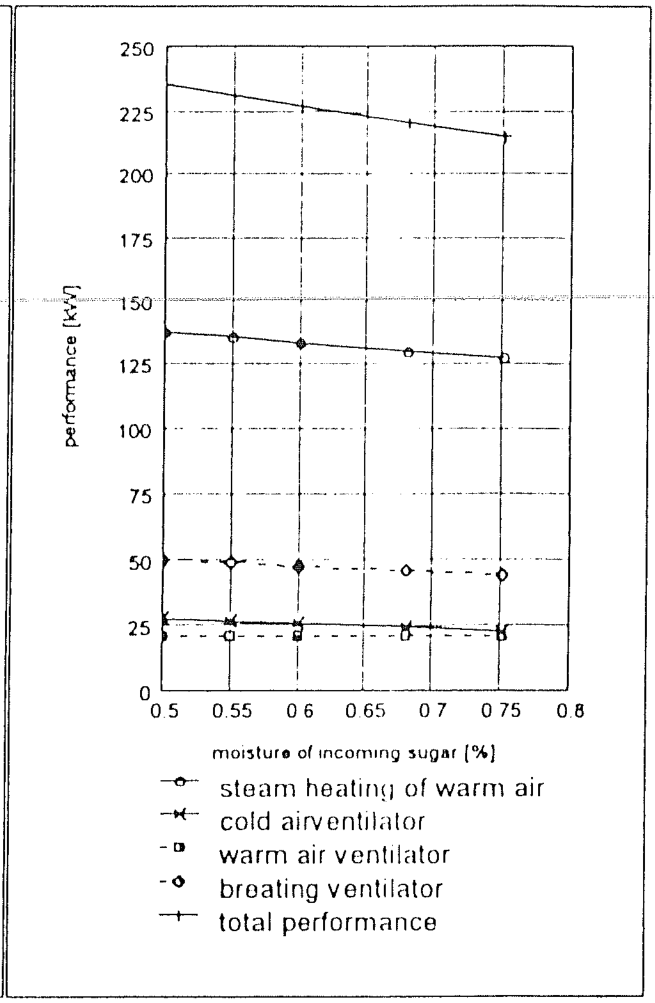

Fig.5

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ACKNOWLEDGEMENT

This work has been supported by grant OTKA 22846 of the Hungarian Fund for Scientific Research.