*Journal of Engineering Physics and Thermophysics, Vol. 71, No. 6, 1998*

# CONDUCTIVE-CONVECTIVE DRYING INSTALLATIONS: PROBLEMS AND CALCULATION

A. P. Bel'skii and L. V. Mol'vo

UDC 676.2.026.5.012.7

*We present a procedure to calculate multicylinder conductive-convective drying installations and equations to determine the temperatures of a paper strip when on cylinders and off them. Dependences are obtained to calculate the intensities of moisture evaporation and reduction of the moisture content of fibrous wood-pulp paper materials over corresponding portions, as well as a formula to calculate the relationship between evaporated moisture on cylinders and off them in the "on a drying cylinder-off a drying cylinder" cycles.*

Multicylinder conductive-convective drying installations have come into wide use in the wood-pulp and paper, textile, and chemical industries for drying cellulose, paper, cardboard, fabric, and other thin materials in rolls due to their high efficiency, small energy expenditures, and the ability to impart the necessary consumer properties to the products manufactured. But they are very bulky and metal-intensive and have a high inertia in controlling operating regimes and a high fabrication cost, and therefore problems associated with calculation of the necessary number of drying cylinders to ensure the design capacity of paper- and cardboard-making machines press-parts for the prescribed temperature chart of drying and technological characteristics of the products manufactured are of current interest.

Figure 1 presents a schematic diagram of a multicylinder conductive-convective drying installation consisting of drying cylinders, a ventilation hood, a system for heat regeneration, a pressing grid, and other units. In such installations a moist strip of material alternately bends around the heated surfaces of drying cylinders, which heat it, and then it is cooled on coming in contact with the surrounding air, and the oscillating effect of heat sources on the material results in intense heat and mass exchange between the moist surface of the paper strip and the surrounding medium. In order to improve the contact between the moist material and the heating surface of the cylinders and to decrease the breakoff of the paper strip, drying nets are used. The water vapor formed is removed as a vapor-air mixture into the system for heat recuperation to decrease the expenditure of heat energy on drying the material.

The process of drying moist materials on multicylinder installations is a rather complex process, because the heat and mass transfer on drying cylinders and in the space between them has a different character: on a drying cylinder the heat is supplied to one side of the material by conduction, as a result of which the material is heated and it accumulates a certain amount of heat, whereas over the stretches between cylinders convective heat and mass exchange occurs from both sides of the material with intense evaporation of moisture. Moreover, the nonstationarity of the processes of heat and mass exchange is attributable to the periods of drying, namely, to the heating of the material, and to the periods of constant and declining rates of drying. The mechanism, heat and mass exchange, and kinetics of combined conductive-convective drying of moist materials were studied in [1-4]. In [5], a procedure was developed to calculate multicylinder conductive-convective drying installations using averaged thermophysical quantities: the temperature of the paper strip and the drying cylinders, the moisture content of the material, and other performance figures; but this introduces a considerable error into the determination of the efficiency and the number of cylinders of such machines.

The structural characteristics of multicylinder conductive-convective drying installations are determined by the diameter $D$ and length $B_c$ of the cylinders, the distance between the axes of the cylinders along the horizontal

---

St. Petersburg State Technological University of Plant Polymers. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 71, No. 6, pp. 1000-1005, November-December, 1998. Original article submitted April 8, 1997; revision submitted December 2, 1997.

1062-0125/98/7106-0963$20.00 ©1999 Kluwer Academic/Plenum Publishers 

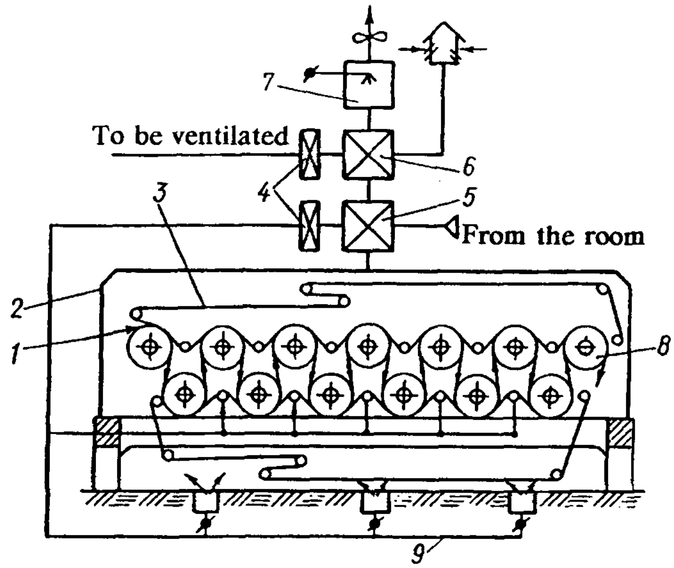


Fig. 1. Diagram of a multicylinder conductive-convective drying installation: 1) paper strip, 2) ventilation cover, 3) drying grid, 4) air heaters, 5) 1st-stage heat collector, 6) 2nd-stage heat collector, 7) scrubber, 8) drying cylinder, 9) supply of drying air.

$L$ and the vertical $H$, on which the fractional coverage $\varphi_c$ and the free space between the cylinders $l_{off}$ depend, and the presence of a cover for the drying portion.

The parameter $\varphi_c$ is calculated by the formula

$$\varphi_c = 1 - \frac{1}{0.318}\left(\arccos\frac{H}{\sqrt{\left(H^2 + \left(\frac{L}{2}\right)^2\right)}} + \arccos\frac{\frac{d+D}{2}}{\sqrt{\left(H^2 + \left(\frac{L}{2}\right)^2\right)}}\right). \quad (1)$$

In the design the parameters $D$, $H$, and $L$ are selected so as to obtain the maximum intensity of moisture evaporation and correspondingly to decrease the overall dimensions of the drying installation.

The length of the free space for the paper strip between the cylinders is equal to

$$l_{off} = \sqrt{\left(H^2 + L^2 - \left(\frac{d+D}{d}\right)^2\right)}. \quad (2)$$

In recent years the so-called nonbreakoff guide of a paper strip in conductive-convective installations has come into use, in which the lower row of cylinders is replaced by nonheated large-diameter guiding rollers, upon which a drying net moves, with the paper strip on it; it is the reason why formulas (1) and (2) contain the diameter of the shaft $d$.

The regime characteristics of the drying portion are determined by the temperature chart, the physicomechanical and physicochemical properties of the products manufactured, and the duration of stay of the paper strip on the cylinders and between them.

The basic problem of structural calculation of the drying section, just as in other thermal calculations, is the determination of the number of paper-drying cylinders for attaining the required final moisture content of the paper strip for the prescribed prodictivity, the necessary temperature chart of drying, the density of a square meter of the material to be dried, and its physicomechanical and chemical properties.

A further development of calculation of conductive-convective drying installations is a procedure devised by the present authors and based on determination of the temperature, the intensity of moisture evaporation, and the decrease in the moisture content of the paper strip after each cylinder and the free space in between.

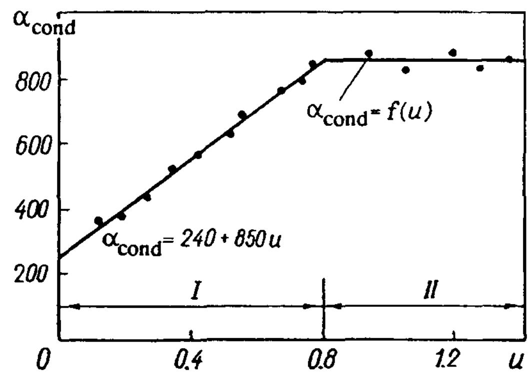

Fig. 2. Change in the coefficient of conductive heat exchange ($\alpha_{cond}$) as a function of the moisture content of the paper strip ($u$) in the period of declining (I) and constant (II) rates of drying. $\alpha_{cond}$, W/(m$^2$·K); $u$, kg/kg.

The cycle includes the duration of stay of the strip on a cylinder ($\tau_{cont}$) and in a free space ($\tau_{off}$):

$$\tau_{cyc} = \tau_{cont} + \tau_{off}\,. \tag{3}$$

Using equations of heat balance and heat exchange between the heating surface and the paper strip, we obtain a formula for determining the temperature of the strip on leaving a drying cylinder:

$$t''_r = t_c - \frac{t_c - t'_r}{\exp \dfrac{(1-\varphi_1)\,\alpha_{cod}\,\tau_{cont}}{p_{d.s}\,(c_{d.s} + uc_m)}}\,. \tag{4}$$

The coefficient of conductive heat exchange $\alpha_{cond}$ was determined experimentally. It depends on the condition of the drying-cylinder surface and the smoothness of the material being dried, the pressure at which the material is pressed against the heating surface, the temperature of the drying cylinders, and other factors. In the period of constant rate of drying for newsprint and writing-printing types of paper the coefficient of conductive heat exchange $\alpha_{cond}$ turned out to be equal to 800-850 W/(m$^2$·K). In the period of declining rate of drying, when the current moisture content $u$ becomes lower than the critical value $u_{cr}$, the coefficient $\alpha_{cond}$ decreases due to worsening of the contact between drier layers of paper and the heating surface and formation of a vapor interlayer, which leads to an increase in the thermal resistance to the propagation of the heat flux from the condensed vapor in the cavity of a cylinder to the paper strip (Fig. 2).

The periods of constant and declining rates of drying are separated by the quantity $u_{cr}$, which depends mainly on the density of the material being dried and can be calculated from the linear dependence

$$u_{cr} = 1.6p_{d.s} + 0.72\,. \tag{5}$$

Over the stretch between cylinders moisture evaporates intensely due to convective heat and mass exchange and mainly owing to the heat accumulated during the stay of the paper strip on the drying cylinders.

In order to determine the temperature of the paper strip at the end of a stretch between cylinders, we found a solution of the differential equation of heat balance and mass exchange in the form

$$\frac{11.12P_a^{0.67}\,\beta_p r}{(c_{d.s} + uc_m)\,p_{d.s}}\left(\frac{u}{u_{cr}}\right)^n \tau_{off} = \ln\frac{(P_{v1}^{0.33} - P_a^{0.33})^2\,[P_{v2}^{0.67} + (P_{v2}\,P_a)^{0.33} + P_a^{0.67}]}{(P_{v2}^{0.33} - P_a^{0.33})^2\,[P_{v1}^{0.67} + (P_{v1}\,P_a)^{0.33} + P_a^{0.67}]} -$$

$$-\,3.46\left(\arctan\frac{2P_{v1}^{0.33} + P_a^{0.33}}{1.73P_a^{0.33}} - \arctan\frac{2P_{v2}^{0.33} + P_a^{0.33}}{1.73P_a^{0.33}}\right). \tag{6}$$

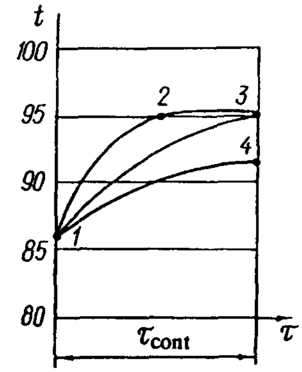


Fig. 3. Regimes of drying of a paper strip: low-intensity (curve 1-4), high-intensity (curve 1-2-3), and rational (curve 1-3). $t$, °C.

Using the method of bisection (dividing in half), from Eq. (6) we found the partial pressure of the vapor at the end of a free stretch $P_{v2}$, from which we determined the saturated-vapor temperature, which corresponds to the temperature of the paper strip in the period of constant rate of drying. This temperature was taken as a reference temperature in arrival at the next cylinder.

The coefficient of mass exchange $\beta_p$ in evaporation of moisture over the stretches between cylinders was determined from the formula

$$\beta_p = \frac{1.736 \cdot 10^{-6} \left(\frac{w_{mach}\, l_{off}}{60 \nu_{m.a}}\right)^{0.75} (273 + \bar{t}_p)}{l_{off}\, R_g} . \tag{7}$$

Over the active length of a drying cylinder and over a stretch between cylinders, the evaporation of moisture leads to a decrease in the moisture content of the paper strip whose magnitude for an individual cycle was determined from the following formulas: over the active length of a drying cylinder

$$\Delta u_{cont} = \frac{3.6\,(1 - \varphi_1)\, \alpha_{cond}\, (t_c - \bar{t}_p)\, \varphi_c\, \pi D_c}{60\,(2493 - 2.22\bar{t}_p)\, p_{d.s}\, w_{mach}} , \tag{8}$$

over a free stretch between cylinders

$$\Delta u_{off} = \frac{2\beta_p\, (\bar{P}_v - P_a)}{60 p_{d.s}\, w_{mach}} . \tag{9}$$

The total decrease in the moisture content of the paper strip in one "on-off" cycle is equal to

$$\Delta u_{cyc} = \Delta u_{cont} + \Delta u_{off} . \tag{10}$$

Using the above equations and coefficients obtained experimentally on a laboratory rig and on operating paper-making machines, we compiled a program for heat-engineering calculation of a multicylinder conductive-convective installation for individual "on a drying cylinder-off the drying cylinder" cycles with determination of the temperature and moisture content of the paper strip before and after the drying cylinders and between them, the intensity of moisture evaporation, vapor flow rates, and other parameters, which made it possible to develop rational regimes of the processes of drying paper, cardboard, and cellulose.

Of great importance is the problem of the quantitative relationship between the amounts of moisture evaporating on a drying cylinder and between cylinders. Based on analytical and experimental investigations carried out, it is established that the fraction of moisture evaporating over a stretch between cylinders is equal to

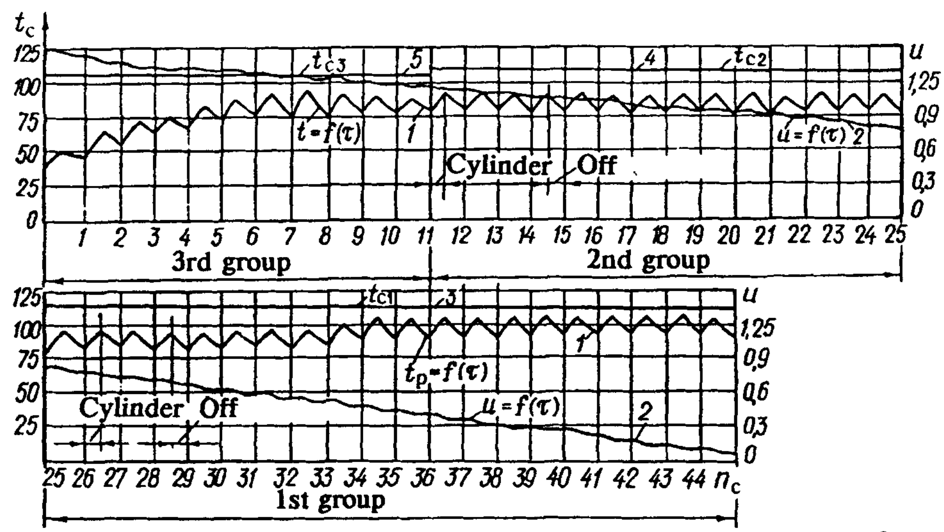


Fig. 4. Calculated parameters of drying of newsprint of density 50 g/m$^2$ on a multicylinder conductive-convective installation at a speed of the machine of 1000 m/min (the diameter of the cylinders is 1800 mm): 1) thermogram of drying of a paper strip, 2) curve of the kinetics of drying, 3, 4, 5) temperatures of the cylinder surfaces in the 1st, 2nd, and 3rd vapor groups, respectively.

$$K_{\text{off}} = \left[ 1 + \frac{8.2 \cdot 10^7 \, \Delta u_{\text{cyc}} \, p_{\text{d.c}} \, R_g \, l_{\text{off}}^{0.25} \, v_{\text{m.a}}^{0.75}}{w_{\text{mach}}^{0.75} \, (273 + \bar{t}_p)^{0.87} \, (\bar{P}_v - P_a) \, \tau_{\text{cont}}} \right]^{-1} . \tag{11}$$

In the case of high-speed machines ($w_{\text{mach}} > 800$ m/min) in the drying portion the main amount of moisture evaporates over the stretches between cylinders ($K_{\text{off}} = 0.7-0.9$, the cylinders heat the paper strip), whereas on low-speed machines the main amount of moisture evaporates on the drying cylinders ($K_{\text{off}} = 0.2-0.3$). Moreover, this relationship depends on the surrounding-medium parameters, the density of the product manufactured, and other factors.

Figure 3 presents thermograms of regimes of drying a paper strip in the period of constant rate, which consist of the segment of material heating from the initial temperature to the saturation temperature (curve 1-2) and the segment of moisture evaporation (curve 2-3). In such a regime the intensity of moisture evaporation on a cylinder is rather high; however the vapor formed here in contacting layer is filtered through the material by the pressure gradient, imparting increased porosity and air permeability to the paper strip.

Using the equations derived, we performed a computer calculation of the processes of drying a paper strip on a multicylinder conductive-convective installation (Fig. 4). We obtained a thermogram and a curve of the kinetics of drying for the corresponding temperature chart of the drying cylinders. The calculation by cycles was carried out until the material acquired moisture-content equilibrium with the surrounding medium.

Under low-intensity operating conditions the paper strip is heated up to an intermediate temperature not attaining the temperature of the saturated state (curve 1-4). Here the main amount of moisture evaporates over the stretches between cylinders. Obviously, an operating regime where on leaving a drying cylinder the paper strip acquires a temperature equal to the temperature of the saturated state at atmospheric pressure should be considered optimum; here the maximum intensity of moisture evaporation is attained, and the material acquires a locked structure (curve 1-3). In view of this, high requirements should be imposed on the systems for ventilation of the intercylinder spaces to obtain the maximum values for the difference in the partial pressures of the vapor at the evaporation surface and in the ambient air.

Moreover, the drying portion of a paper-making machine consumes a large amount of thermal energy. To decrease unproductive losses to the surrounding medium, the cylinders are covered by a ventilation hood, and the heat of the spent vapor-air mixture is used to heat the ventilating and drying air and the process water.

On the basis of the computational procedure developed by us it is possible to calculate the discharge of vapor on each drying cylinder, which allows one to select rather exactly the condensate-removing facilities and the throttling orifices, as a result of which losses of heat with the discharged vapor decrease.

## CONCLUSIONS

1. The procedure developed by us to calculate multicylinder conductive-convective drying installations for individual "on a drying cylinder-off the drying cylinder" cycles in designing new installations makes it possible to determine more exactly the structural characteristics from the prescribed temperature chart of drying, the machine capacity, and the type of product manufactured.

2. Applying the procedure suggested to machines now in use, it is possible to find rational temperature regimes of drying for obtaining maximum productivity and the qualitative indices of the finished products, to determine the discharge of vapor on each cylinder, and to select the condensate-removing facilities. An expression is obtained to determine the relationship between the amounts of moisture evaporating on the cylinders and over the stretches between cylinders for a paper strip.

## NOTATION

$D$, $d$, diameters of a drying cylinder and a guiding lower shaft, m; $n_c$, number of cylinders; $B_c$, length of a drying cylinder, m; $H$, $L$, distances between the axes of the drying cylinders along the height and the horizontal, m; $l_{off}$, length of the stretch for the paper strip between drying cylinders, m; $\varphi_c$, fraction of a drying cylinder covered by the paper strip; $\varphi_1$, fraction of heat expended to evaporate moisture on a drying cylinder; $\tau_{cont}$, $\tau_{off}$, $\tau_{cyc}$, duration of contact of the moist material with the heating surface, of stay off the heating surface, and of the cycle, respectively, sec; $t'_p$, $t''_p$, $\bar{t}_p$, $t_c$, temperatures of the paper strip ahead of and behind a drying cylinder, the mean temperature of the paper strip, and the temperature of the heating surface of a drying cylinder, $^oC$; $\alpha_{cond}$, coefficient of conductive heat transfer to moist paper, $W/(m^2 \cdot K)$; $\rho_{d.s}$, density of 1 $m^2$ of the paper strip, $kg/m^2$; $c_{d.s}$, $c_m$, specific heats of the dry mass of the paper strip and the moisture, $kJ/(kg \cdot K)$; $u$, $u_{cr}$, current and critical moisture contents of the paper strip, kg/kg; $\Delta u_{cont}$, $\Delta u_{off}$, $\Delta u_{cyc}$, decrease in the moisture content over the stretch of contact of moist material with a cylinder, over the stretch between cylinders, and for a cycle; $P_a$, $P_{v1}$, $P_{v2}$, partial pressures of the water vapor in the ambient air and at the surface of the paper strip at the beginning and at the end of the stretch between cylinders, Pa; $\bar{P}_v$, mean partial pressure of the water vapor at the material surface over the stretch between cylinders, Pa; $\beta_p$, coefficient of mass exchange referred to the difference in the partial pressures of the vapor, $kg/(m^2 \cdot h \cdot Pa)$; $r$, heat of vaporization, kJ/kg; $R_g$, gas constant, $J/(kg \cdot K)$; $\nu_{m.a}$, kinematic viscosity of moist air, $m^2/sec$; $w_{mach}$, speed of the paper-making machine, m/min; $K_{off}$, fraction of the moisture evaporating over the stretch between cylinders for the paper strip. Subscripts: mach, machine; c, cylinder; p, paper; g, gas; v, vapor; a, air; m.a, moist air; m, moisture; d.s, dry strip; off, off a cylinder; cyc, cycle; cr, critical; $p$, partial pressure; cont, contact; cond, conductive; $n$, exponent.

## REFERENCES


1. A. V. Luikov, Theory of Drying [in Russian], Moscow (1968).
2. V. V. Krasnikov, Conductive Drying [in Russian], Moscow (1973).
3. D. M. Flyate, Properties of Paper [in Russian], Moscow (1976).
4. O. Krisher, Scientific Foundations of Drying Technology [Russian translation], Moscow (1961).
5. P. A. Zhuchkov, Thermal Processes in the Wood Pulp-Paper Industry [in Russian], Moscow (1978).